Pergamon

Adv. Space Res. Vol. 20, No. 4/5, pp. 883–894, 1997

Printed in Great Britain
0273-1177/97 $17.00 + 0.00

PII: S0273–1177(97)00496–1

TESTING SUBSTORM THEORIES: THE NEED FOR MULTIPOINT OBSERVATIONS

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ABSTRACT

The requirement for multipoint observations to test theories of magnetospheric substorms is reviewed. A wide variety of such theories have been proposed, but these cannot be properly evaluated because we do not understand how the various features of a substorm are causally linked. In terms of explaining certain substorm features, some theories may be mutually-exclusive rivals. But this is not always the case, making it possible that theories may be either combined into a synthesis model or loosely connected in a more modular view of substorms. Some key questions are defined which require multipoint in-situ measurements, combined with remote sensing observations, of the development and relationship of the major substorm features.

INTRODUCTION

Any comprehensive theory of magnetospheric substorms must explain all of a number of features and phenomena which are regularly observed during the typical sequence of events that we refer to as a substorm. Different theories allow varying degrees of flexibility, such that a variety of different behaviours and sequences can be explained. The extent to which we need a "modular" view of substorms (Elphinstone *et al.*, 1996) is not yet clear because we do not know which of the various substorm features always appear in association with which other features and, in many cases, we do not know the precise order in which they happen. Without this information the causal sequences and mechanisms are not known. The features that must be explained include:

- near-Earth signatures (such as onset, expansion and enhancement of auroral precipitation and electrojet, particle injections, Pi2 pulsations, the current wedge, field dipolarizations, etc.)
- mid-tail signatures (bursty-bulk flows, plasma sheet thickness variations, magnetic field threading the current sheet, dipolarizations)
- far-tail signatures (plasmoids/flux ropes in the plasma sheet, travelling compression regions (TCRs) in the lobe)
- removal of stress (reduction of lobe field strength)

This paper will not attempt to describe these features and signatures as they are extensively discussed in the cited literature. However, the last point of the above list is important and worthy of some elaboration. Considering that it was the last of the phases of the substorm cycle to be defined, there is now remarkable agreement on the features of the growth phase. These include: the growth in the lobe field at a variety of locations and the corresponding expansion of the ionospheric polar cap; the flaring of the tail lobe; the erosion of the dayside magnetopause; the enhancement of dayside ionospheric convection and the associated DP2 current system; stretching of the tail field; the association with southward interplanetary magnetic field (IMF). All of these are uniquely well explained by one process, namely the production of open flux by reconnection (of northward-pointing geomagnetic field with draped IMF in the magnetosheath that has a southward component) and the consequent accumulation of such open flux in the tail lobes (under the joint action of magnetic tension and the solar wind flow). As a result, there is little reasonable doubt that the features that make up a substorm are the collective response of the coupled magnetotail-ionosphere system to excess lobe flux. Furthermore, the tail lobe field is consistently seen to decrease at a variety of locations throughout the expansion and recovery phases (McPherron *et al.*, 1993) and so a substorm must be regarded as a means (total or partial) for relief of the stress exerted on the tail current sheet by the accumulation of tail lobe flux in the growth phase. Thus a theory of substorms which does not account for the closure of open lobe flux by reconnection in the tail current sheet at some interval during the cycle can immediately be classed as inadequate and is, at most, just one module of a more comprehensive theory.

SUBSTORM THEORIES

Substorm theories are rivals where they attempt to explain the same features: however in many cases they concentrate on different features. The theories fall into a number of classes:

- Near-Earth Current Disruption Models: these include both local effects (like cross-field current instability and current sheet catastrophe) and also more global MHD instabilities (such as the ballooning, flute and interchange instabilities).
- Near-Earth Neutral Line (NENL) Models: the "classical" form places the NENL at the same location as the near-Earth current disruption, but more recent "action at a distance" variants allow the current disruption to be closer to the Earth than the NENL (for example because of magnetic flux pile up or Earthward current diversion caused by the NENL).
- Boundary Layer Models: these invoke wave processes on the boundaries between plasma regimes, for example the inner edge of the low-latitude boundary layer and the outer edge of the plasma sheet.
- Ionospheric Coupling Models: these introduce ionospheric effects as part of a feedback loop which destabilises the onset region, they include modification of ionospheric conductivities and destabilising effects of upwelling ionospheric O^+ ions injected into the plasma sheet.

These, and other, theories have generally been evolved to explain certain features of a substorm. For example, the near-Earth current disruption theories are most effective in explaining the development and location of the early auroral expansion and electrojet, but do not explain the plasmoids/flux ropes and TCRs in the far tail, nor do they explain why a substorm removes the stress caused by excess lobe flux. On the other hand, the NENL models do a uniquely good job of explaining the plasmoids and TCRs and the removal of lobe flux, but do not include a satisfactory mechanism to explain the near-Earth signatures. Boundary layer models can provide explanations of auroral spirals, but these could be considered to be common to all transient filamentary field-aligned currents. The ionospheric conductivity changes and O^+ upflows undoubtedly occur but their consequences are not yet understood. One possibility is a synthesis view of models whereby, for example, the cross-tail current disruption leads to the formation of the NENL (Lui, 1991), or vice-versa (Baker *et al.*, 1993; Birn and Hesse, 1991). These call for a direct causal relationship between the various features. Another possibility is the "modular" approach, whereby the different mechanisms occur, often in different parts of the magnetosphere, in response to excess tail lobe flux but do not have more than a loose association with each other (Reeves *et al.*, 1993; Elphinstone *et al.*, 1996).

THE LOCATION AND TIMING OF ONSET AND OF NENL FORMATION

A highly influential finding of recent years has been that substorm onset (i.e. the first auroral brightening and the first disruption and diversion of the cross-tail current into the ionosphere in the current wedge) is on field lines which thread the current sheet relatively close to the Earth - at X between about -8 and -10 R_E (an Earth Radius, $1R_E$ = 6370 km and the positive X direction is from the Earth towards the sun). This has been deduced by a wide variety of methods (see review by Lockwood, 1995) of which just one is highlighted here because it demonstrates an interesting application of multipoint observations to the problem of determining the magnetic topology. Baker *et al.* (1993) deduced such a near-Earth onset location by mapping global UV images from both hemispheres into the tail using a magnetic field model. However, such models do not have adequate representation of the tail field changes during the substorm cycle and, indeed, one could argue that many of the major puzzles about substorms would already have been solved if they did. To overcome this, Baker et al. employed the work of Pulkinnen *et al.* (1991) who allowed for the changes in the field with an additional neutral sheet current which was increased until the model field matched observations made by a variety of satellites, spread throughout the middle and near-Earth tail.

The studies which found onset to take place close into the Earth were considered highly significant because reconnection signatures in the tail (accelerated ion flows with associated field threading the current sheet) never revealed a reconnection NENL Earthward of about X = $-19R_E$, at least in the statistical survey of AMPTE-IRM data by Baumjohann *et al.* (1989). However, a more recent survey by Nakamura *et al.* (1994) has found a few cases of tailward flows accompanied by southward-pointing field, such that the NENL is inferred to be Earthward of X = -19 R_E. Furthermore Sergeev *et al.* (1995) have recently presented an almost ideal set of dual-craft observations which unambiguously reveal a NENL moving tailward over both satellites which were on opposite sides of the current sheet and as near to the Earth as X = -15 R_E. These authors have also shown that the total pressure and plasma sheet thickness (remotely sensed using energetic particles) are also consistent with this interpretation. The flows seen after the passage of the X-line would be classed as a "bursty bulk flow" (BBF) event which have been shown by Angelopolous *et al.* (1994) to be responsible for the majority of Earthward flux and energy transport in the mid-tail neutral sheet. However, these events do not appear to have a clear relationship with substorms in general, and with onset in particular, although they can be co-incident in time with an intensification of the electrojet (Lopez *et al.*, 1994; Angelopolous *et al.*, 1996). This lack of a clear association is also apparent in the case reported by Sergeev *et al.* (1995), where the BBF, and the NENL which caused it, are seen just prior to the start of only a very weak substorm.

The identification of NENLs closer to the Earth than X = $-19R_E$ is significant because it means that their absence from the survey by Baumjohann *et al.* (1989) is not because this does not happen but, rather, is due to a small probability of seeing the signatures so close to the Earth. Sergeev *et al.* (1995) make the important point that a lack of such signatures can be regarded as a prediction, rather than a failure, of the reconnection-based models because the outflow wedge close to the NENL will be very thin. Thus the satellite must be in a very small range of Z values, relative to where the NENL forms, to see it. Furthermore, it must be in this special location for the interval when the NENL is Earthward of the satellite and this could be very brief because the NENL migrates tailward very rapidly after formation. Lastly, Angelopolous *et al.* (1996) have argued that the X-line and its BBF outflow signatures may be very localised in the cross-tail (Y) direction. These factors would lead to a very low probability of observation which, for a certain size dataset, leads to the occurrence frequency falling below the "one count level" at small X, the threshold being at X = - 19 R_E for the survey by Baumjohann *et al.* (1989). Angelopolous *et al.* (1996) considered the spatial localisation in 3 dimensions of reconnection signatures in the mid-tail. They looked forward to key questions being answered by the Cluster mission: this is just one of a number of examples which stress the vital importance of the attempts to recover the smaller-scale multipoint science that was promised by that mission.

Much of the evidence for onset being close to the Earth has relied on average models of the magnetic field and the accuracy of the connectivity that they predict has always been difficult to test, even for the dipole-like field lines inferred. However, recent observations by Hones *et al.* (1996) have matched energetic electron data from the LANL satellites in geostationary orbit with those from the polar-orbiting DMSP satellites in the ionosphere. This technique will only work if there are no major acceleration nor scattering mechanisms between the two. One example presented by these authors shows that the auroral arc which brightens at onset (seen just after onset but outside the current wedge) does indeed map to geostationary orbit and that the uncertainties in the models are not severe in this region. However, other examples find varying degrees of over- and under-stretching of the field in the models. The peak error in the ionospheric footprint of geostationary orbit was estimated to be about 1000 km, although it was typically less than 300 km. Because many rival models of substorms assume different magnetic connectivity to the substorm onset region in the ionosphere, these comparisons are of vital importance in testing the theories.

However, even if a NENL can sometimes form closer into Earth than has previously been inferred, and even if onset may not be quite as close to the Earth as has sometimes been suggested, it is unlikely that the two can be at the same location. This argument has been made in a number of ways, and is here presented in terms of the flux in the plasmoid/flux rope which is produced by the NENL and which is "pinched off" when the NENL starts to reconnect the open magnetic flux of the lobe. The left hand plots in figure 1 show a cross-section of the magnetotail in the ZX plane with positive Z (northward) up the page and positive X (toward the sun) to the left. The new NENL and the old far X-line are marked by the electric fields $\underline{E}_n$ and $\underline{E}_f$ which are the reconnection rates acting along their respective lengths. The right hand plots show the ionospheric projections of unit-length segments of these two X-lines, which are L_n and L_f long and are separated by a distance W in the north/south direction (up the page). The area of shown contains magnetic flux F which threads unit Y of the tail neutral sheet between the two X-lines and which is still connected to the ionosphere. The top panel shows the situation at a time t_o, when the NENL first forms. At this time $W = W_o$ and $F = F_o$ where the flux F is given by

$$F \approx B_i\, W(L_n + L_f)/2, \tag{1}$$

B_i being the magnitude of the ionospheric field (which is constant at about 5×10^{-5} T). The middle panel shows the situation at a later time t at which the NENL has reconnected some flux, the plasmoid has grown in size, and the length W has decreased from its initial value of W_o. The third panel shows the situation at the pinch off time t_p at which the NENL reconnects open lobe flux for the first time and the far X-line becomes disconnected from the Earth. The length W has reduced to zero at this time. We here consider a unit cross section of the plasmoid/flux rope. Per unit length in the Y direction (out of the plane of the left-hand diagrams in figure 1), the plasmoid contains a magnetic flux f at the time t, which rises from zero at time t_o to f_p at the time t_p at a rate given by Faraday's law, $df/dt = E_n$. As a result,

$$f(\,t_p \geq t > t_o) = \int_{to}^{t} E_n\, dt \tag{2}$$

and the flux F draped over the unit-length plasmoid decreases according to

$$F_o - F(t_p \geq t > t_o) = \int_{to}^{t} E_n\, dt - \int_{to}^{t} E_f\, dt = f(t_p \geq t > t_o) - \int_{to}^{t} E_f\, dt \tag{3}$$

When observed after pinch-off, the plasmoid contains a flux $f(t > t_p)$ per unit length which is approximately given by aB, where a is the dimension shown in panel 3 of figure 1 and B is the field inside the plasmoid (assumed to be constant). The NENL model requires that $E_n > 0$ at all $t > t_o$, so that after pinch-off, the flux in the unit-length plasmoid $f(t > t_p)$ must exceed that at the pinch-off time $f(t_p)$. This assumes that reconnection at the far X-line cannot run backwards (i.e. E_f must be positive) because after pinch off $df/dt = E_t$. Because it is generally thought that $E_f > 0$ is valid at all times, (3) yields the condition $F_o - F(t_p \geq t > t_o) < f(t > t_o)$. Because $F(t_p) = 0$, we therefore find that $f(t_p) > F_o$.

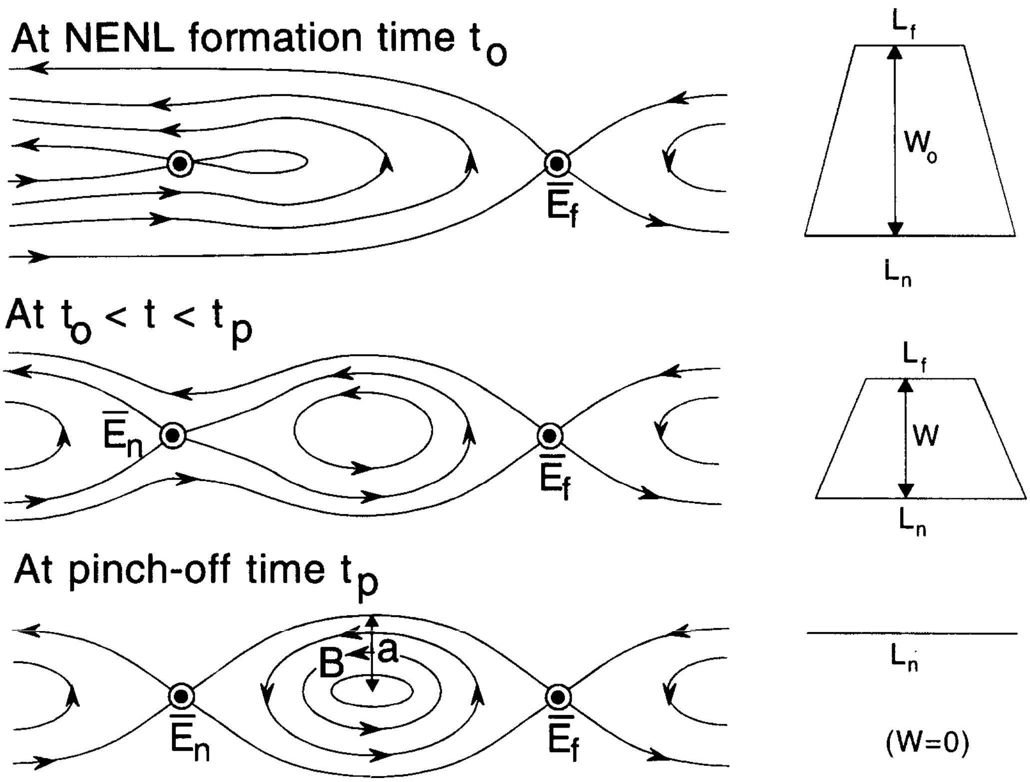

Figure 1. Growth of a plasmoid after formation of the NENL (at time $t = t_o$), to the time it is "pinched-off" ($t = t_p$). The left hand diagrams show cross-sections in the GSM Z-X plane, with the X direction (toward the sun) to the left and Z (northward) up the page. The right hand diagrams are ionospheric maps of unit-length segments of the two reconnection X-lines, with the poleward direction up the page.

From the above we derive the inequality:

$$aB \approx f(t>t_p) > f(t_p) > F_o \approx B_i W_o(L_n + L_f)/2 \qquad (3)$$

Observations of plasmoids yield peak values for the dimension a of about 7.5 R_E and values for the internal field of $B \sim 6$ nT (Slavin *et al.*, 1993). This gives a flux in unit length of cross section of the plasmoid of $f(t>t_p) \sim 0.3$ Wb m^{-1}. The lengths L_n and L_f can be taken from the mapping for the end of the growth phase in the study by Baker *et al.* (1993), as discussed above. This study yields values for L_n and L_f of (1/30) and (1/40), respectively. These are generally consistent with the Y-dimension of large plasmoids of 15 R_E, as deduced from the statistical survey by Slavin *et al.* (1993), which would map to full extent of the substorm electrojet and expansion of order 3000 km. Using (3), this enables us to set an upper limit to W_o of 170 km.

The above analysis thus leads to the conclusion that the NENL forms at a location which has an ionospheric projection, at most, 170 km equatorward of the open-closed field line boundary. This can be compared with the locations where onset is typically observed. The study by Elphinstone *et al.* (1995) uses a series of global UV images taken by the VIKING satellite to illustrate that onset can be much further from the open/closed boundary than 170 km. These images show a double oval configuration, which is unusual in that it is clearly seen in the growth phase of a substorm, due to prior activity. The sequence shows the growth phase ends with an auroral substorm, with onset taking place on the equatorward edge of the equatorward-most arc, roughly 600 km equatorward of the poleward arc of the double oval. This implies that onset was this far equatorward of the open/closed boundary, and this is confirmed by data from an overpass of a DMSP satellite, shortly before onset. The electron precipitation producing the arcs of the double oval configuration can be identified and the equatorward-most arc (which intensifies at onset) was more than 600 km equatorward of the open-closed boundary. This boundary is defined by a change in the electron characteristics (the edge of the weak polar rain precipitation) and the start of a VDIS (velocity-dispersed ion structure, see Bosqued *et al.*, 1993) which is well-explained as being on closed field lines contracting Earthward from a distant X-line (Onsager and Mukai, 1995; 1996). Other observations (eg. Gazey *et al.*, 1995; Fox *et al.*, 1995) confirm that onset can occur this deep into the closed field line region.

The "classical" NENL model, with onset at the location of NENL formation, would therefore have to explain a W_0 of order 600 km in these cases. This calls for a larger plasmoid field, B, and/or dimension, a, such that their product aB is increased by a factor of at least 4. In fact, the largest substorms do not tend to produce such extra-large plasmoids; rather, they yield a string of 4 or 5 smaller ones (Slavin *et al.*, 1993). The anomaly cannot be explained by summing the flux contained in these: 4 or 5 NENLs would be required, with each closer to the Earth than the previous one and each pinching off their respective plasmoid by reconnecting through to open-closed boundary. This would map to series of intensifications in the ionosphere, each one at lower latitudes than its predecessor, which is not a typical substorm behaviour and is not consistent with the location of onset.

Arguments of this kind have led to an acceptance that onset does not mark the location of NENL formation and that the classical NENL model must be modified to allow for this (see review by Lockwood, 1995). However, it is important to remember that the major and unique successes of the NENL model must be retained in any generalised model, namely the formation of plasmoids and TCRs and the removal of the excess tail lobe flux responsible for the substorm. Modifications to the classical NENL model include the concepts of flux pile up (Birn and Hesse, 1991) and cross-tail current diversion (Baker *et al.*, 1993), whereby reconnection at the NENL causes the current sheet disruption in a region closer to the Earth. However, in both cases the precise mechanism which can cause the near-Earth signatures is poorly defined. On the other hand, there are alternative models in which the NENL is established only after, and as a consequence of, the onset of a near-Earth cross-tail current disruption (Lui, 1991).

EQUATORWARD-DRIFTING ARCS

In the region between substorm onset and the open closed boundary, interesting features are often observed in the form of equatorward-drifting auroral arcs (Persson *et al.*, 1994a; b, Gazey *et al.*, 1995). Because these are seen in the late growth phase and early expansion phase, we must consider them as yet another response of the magnetosphere to the stimulus of excess tail lobe flux. Their importance in the overall sequence of events is not yet clear. What is known is that the poleward expansion of the substorm aurora does not alter their equatorward drift nor their luminosity, implying that they are formed in a region which is quite distinct from the onset region where the cross-tail current is initially disrupted. The poleward-expanding substorm aurora engulfs each arc and they are no longer seen when the expansion has moved beyond the persistent location where they are formed. This is often thought to be the open-closed boundary as it marks the edge of a completely dark polar cap. The formation of these arcs has been monitored by de la Beaujardiere *et al.*, (1994) who associated them with weak

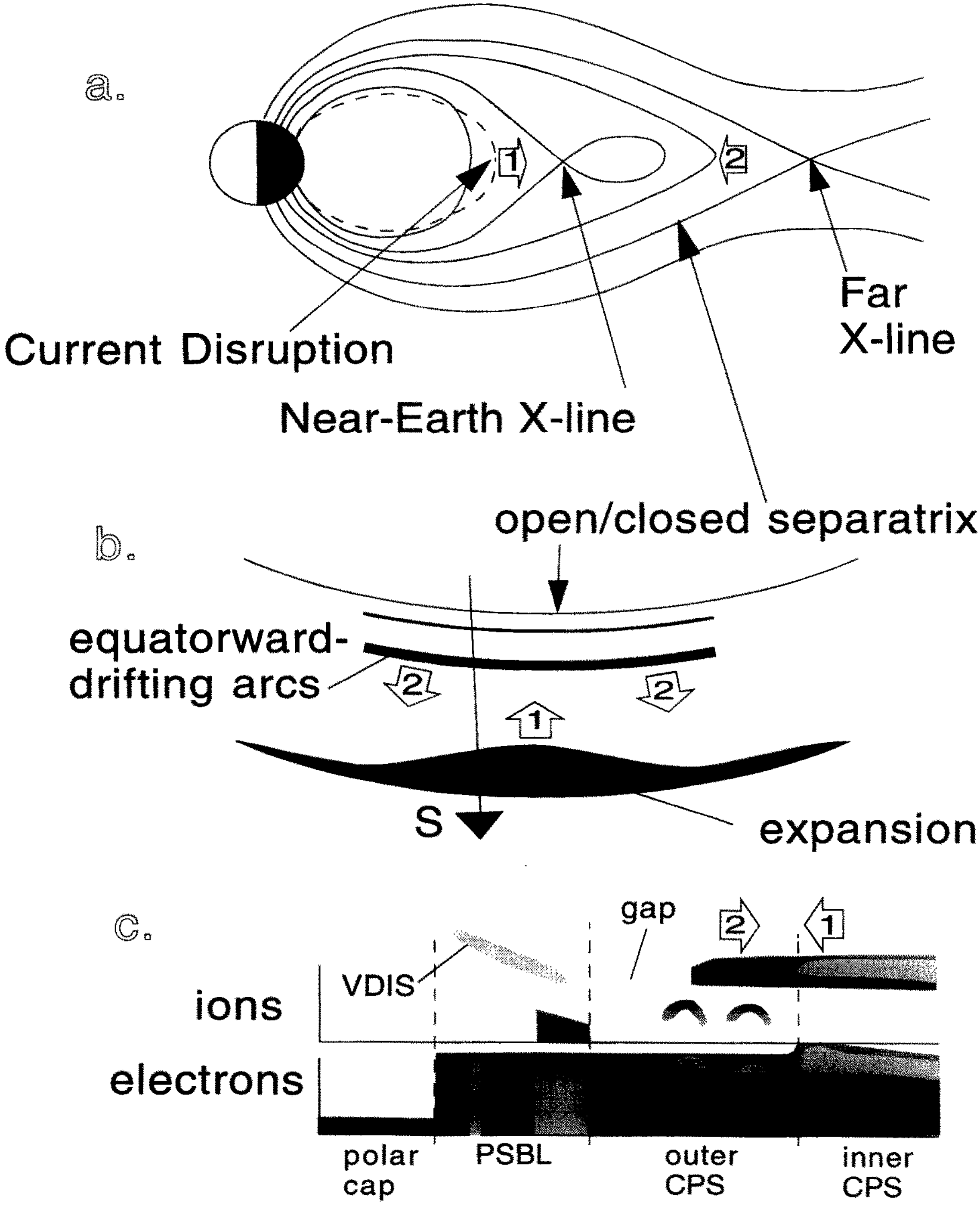

Fig.2 A schematic of the inferred situation in the early expansion phase of substorms, showing the relationship of the equatorward-drifting arcs and the auroral expansion. See text for details.

bursts of reconnection at the open-closed boundary, i.e. at a far X-line, in quiet times. The arcs do indeed appear to be on closed field lines. The electrons that cause them are seen poleward of the persistent aurora that intensifies at onset (Elphinstone *et al.*, 1995) but equatorward of the boundary field-aligned currents on the open-closed boundary (Fukunishi *et al.*, 1993). They are also found in the VDIS ramp and gap region, which are both well explained as being on field lines contracting sunward away from the far reconnection X line (Onsager and Mukai, 1995; 1996). Thus the equatorward-drifting arcs appear to be in the region between the projections of the NENL and the far X-line, i.e. in the area shown in the right hand plots of figure 1. This means that they would be seen only until the plasmoid has been pinched off. It appears that even near the MLT of onset the equatorward-drifting arcs can persist for up to about 10 min after onset (Elphinstone *et al.*, 1995), implying that the plasmoid is not pinched off until after this time.

The view of the early expansion of substorms that emerges from these studies is shown schematically in figure 2. Part (a) shows the noon-midnight (XZ plane) cross-section of the magnetotail, with the NENL feeding the plasmoid, but disruption of the cross tail current and associated dipolarisation and particle injections taking place in the onset region, which is somewhat closer to the Earth. The middle panel shows the ionospheric footprint of these regions and (c) shows the particle spectrograms which would be seen by a low-altitude satellite S, moving equatorward along the orbit shown in (b). The spectrograms sketched in (c) are after Fukunishi *et al.* (1993) and illustrate the typical differential energy fluxes of ions (top) and electrons (bottom) as a function of energy (30eV-30 keV) and observing time as the satellite moves equatorward. The arrows marked 1 in all parts of the figure show the poleward expansion of the substorm aurora which relates to the tailward expansion of the current disruption region [Jacquey et al., 1993; Baker et al., 1993]. The arrows marked 2 show the equatorward motion of the arcs poleward of onset which appear, from the relationship to the VDIS, to be on closed field lines that thread the current sheet in the far tail, beyond the plasmoid but earthward of the far X-line. This large separation from the current disruption region and the source of the equatorward-drifting arcs may explain why the latter are not influenced by the substorm onset and early expansion.

These arcs are thus a clue to the field topology in the early development of a substorm expansion. But there have been suggestions that they may also be a significant part of the sequence of events that causes onset. Observations at geostationary orbit show that the first injection seen in a substorm contains some O^+ ions, whereas the second is frequently rich in such ions (e.g. Gazey *et al.*, 1996). As a result, it has been suggested that the destabilisation responsible for the second injection is due to the arrival of O^+ ions extracted from the ionosphere by the first (Daglis *et al.*, 1996). Because these ions have relatively long travel times (tens of minutes), the sunward convection of field lines means that the ionospheric sources of the O^+ must be poleward of the injection region. Gazey *et al.* (1996) have recently shown that the time taken for the equatorward-drifting arcs to drift into the pre-onset (equatorward) aurora is sufficient for ionospheric O^+ ions to reach the current disruption region and that when the arcs passed over the EISCAT radar they were indeed observed to cause large upflows of O^+. This raises the possibility that ions from these equatorward-moving arcs are responsible for the initial destabilisation at onset.

MULTIPOINT MEASUREMENTS

The schematic shown in figure 2 has been derived from a number of multipoint studies. These have gone some way toward distinguishing substorm theories. The field-line connectivity implied by this schematic is not consistent with the "classical" NENL model (with onset at the NENL) nor with boundary-layer models. However, key questions about what causes onset and how the substorm expansion and recovery develop have still to be answered.

The problem is principally one of determining causality and thus unambiguous confirmation of the order in which events take place is vital. Unfortunately, this is complicated by spatial considerations because a certain feature may appear at any one point, not because of an onset but because it has expanded or moved over the satellite. An example of this is provided by the study of Gazey *et al.* (1995). They observed an onset of auroral precipitation and a change in the convection from single-point measurements by the EISCAT radar which were roughly 2 hours in MLT to the west of where a substorm onset was observed. This could have been an interesting indicator of a global MHD instability (eg. ballooning) causing onset, with azimuthally extended features (see Elphinstone *et al.*, 1995). However, inspection of the all-sky camera data revealed that this was a southward-drifting arc that had existed for 15 minutes prior to onset and happened to drift into the radar field of view at precisely the time of onset. The problem is the same for all single-point satellite observations. For example the observation of the start of a BBF event can be because it has arrived at the satellite by an expansion or motion of the flow channel or because of an onset of a flow with the satellite already in the required location to see it. Resolution of these temporal-spatial ambiguities needs multipoint measurements on 1-5 R_E scales and monitoring of the development of features with remote sensing.

Many global-scale (5-100 R_E) multipoint in-situ observations use timing of features which can be subject to these spatial/temporal ambiguities. However, remotely-sensed observations usually give more reliable timings. For example, onset times are reliably estimated if sensed by Pi2 pulsations, provided there are stations at mid-latitudes which are not too far from the MLT of onset (Yeoman *et al.*, 1994). Similarly AKR gives a good indicator of onset time. Dispersed injections are also valuable for identifying onset (or dispersionless ones that have drift echoes to distinguish them from satellite entries into the plasma sheet from the lobe). Thus the timing of the appearance of near-Earth signatures can often be relatively good. The problem is much greater when one looks at fields and flows in the mid- and far-tail. Auroral images may be of some help here, but applications are limited by the field line mapping uncertainties. Other possibilities include remote sensing using energetic charged and neutral particles.

Most studies of substorms are now multipoint in nature, and there is not space here to review all recent measurements. The few examples given below are chosen to illustrate some principles of multi-point observations being used to test substorm theories.

Henderson *et al.* (1996) have recently presented a multi-point study specifically aimed at testing the theory that all substorms have a trigger in the interplanetary medium. They used near-Earth indicators of substorms (geostationary injections, AKR, Pi2s, ground-based magnetometers) to identify the time of onset with some precision. They compared with data on the interplanetary medium from a variety of locations and were able to define cases where the solar wind and IMF were stable for such long periods that there is no doubt that the substorms were not externally triggered, even allowing for extreme uncertainties in the propagation delay across interplanetary space and the magnetosheath. This study therefore supports the work of Farrugia *et al.* (1993), even allowing for any debate as to what constitutes separate substorms when they occur in a sequence under strong, steady and unusually prolonged southward IMF. This is not to say that some substorms may not be triggered by interplanetary changes; however, the fact that onset can occur spontaneously within the magnetosphere is very important and the potential role of triggers is reduced to shortening the growth phase and making substorms weaker and more frequent than they otherwise may have been.

Slavin *et al.* (1993) have examined the delay between substorm onset and the observation of a TCR or a plasmoid. Allowing for the propagation delay down the tail to the satellite, these authors deduce that the plasmoids were pinched off soon after onset in each case. Their observations do clearly show that a NENL is active (with high E_n) at least by shortly after onset, although the propagation uncertainties do not allow us to determine if the current disruption leads to the NENL or vice-versa. There are also ambiguities in the interpretation because plasmoids may be able to move down he tail (motion is necessary for them to be observed) before they are pinched off (see discussion by Lockwood, 1995). This idea is supported by observations of the directions of flow streams coating the plasmoid (Owen and Slavin, 1992), particularly those that are moving relatively slowly (Kawano *et al.*, 1996). These plasmoids which have not been pinched off may sometime become the sunward-drifting, reverse-polarity plasmoids reported by Moldwin and Hughes (1994) during quiet times.

Angelopolous *et al.* (1996) have used a wide variety of satellites to study the relationship of mid-tail signatures, in particular a BBF event and associated dipolarisation seen by the AMPTE-IRM satellite, to a variety of near-Earth signatures. The substorm showed an onset with a subsequent major intensification. Only the latter was accompanied by a BBF event in mid-tail, similar to the case reported by Lopez *et al.* (1994). Auroral images reveal that the onset and the intensification took place at different MLT and that the intensification was much closer to the MLT of the AMPTE-IRM satellite than the onset. As a result, the authors suggest that a BBF event was present at onset but it was sufficiently localised to be missed by AMPTE-IRM. The authors show that the BBF that was seen gave a flux transfer rate of 67 kV R_E^{-1} (i.e. per unit length (in R_E) in the cross-tail (Y) dimension). As this is more than half of a typical ionospheric convection voltage, the authors conclude that the BBF event was less than about 2 R_E in extent and that the flows spread out in the Y direction to give the dipolarisations seen over a greater range of Y near geostationary orbit. However, the 67 kV R_E^{-1} flux transfer rate of the BBF only lasts for 10 minutes, whereas ionospheric convection carries on throughout the expansion phase and slowly decays in the recovery phase (Lester *et al.*, 1995; Weimer et al., 1992; Fox *et al.*, 1994). No further injections and dipolarisations were seen at geostationary orbit and so one cannot invoke other localised BBFs at other MLTs as a cause for continued ionospheric convection. The implication would then be that the BBF was larger than the estimated 2 R_E long, such that it causes sufficient flux transfer that the average rate broadly matches the total associated with ionospheric convection throughout the expansion and recovery phases. Induction effects of the dipolarisation associated with the BBF mean that the convective surge in the plasma sheet is decoupled from the motions in the ionosphere on sufficiently short time scales. Indeed observations show that the ionospheric feet of dipolarising field lines experience of drop, rather than a rise, in flow speeds because of the rise in conductivity associated with the precipitation (Kirkwood *et al.*, 1988; Gazey *et al.*, 1995; Fox *et al.*, 1994; Fujii *et al.*, 1994; Weimer *et al.*, 1994).

CONCLUSIONS

Reconnection in the tail is a vital part of any substorm theory needed to, at the very least, remove the stress which is caused by excess tail lobe flux and which accumulates during the growth phase. The formation of plasmoids, and their lobe signatures (TCRs), shows that enhanced reconnection takes place at a location Earthward of the old reconnection site (i.e. at a near-Earth neutral line). However, the relationship of these mid- and far-tail responses to those closer to Earth are not clear. In particular, we need multipoint observations to answer the questions:

- Where and when do NENLs form relative to the onset of cross-tail current disruption?
- What is the probability of observing NENL signatures as a function of position and time?
- When does a NENL start to close open flux of the lobe (and so pinch off the plasmoid)?
- What are the temporal and spatial variations of the reconnection rate?
- Are near-Earth signatures a consequence of NENL reconnection, if so what mechanisms are at work?
- Is the NENL a consequence of cross-tail current disruption, and if so what mechanisms are at work?
- Are the current disruption and NENL different responses to the same external stress?

Only with answers to these questions can we begin to evaluate the relative merits of the various theories and see the possibilities for synthesising models into a more comprehensive theory of substorms. The answers may show that we need to take a more modular approach in which there are a variety of possible behaviours and mechanism chains which are only loosely connected but share the same ultimate cause. In answering these questions we need to be aware of the problems in determining causality, due to the difficulty in timing changes where there is spatial and temporal ambiguity inherent in the measurements. We need to understand the spatial extent of events in three dimensions, not just to assess their significance and contributions (to flux transport, energy flow etc.), but also to understand the probability of detecting them.

Acknowledgements. ML is supported by the UK Particle Physics and Astronomy Research Council.

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