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SUBSTORM THEORIES: UNITED THEY STAND, DIVIDED THEY FALL

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1. Introduction

Consensus on the timing and mapping of substorm features has permitted a synthesis of substorm models. Within the synthesis model the mechanism for onset of substorm expansion is still unknown. Possible mechanisms are: growth of an ion tearing mode, current disruption by a cross-field current instability, and magnetosphere-ionosphere coupling. While the synthesis model is consistent with overall substorm morphology, including near-Earth onset, none of the onset theories, taken individually, appear to account for substorm expansion onset. A grand synthesis with unification of the underlying onset theories appears necessary.

1.1. Relevance to Space Weather Prediction

One important element in the development of a space weather predictive capacity [see the article by N. Maynard, this issue] is the prediction of onset of magnetospheric substorm expansions. The transfer of solar wind energy to Earth's inner magnetosphere and upper atmosphere occurs not only in a more or less directly driven fashion. Part of this transferred energy is stored in the geomagnetic tail in plasma and magnetic flux (the substorm growth phase) and is released intermittently in events known as substorm expansions. Like earthquakes and volcanoes to the lithosphere and cyclones to the troposphere, the substorm is the release of stress and stored energy in the magnetosphere, only on a much larger scale, 6 times per day, on average. While much of this energy is released away from Earth, a significant amount is injected toward Earth. This intermittent release not only results in auroral breakup and spectacular auroral displays, but can interfere with or cause damage to geosynchronous and ground-based facilities.

Substorm expansions are characterized by the sudden dipolarization of previously stressed (taillike), near-Earth, plasma-sheet flux tubes, which energizes and injects plasma into the geosynchronous environment. These high fluxes of energetic particles can interfere with the performance of geosynchronous spacecraft or cause them permanent damage. The dipolarization is associated with a diversion of roughly a million amps of dawn-to-dusk plasma sheet drift current along magnetic field lines into the auroral ionosphere as the substorm current wedge. Ionospheric densities and temperatures are increased, which can interfere with communications, radars, and low-altitude spacecraft. The sudden intensification and

expansion of ionospheric electrojet currents results in rapidly changing magnetic flux at ground level which can induce damaging emfs and resultant currents in ground equipment, especially when substorm expansions occur in association with geomagnetic storms. Predictive ability with regard to onset of substorm expansions will depend on our understanding the initiation mechanism.

2. Development of Substorm Models

As we entered this quadrennial period, several substorm models had been put forth. Each described an observed substorm process, and owing to ambiguities in the timing and mapping of substorm features, each could stake claim to being the description of the substorm.

2.1. M-I Coupling Models

It was not long after the identification of the substorm as a distinct phenomenon [Akasofu, 1964] that the earliest substorm models were introduced involving magnetosphere-ionosphere (M-I) coupling or reconnection (magnetic merging). The M-I coupling models evolved from models to describe auroral arc intensification and expansion [e.g., Heppner *et al.*, 1967; Coroniti and Kennel, 1972] in which the power supplied by magnetospheric convection was either implicitly or explicitly assumed. Later versions of these models include those of Zhu and Kan [1990], who model Alfvén wave transmission between ionosphere and magnetosphere including precipitative enhancements of conductance, and Rothwell *et al.* [1988; 1991], who model the circuit analogy, including field-aligned potential drops. Auroral arc brightening and expansion results from the interplay of Hall and Pedersen conductance gradients. In the Zhu and Kan model, apart from an initial electric field pattern imposed on the ionosphere, the magnetosphere is passive, represented by reflection coefficients between -1 (open field lines) and $+1$ (sub-auroral, closed field lines). In the Rothwell *et al.* model, the substorm emf is assumed which powers auroral breakup.

2.2. The Near-Earth Neutral Line Model

Within the open-magnetosphere model [Dungey, 1961], reconnection in the geomagnetic tail was recognized early-on as a mechanism to power substorm expansions. Atkinson [1967] assumed impulsive reconnection at the far-tail neutral line and resulting earthward flow of flux tubes to explain geomagnetic

bays and the pile-up of these flux tubes near Earth to explain the auroral bulge observed during substorms. Based on stress-balance arguments, *Siscoe and Cummings* [1969] argued the need for reconnection to occur near Earth. *McPherron et al.* [1973] presented an observationally-based description of the substorm which emphasized the substorm current wedge resulting from local current disruption initiated near Earth in a thin current sheet. They suggested that the current disruption might have resulted from neutral-line formation. *Hones et al.* [1973] observed that while the plasma sheet expanded (dipolarized) near Earth, the mid-tail plasma sheet dropped out (thinned) only to reappear later (at substorm recovery) in association with fast earthward flows. They suggested that these observations were consistent with near-Earth neutral line (NENL) formation at about 10–15 R_E (Earth radii) in the tail at substorm expansion onset and its retreat downtail at substorm recovery. Their observations were summarized by the Hones' cartoon [*Hones*, 1977]. Theoretically, *Schindler* [1974] suggested that the geotail was unstable to the growth of the collisionless ion tearing instability leading to neutral-line formation. However, it appeared that the collisionless ion tearing mode was stabilized by electron magnetization unless the wavelength of the mode were unrealistically long. (See the discussion by *Coroniti* [1985].) In the NENL model, the ionosphere is passive; substorm onset results from an instability internal to the plasma sheet. For almost two decades the NENL model was the leading substorm model because (1) it most clearly encompassed most of the morphology of substorms as it was perceived, (2) invoked magnetic merging to account for substorm power, and (3) had predicted the occurrence of plasmoids, i.e., tailward flowing closed magnetic loops disconnected from Earth, which were indeed observed in the far tail (see §2.4). Work has progressed detailing the dynamics of the NENL model through the MHD simulations of *Birn and Hesse* [e.g., *Birn and Hesse*, 1991; *Hesse and Birn*, 1994] and *Lyon and Fedder* [e.g., *Lyon and Fedder*, 1994].

2.3. The Rarefaction Model

Observational evidence for the NENL model did not go unquestioned. *Lui et al.* [1977a, b] argued that observed plasma flows in the geomagnetic tail within $\sim 30 R_E$ were predominantly earthward and that the occurrence of southward field near Earth, as would be expected in connection with a near-Earth neutral line, merely resulted from the southward tilting of strong

taillike field lines (consistent with the results of a later survey by *Fairfield et al.* [1987]). *Chao et al.* [1977] offered the rarefaction wave model as an alternative explanation for the Hones et al. observations. In this model, feedback from electrojet enhancement in the Coroniti-Kennel model on plasma flows near the inner edge of the plasma sheet causes the inner part of the plasma sheet to lurch earthward, launching a rarefaction down the tail which would result in deflation, i.e., the expansion phase thinning of the plasma sheet. An alternative to the NENL model was thus available. Either substorm onset was the result of M-I coupling with the tail responding, or onset resulted from onset of reconnection near Earth. This evolved into a debate of whether substorm expansion was directly driven by the solar wind-magnetosphere interaction via M-I coupling or resulted from an unloading phenomenon resulting from instability internal to the magnetotail.

However, in the Chao et al. model the plasma was assumed adiabatic; the predicted thinning was significantly less than observed. Also, while the energy available in the closed-field-line plasma sheet is sufficient to account for the energy dissipated in the ionosphere during substorms (if we do not also have to account for plasmoids), it was merely an assumption that the plasma sheet could deflate fast enough to account for substorm power. Later calculations would show that unless ions could somehow be released (demagnetized) or deenergized, plasma compression would prevent rapid earthward transport of magnetic flux from downtail and dipolarization of stressed plasma-sheet flux tubes [e.g., *Erickson and Wolf*, 1980; *Schindler and Birn*, 1982] – the so-called “pressure-balance inconsistency” argument. Indeed, plasma compression causes the earthward return rate of flux transport in the plasma sheet to lag the day-side reconnection rate. Thus, this argument complemented the stress-balance argument of *Siscoe and Cummings* [1969] in providing an explanation as to why plasma and magnetic flux is stored in the tail, only to be released in sporadic events, namely substorms.

2.4. Boundary-Layer Models

Notwithstanding the lack of direct observational support for reconnection near Earth, ISEE-3 observations of substorm-associated plasmoids in the far tail [*Hones et al.*, 1984] provided support for the NENL model. Meanwhile, ISEE-1 observations clarified the properties of the plasma-sheet boundary layer

(PSBL) bordering the central plasma sheet [e.g., *Eastman et al.*, 1984]. In a study of auroral precipitation morphology, *Winningham et al.* [1975] had classified diffuse (unaccelerated and unstructured) precipitation as CPS (“central plasma sheet”) type and discrete (structured by field-aligned acceleration) BPS (“boundary plasma sheet”) type. The same characterization can be applied to the isotropic central plasma sheet plasma and the beam-like distributions in the PSBL. *Winningham et al.*’s BPS is associated with arcs and auroral expansions, and during the course of substorm expansion the aurora do involve boundary-layer associated behavior. This added fuel to the directly driven versus unloading debate. While a natural explanation associated the PSBL with the separatrix mapping to an X-type neutral line separating the closed plasma sheet and the open tail-lobe field lines, owing to a lack of near-Earth reconnection signatures, various boundary-layer models were put forth as substorm mechanisms [e.g., *Rostoker and Eastman*, 1987; *Goertz and Smith*, 1989]. To the debate over whether the substorm was directly driven or an unloading phenomenon entered confusion over the timing and mapping of substorm processes. One model was suggested by *Lyons and Nishida* [1988] which included onset of reconnection within the equatorial source of the BPS, mistakenly equated with the PSBL. Generally regarded as a boundary-layer model for substorm expansion, this model might be more appropriately called a “not-so-near-Earth neutral-line” model.

2.5. The Current Disruption Model

Out of chaos would come order, but there is one more piece of the substorm puzzle to set the stage for the progress of this quadrennial. *Kaufmann* [1987] demonstrated that the growth-phase stretching of the magnetic field at geosynchronous distance required an intense current sheet between 7 and 10 R_E , more so than had previously been appreciated. Shortly thereafter, results from the AMPTE satellite missions with their near-equatorial orbit and fast sampling rates began to be reported. *Lui et al.* [1988] reported observations of magnetic field turbulence in association with dipolarization in the near-Earth plasma sheet. A current disruption theory for substorm onset based on a cross-field current instability (CFCI) was offered [*Lui et al.*, 1990]. In this theory, as the current drift speed in the current sheet neared the local sound speed, kinetic instability would ensue, resulting in electromagnetic turbulence which disrupts the current. Multi-

satellite observations involving AMPTE and geosynchronous satellites [e.g., *Lopez and Lui*, 1990] show the close association in time between first signs of onset in the near-Earth plasma sheet and ground onset. Such observations are consistent with earlier observations by *McPherron et al.* [1973], *Nagai* [1982] and others which show local development of a substorm current wedge and subsequent expansion both radially and in local time. *Baumjohann et al.* [1990] showed that within AMPTE/IRM apogee ($\sim 19R_E$), fast flows are predominantly earthward, and tailward flows are infrequent, consistent with the earlier findings of *Lui et al.* [1977b]. If an X-line forms in association with substorms, it would appear that it usually forms tailward of $19R_E$.

3. Consensus on Substorm Morphology

The success of the AMPTE, ISEE, and Viking satellite missions in concert with ground and geosynchronous observations and the improved magnetic field models of *Tsyganenko* [1987, 1989] clarified many of the issues surrounding the location and timing of substorm processes. A new consensus on the spatial relationship between ionosphere and magnetosphere was reached in accord with the review by *Galperin and Feldstein* [1991]. Highlighting the new consensus was the recognition that the low-latitude extent of the BPS, which contained the equatorward-most arc which intensified at substorm onset, maps close to Earth and away from the boundary layers. A synthesis was presented by *Lui* [1991], namely, the near-Earth current disruption (NECD) model (paraphrased below) in which the various substorm processes, and associated models, were unified consistent with observed morphology.

3.1. The Near-Earth Current Disruption Model

During the substorm growth phase, magnetic flux in the tail increases, the auroral oval expands, the inner edge of the plasma sheet moves earthward, and cross-tail current increases. In the near-Earth plasma sheet, the current sheet thins to the order of average proton gyroradii, and the current drift speed approaches the local sound speed. Convection during the growth phase maintains the prebreakup arc magnetically connected to the near-Earth plasma sheet.

Substorm expansion onset occurs as the near-Earth cross-tail current is suddenly substantially reduced locally in both radial and local-time extent. (The growth-phase current sheet is thicker away from the

near-Earth, midnight sector.) Cross-tail current shunts around the disruption region along magnetic field lines and westward through the ionosphere as the substorm current wedge. Within the wedge, previously stressed magnetic field dipolarizes consistent with a large dawn-to-dusk induction electric field which injects plasma earthward. A rarefaction is launched which thins the current sheet as it propagates, and the current disruption region may expand.

Current-sheet thinning, the disruption region, and current wedge may spread longitudinally as well in a combination of three ways: (1) longitudinal propagation of the rarefaction wave, (2) negative north-south perturbation magnetic field outside the current wedge, and (3) continuation of the growth-phase magnetic field stressing east and west of the disruption region. Depending on a variety of factors, the current wedge could expand more or less smoothly away from the initial disruption region, or several longitudinal sectors of the near-Earth current sheet could disrupt in a rather haphazard fashion and be observed as multiple substorm intensifications. Alternatively, the disruption may remain local resulting in a "pseudobreakup".

Velocity shear along the eastward and westward edges of the convection surge and rarefaction wave can result in onset of velocity-shear instability. As well, as the rarefaction reaches the low-latitude boundary layer, strong velocity shear may result to yield multiple surge forms and auroral vortices. Plasma depletion tailward of the convection surge launches the rarefaction resulting in a radially extended thin plasma sheet which may be unstable to tearing and neutral-line formation. One or more plasmoids may form to be ejected downtail.

3.2. The Kiruna Consensus

At the First International Conference on Substorms held at Kiruna observed substorm phenomena were reviewed leading to the community consensus, known as the "Kiruna conjecture", that "the auroral substorm onset is closely coupled to events in the geosynchronous region" [Kennel, 1992]. Cogger and Elphinstone [1992] showed results from Viking imagery confirming the new consensus on the timing and mapping of substorm phenomena. As well, many presentations were given demonstrating both a directly driven and unloading component of substorms [e.g., Baker, 1992]. After Kiruna, advocacy for the boundary-layer models for the substorm diminished. Even Larry Lyons, one of the most ardent proponents

of a boundary-layer origin for substorms, is now a champion of near-Earth onset [e.g., Samson *et al.*, 1992]. As well, advocates of a directly driven nature of substorms now admit that M-I coupling models are missing an unloading component [Kan, 1992].

A strong impression was given at the Kiruna meeting that the magnetospheric community now accepts that substorm onset occurs locally near Earth, in the absence of apparent reconnection signatures, and its effects expand radially and in local time, as well as the Galperin-Feldstein renaissance. Indeed, many researchers subscribe to the "strong version" of the Kiruna conjecture that "plasma sheet reconnection and plasmoid formation do not always have to occur in close temporal and spatial proximity to the events defining the geosynchronous substorm" [Kennel, 1992]. In its strong version, the Kiruna conjecture favors the NECD model of substorms. However, case studies exist in which observations appear consistent with neutral-line formation near Earth in close association with ground onset and its tailward retreat, including tailward then earthward bulk plasma flow [e.g., Fritz *et al.*, 1984]. Advocates for the NENL model suggest that much of the evidence against near-Earth reconnection at substorm onset is statistical in nature; even if the NENL model were the correct description of most substorms, owing to the thinness of the current sheet, the localness of onset, and the sparseness of observations, only in a minority of events would clear neutral-line signatures be observed. The reader is referred to the review by Siscoe [1993] for additional discussion of the NECD and NENL models.

4. Theories for Expansion Phase Onset

In this quadrennial we have witnessed the rise of the NECD model to rival the NENL model as the leading model for the substorm, while directly driven and boundary-layer models appear untenable. However, the mechanism of substorm expansion onset is still undetermined. Weimer [1994] shows that the electrojets (*AE*) follow an exponential growth and decline during substorm expansion and recovery. Moldwin and Hughes [1993] show an approximate one-to-one correspondence between plasmoids observed in the far tail and earlier ground onsets. As well as the power involved in substorm expansions, these observations argue for unloading of previously stored plasma and magnetic flux in the tail. However, theories for mechanisms of current-sheet instability face

both theoretical and observational difficulties.

4.1. The Tearing Mode

The close temporal relationship between events at geosynchronous and ground onset does not rule out the tearing mode, or some other global instability, as the cause of substorm onset. If onset results from a large-scale instability, then the plasma sheet near geosynchronous and $20\text{--}30R_E$ downtail can go unstable together. However, as theoretical analysis of the collisionless tearing mode advances, its feasibility as the mechanism of substorm expansion onset is becoming more doubtful. Energy-principle analysis, particle simulations and hybrid simulations all indicate the magnetotail to be stable against collisionless tearing.

Energy-principle analysis by *Wang and Bhattacharjee* [1993] showed the magnetotail to be stable against ion tearing even in the presence of a magnetic shear B_y component. However, they left open the possibility that the electron tearing instability can grow in the presence of a significant shear component. *Pellat et al.* [1991] and *Brittnacher et al.* [1994] used energy-principle analysis to show that even strong electron pitch-angle diffusion cannot remove strong stabilization of the tearing mode caused by electron compression. Particle simulations by *Pritchett* [1994] and *Pritchett and Büchner* [1994] confirm these results. Pritchett and Büchner included a minimum (as small as zero) in equatorial magnetic field strength and a shear B_y component, both observed in the near-Earth current sheet [e.g., *Sergeev et al.*, 1993]. *Winske and Hesse* [1994] found the collisionless tearing mode to be stable in hybrid simulations containing realistic ion-to-electron mass ratio. It must be noted, however, that analysis has been mainly limited to two dimensions. It is possible that stabilization of collisionless tearing owing to electron compressibility might be removed by particle loss, or through three-dimensional effects such as M-I coupling and violation of canonical p_y momentum, which is conserved in two dimensions. Another possibility is that anomalous resistivity resulting from the CFCI (see below) permits resistive tearing to proceed. Given the observation of substorm-associated plasmoids, neutral-line formation seems to occur at some point during substorm expansions.

4.2. The CFCI

Quasi-linear analysis in local approximation by *Lui et al.* [1993] has shown the CFCI to have growth

rates fast enough for the suddenness of substorm onset. However, first results of non-local analysis of a CFCI mechanism by *Chang et al.* [1994] indicates stabilization in high- β plasma. *Hesse and Birn* [1993] and *Erickson* [1993] argue that the CFCI is a driven process. This is not at odds with the scenario presented by *Lui et al.* [1991] whereby the CFCI results as, during the growth phase, the current sheet thins to ion gyroradius scalelength, and ions become unmagnetized to undergo large drifts across the tail. Observations of current disruptions in the near-Earth plasma sheet appear consistent with disruption owing to the CFCI as described by Lui and colleagues, including wave power near the ion cyclotron frequency [e.g., *Lui et al.*, 1992]. Indeed, a rapid (~ 1 minute), several-nT depression of the magnetospheric H component was observed at AMPTE/CCE just prior to local dipolarizations by *Ohtani et al.* [1992] (when the satellite was located earthward of the subsequent current disruption). This “explosive growth phase” is also frequently observed at CRRES just prior to dipolarizations associated with local substorm onsets. Ohtani et al. interpret this as resulting from an explosive enhancement in tail current intensity just prior to current disruption.

Observations of a thin current sheet prior to dipolarization have not revealed a distinction, inherent to the sheet, between thin current sheets which persist for tens of minutes [e.g., *Pulkinnen et al.*, 1992], undergo current disruption resulting in pseudobreakup [e.g., *Ohtani et al.*, 1993], or undergo current disruption which expands into a substorm. *Sergeev et al.* [1994] have inferred a magnetotail configuration during steady magnetospheric convection (SMC) events consistent with the steady-state equilibrium models of *Hau* [1991]. The SMC configuration exhibits a deep minimum in equatorial magnetic field strength and intense, thin current sheet near Earth, as severe or more than any observed prior to substorm onset. Thin current sheets appear remarkably stable at times, prompting *Sergeev et al.* [1994] to ask in regard to their SMC observations: “How can such a stressed configuration with such a thin and intense current sheet in the near-Earth tail remain stable during many hours?” An interesting idea advocated by this researcher is that the CFCI actually maintains the large-scale stability of thin current sheets in the presence of modest growth-phase electric fields. As the current sheet gradually thins to the point where ions begin to unmagnetize, the CFCI growth rate increases, scatters the ions, and ions remagnetize. Thus

under the action of the modestly driven CFCI, the current drift velocity is limited somewhat below the ion thermal speed and the current sheet thickness near ion gyroradii. An additional “kick” provided by a solar-wind trigger or, perhaps, by the evolution of the M-I coupling is needed to reduce the current-sheet thickness below ion gyroradii. If this occurs the CFCI growth rate can increase substantially, and the current sheet might destabilize in the presence of the enhanced anomalous resistivity.

5. The Role of M-I Coupling

There have been various suggestions on a role for M-I coupling in destabilizing the near-Earth current sheet, permitting substorm expansion to proceed.

5.1. The Ionospheric Closure Condition

Lui [1991] and colleagues studying current disruptions in the near-Earth plasma sheet suggest that local current disruption originating in the current sheet may or not expand depending on the ability of the ionosphere to carry the diverted current. Consider what can happen assuming that a local current disruption occurs. A portion of the cross-tail current must divert around the disruption region either earthward, tailward, or along magnetic field lines to close through the ionosphere. Within the disruption region, plasma is heated and diffuses; the magnetic configuration is altered in the vicinity of the disruption region. It is difficult to ascertain how the diamagnetic drift current is altered about the disruption region.

Let’s suppose that the disrupted current does not divert earthward or tailward around the disruption region. Rather, charge accumulates at the edges of the disruption region, enhances the westward electric field and launches an Alfvén wavefront toward the ionosphere carrying the disrupted current. Prior to the Alfvén wavefront reaching the ionosphere, growth-phase sized electric fields and electrojets existed. As the Alfvén wavefront reaches the ionosphere, charge will accumulate to enhance the (westward) electric field; the (westward) electrojet will increase owing to the enhanced electric field – and as Joule heating and precipitation from the disruption region raises the conductivity – until the electrojet is enhanced to carry the disrupted current. Thus, *Lui*’s current disruption model with the ionospheric closure condition is the modern version of the rarefaction wave model of *Chao et al.* [1977] discussed in §2.3. Since the work of *Kaufmann* [1987] and others, we now know

that the near-Earth, pre-onset current sheet is much more intense and thin than had been previously appreciated. With current-sheet thickness near typical proton gyroradii, proton adiabaticity can be violated if the sheet is forced to thin further.

5.2. Ionospheric Overloading

Kan [1993] suggests that current disruption associated with substorm onset might be triggered by the eastward polarization current in an Alfvén wavefront launched from the ionosphere. An Alfvén wavefront carrying an eastward polarization current and eastward polarization electric field can be launched from the ionosphere when westward electrojet current increases faster than field-aligned current is being provided from the magnetosphere. This might happen as the equatorial curvature of field lines increases during the growth phase, and, e.g., *L*-shell splitting occurs at the boundary of trapped energetic electrons (> 30 keV). These electrons isotropize and some scatter into the loss cone (see e.g., *West* [1979] and *Pulkkinen et al.* [1992]). These energetic electrons can reach E-region altitudes, and each can produce many ion-electron pairs (one pair per 35 eV of incident energy). These electrons are super-Alfvénic so the ionospheric current can increase, for a given imposed westward electric field, faster than field-aligned current is being provided by the magnetosphere. The ionosphere becomes polarized as positive (negative) space charge accumulates at the westward (eastward) end of the conductive strip. To equilibrate the charge along field lines, an Alfvén wavefront is launched to transmit the eastward polarization electric field into the magnetosphere. Behind the eastward (westward) side of the wavefront is upward (downward) field-aligned current. The $E \times B$ velocities of field lines slow as the Alfvén wavefront propagates. Along the wavefront is an eastward polarization (inertial) current. The equatorward ends of the field lines convect at the unperturbed $E \times B$ velocity until the wavefront arrives there. During the transit time of the wavefront from ionosphere to equatorial magnetosphere, the field lines become more dipolar reducing their curvature, and the $E \times B$ speed has been slowed. This reduces or turns-off the source of the energetic electrons which started the process.

This mechanism is the explanation for auroral fading given by *Pellinen and Heikkila* [1978]. As ionizing precipitation causes an electrojet to intensify, ionospheric feedback results in the braking of convection and the reduction of the ionization source. (*Pellinen*

and Heikkila note that during auroral fading fluxes of precipitating ions and electrons behave similarly.) While the slowing of convection hardly seems like a substorm onset trigger, nevertheless, auroral fading is a common occurrence just prior to onset, and we cannot know how the nearby current sheet responds to this dipolarization until we test this mechanism in a global MHD code. The response could be minor, or the dipolarization could launch waves resulting in current-sheet thinning downtail.

5.3. Mass Exchange

Motivated by detailed particle and field observations at geosynchronous orbit, Roux *et al.* [1991] suggested the ballooning instability as the mechanism for substorm onset. At the Second International Conference on Substorms held at Fairbanks this past year, several presentations were given supportive of some sort of ballooning scenario for substorm onset. Conventional ballooning is stabilized by compression of the plasma as flux tubes alter their volumes. Very special conditions are required if conventional ballooning is to be unstable in the near-Earth plasma sheet. Whether or not such conditions exist is an issue of debate [e.g., Pu *et al.*, 1992; Ohtani and Tamao, 1993; Lee and Wolf, 1992]. (The ballooning discussed here and below is not the usual short-wavelength perturbation; rather, long wavelengths are considered in which the fundamental mode consists of a half-wavelength between conjugate ionospheres.)

Based upon MHD energy-principle analysis of two-dimensional, quasi-static equilibrium models of growth-phase convection, modified ballooning scenarios have been suggested as substorm onset triggers. The modification is to take account of the exchange of mass between ionosphere and the near-Earth plasma sheet. The suggestion is that stabilization provided by plasma compression can be nullified by precipitation of energetic ions into the ionosphere – the “ideal tearing mode” description of Birn *et al.* [1994], or via redistribution of ion pressure along field lines in association with growth of field-aligned potential drops – the “global ballooning” description of Erickson and Heinemann [1992]. In either scenario, the normal-mode, inward/outward oscillation of plasma-sheet flux tubes can overshoot their equilibrium position. The pressure distribution along near-Earth plasma-sheet flux tubes adjusts to the requirements of M-I coupling on a timescale faster than the global, growth-phase, quasi-static equilibrium evolves. The suggestion is that a pressure distribution consistent

with M-I coupling can evolve near-Earth which is inconsistent with the slowly evolving growth-phase equilibrium. This puts the near-Earth plasma sheet out of equilibrium with the tail lobes, resulting in forced thinning of the near-Earth plasma sheet. This launches a rarefaction wave and drives a current-disruption mechanism, the CFCI and/or tearing. As with the other suggested roles of M-I coupling in substorm onset, this mechanism needs detailed modeling and testing in a global context.

6. Summary

During this quadrennial we have seen the rise of the near-Earth current disruption (NECD) model to rival the near-Earth neutral line (NENL) model as the leading model for the substorm. In the NECD model, substorm expansion onset occurs in the near-Earth portion of the nightside plasma sheet as stressed magnetic field dipolarizes. Substorm-associated boundary-layer processes evolve as a consequence of substorm expansion. As well, in the NECD model magnetic neutral-line formation is regarded to result from substorm expansion, rather than to be responsible for its onset.

What triggers onset of substorm expansion is still undetermined. Possible mechanisms are growth of an ion tearing mode, current disruption by a cross-field current instability, and magnetosphere-ionosphere coupling. A thin current sheet, favorable to chaotization of particle orbits, demagnetization of ions, and the growth of a cross-field current instability or the ion tearing mode, is observed in the near-Earth plasma sheet prior to dipolarization. Yet, recent advancements of these onset theories are revealing these mechanisms to be stable or to have growth rates which are too slow unless driven. Furthermore, a thin current sheet can persist for tens of minutes, in some cases hours, prior to local dipolarization, and not all local dipolarizations evolve into full-fledged substorm expansions. A current-sheet instability is needed to account for the rapid return transport of magnetic flux associated with substorm expansions as well as for plasmoid formation and release. The notion that magnetosphere-ionosphere coupling plays a role in triggering current-sheet instability and substorm expansion onset is gaining support. It appears that M-I coupling, cross-field current instability, and tearing operate in concert to result in substorm expansions.

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