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A MECHANISM FOR MAGNETOSPHERIC SUBSTORMS

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Abstract

Energy-principle analysis performed on two-dimensional, self-consistent solutions for magnetospheric convection indicates that the magnetosphere is unstable to isobaric (yet still frozen-in) fluctuations of plasma-sheet flux tubes. Normally, *pdV* work associated with compression maintains stability of the inward/outward oscillating normal mode. However, if Earth's ionosphere can provide sufficient mass flux, isobaric expansion of flux tubes can occur. The growth of a field-aligned potential drop in the near-Earth, midnight portion of the plasma sheet, associated with upward field-aligned currents responsible for the Harang discontinuity, redistributes plasma along field lines in a manner that destabilizes the normal mode. The growth of this unstable mode results in an out-of-equilibrium situation near the inner edge. When this occurs over a downtail extent comparable to the half-thickness of the plasma sheet, collapse ensues and forces thinning of the plasma sheet whereby conditions favorable to reconnection occur. This scenario for substorm onset is consistent with observed upward fluxes of ions, parallel potential drops, and observations of substorm onset. These observations include near-Earth onset, pseudobreakups, the substorm current wedge, and local variations of plasma-sheet thickness.

1. Introduction

In the 30 years since the substorm was first recognized as a distinct phenomenon by Akasofu [1964], identification of the mechanism responsible for triggering the magnetospheric substorm has eluded the space physics community. In this paper, we wish to set forth the fundamental theoretical/physical context in which the substorm should be viewed. This is the context of M-I coupled convection and the compression of magnetospheric plasma. Within this context we argue that the process of substorm expansion

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connection rate and rate of earthward transport can exceed the dayside merging rate. Over several hours the magnetosphere can relax toward a closed-field-line configuration. Second, during extended periods of steady, southward IMF, the magnetosphere can enter a steady convection state in which the dayside merging rate and nightside reconnection rate are balanced. This is known as a "steady magnetospheric convection" (SMC) event. Theoretically, the PBI problem can be avoided in highly-stretched configurations which contain a deep, near-Earth, local minimum in equatorial magnetic field strength. The B_e-minimum permits plasma-sheet flux tubes to convect earthward without substantial decrease in their volumes, thereby permitting a plasma-sheet pressure scalelength matching that of the lobe pressure. Theoretical steady-state configurations were constructed by Hau [1991]. Recently, Sergeev et al. [1993] have observationally inferred a magnetospheric configuration during an SMC event consistent with the Hau steady-state model.

The last exception to the usual state of affairs is the magnetospheric substorm. In this context, the magnetospheric substorm is the process in which pressure-bearing ions are released from the midnight-sector; plasma-sheet flux tubes are transported rapidly earthward and toward the day side to complete the convection cycle. The release of ions from midnight-sector flux tubes causes these flux tubes to contain less cross-tail drifting plasma than flux tubes nearer the flanks. This, combined with shear as depleted flux tubes rapidly move earthward, requires the substorm current wedge of region-1 sense to maintain charge conservation and quasi-neutrality. M-I coupling via this field-aligned current wedge provides for the enhanced electric field, i.e., enhanced transport within the wedge. The energy stored in the forms of plasma and magnetic flux in the tail during the preceeding growth phase, i.e., the usual state of affairs described earlier, is released via rapid transport of depleted plasma-sheet flux tubes toward the day side, injection into the ring current, energy deposition into the ionosphere, and the release of excess plasma within a plasmoid.

It should be noted that without the escape of plasma from flux tubes which close through the Earth's main field, the PBI problem remains for those flux tubes. Earthward transport is retarded owing to compression of plasma in those flux tubes as their volumes shrink. If rapid return transport of more than merely the closed, near-Earth magnetic flux is to be involved in the substorm, then formation of a near-Earth X-line and plasmoid escape seems to be an essential requirement for substorm expansion. Note the approximate one-to-one correspondence between observation of plasmoids or travelling compression regions and substorm onsets [Moldwin and Hughes, 1993]. (For the purposes of this discussion, "near-Earth" refers to that portion of the plasma sheet out to roughly $25R_E$ on the night side.)

A description similar to the PBI description of the problem imposed on the transport of magnetic flux in the return leg shown in Figure 1, whereby stored energy can be released to drive the dynamic substorm expansion phase. Whether viewed within the context of the PBI problem (excepting SMCs) or viewed within the large-scale stability of the magnetospheric configuration, the central problem is the same. For rapid return transport of substantial magnetic flux to proceed, i.e., the magnetospheric substorm, pressure-bearing ions must escape from nightside flux tubes closed through Earth's main field. This points to reconnection as the operative mechanism of substorm expansion.

M-I coupling will prevent substantial, substained ion loss if flux tubes are not opened. Suppose ions try to drift westward out of closed flux tubes whether in the "wall" description of Ashour-Abdalla et al. [1992] or if the current sheet were so thin that ions demagnetize. The result of M-I coupling in such cases is the same as described in connection with the Harang discontinuity [Erickson et al., 1991]. Current continuity would require upward field-aligned current into (and electron precipitation from) the loss region. Ionospheric current closure would result in modification of the convection electric field such as to oppose the separation of the charge species. Furthermore, the sense of the field-aligned current is opposite that of the substorm current wedge. Also, a local response, namely the cross-field current instabilities described by Lui et al. [1990, 1991, 1993], will probably prevent sustained demagnetization of ions in the absence of an external driver (see §4).

Thus, as noted earlier, reconnection appears to be the operative mechanism required for substorm expansion to proceed. Without near-Earth X-line formation, a pseudobreakup or even what some might call a small substorm can proceed. However, it appears that the energy release and magnetic flux transport of what all would call a substorm expansion requires that a near-Earth X-line forms. While reconnection appears to be the operative mechanism of substorm expansion, what triggers onset of substorm expansion?

4. Suggested Trigger Mechanisms

The classes of mechanisms suggested as responsible for triggering substorm onset include M-I coupling, tearing, current disruption, ballooning, and boundary-layer mechanisms. A lengthy discussion of these mechanisms is provided by Erickson [1994 – paper 1]. Here, we briefly summarize.

While the boundary layers cannot in the last analysis be ignored when attempting to resolve all the questions concerning substorm occurrence, in light of the Kiruna conjecture [Kennel, 1992] and the discussions above, we can defer discussion of their role in substorm onset. M-I coupling mechanisms such as those suggested by, e.g., Chao et al. [1977], Haerendel [1992], or Zhu and Kan [1990] are perhaps best considered as auroral intensification models like those of Heppner et al. [1967], Coroniti and Kennel [1972] and Rothwell et al. [1991]. The "unloading instability" suggested by Kan [1993] might not be more than the pressure gradient nor for that matter the j×B force as we leave the local approximation. We can attempt to analyze the outcome. At the earthward edge of the disruption region, a flux tube will see an unbalanced earthward j×B force, consistent with some escape of ions as they are scattered. A BBF can be spawned to interchange with its surroundings and result in weak injection at geosynchronous distance. Tailward in the disruption region ions left behind enhance the energetic-particle population of flux tubes and retard their earthward convective transport. Since the background current sheet is thicker further out, the CFCI is quenched, and the growth phase continues. With this constraint, the CFCI should merely result in thickening the current sheet in the central portion of the disruption region. This description is consistent with the pseudobreakup observations of Koskinen et al. [1993] and Ohtani et al. [1993].

Mathematical consideration of the CFCI in non-local approximation, i.e., including the background plasma and field gradients, leads to consideration of the lower-hybrid drift instability (LHDI) [Lui, 1992]. The LHDI is stabilized by high plasma β [Huba and Papadopoulos, 1978]. In our view, current sheet thinning drives the CFCI, and the so-called "driven" LHDI has been considered by Papadopoulos et al. [1990]. Their results show that if the current sheet thins fast enough, say with substorm-sized electric fields, the central plasma sheet can be unstable to the driven LHDI; growth times are long if only growth-phase sized electric fields are present.

We suspect that the CFCI provides stability of the current sheet against significant ion demagnetization during normal growth-phase thinning as described above. Thin current sheets, with thicknesses comparable to typical ion gyroradii, are commonly observed in the near-Earth plasma sheet, in some instances for tens of minutes, prior to substorm onset [e.g., Pulkkinen et al., 1992]. During SMCs such thin current sheets can persist for hours before a change in solar-wind conditions results in substorm onset, marking the end of the SMC. (See, e.g., Sergeev et al. [1993].) These persistent thin current sheets tend to belie the notion that current disruption or tearing trigger substorm onset. However, the current disruption mechanism, when considered non-locally and in conjunction with tearing, is quite a complex problem. Much more analysis is needed before its role as an onset triggering mechanism can be determined.

Motivated by detailed particle and field observations at geosynchronous orbit, Roux et al. [1991] suggest the ballooning instability as the mechanism for substorm onset. Several talks at this meeting were supportive of some sort of ballooning scenario for substorm onset. Like the other proposed trigger mechanisms 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 active debate [e.g., Pu et al., 1992; Ohtani and

The destabilization of the fundamental, inward/outward, normal-mode oscillation of plasma-sheet flux tubes czn be viewed in the following manner. As growth phase stretching of the tail proceeds, the transition region between dipolar and taillike flux tubes in the inner-edge region of the plasma sheet shortens. The gradient in flux-tube volume in this transition region steepens, intensifying the differential gradient/curvature drift of charge species, and requires increasing upward (Harang) field-aligned current into the region. Also, as the transition region narrows, the deceleration of earthward plasma flow and azimuthal acceleration increase which might require field-aligned closure of inertial-driven currents. The development of potential drops will accelerate ionospheric ions into these braking flux tubes and cause the pressure along the flux tubes to shift toward the equator. This pressure redistribution can cause the equatorial, normal-mode oscillating electric field to overshoot the background convection electric field (reversing the electric field) as the equatorial ends of flux tubes displace tailward.

While this occurs, the lobe magnetic pressure is essentially unperturbed. Since the pressure gradient is earthward, tailward displacement of the equatorial pressure profile results in $P_{lobe} > P_{eq}$ near the inner edge, and $P_{lobe} < P_{eq}$ tailward of the inner edge. If the pressure displacement occurs over too-limited a radial extent, flux tubes on either side will be over- and under-compressed, and the mode will be stabilized. If however, pressure displacement occurs over a radial extent comparable to the plasma-sheet thickness, then the vertical pressure imbalance can be communicated to the lobes before the radial compressional mode can provide stabilization. This results in the out-of-equilibrium "protoplasmoid" or "global ballooning" picture of paper 2. Collapse ensues. Dipolarization occurs on the earthward side of the collapse; forced thinning of the plasma sheet occurs as the collapse travels downtail causing "neutral sheet" formation. The global ballooning triggers the end of the quasi-static growth phase and start of a dynamic phase. In this dynamic phase forced thinning of the current sheet can drive the CFCI mechanisms and tearing leading to X-line formation.

Various observations are supportive of this scenario. Daglis et al. [1993] show that the contribution to near-Earth plasma-sheet pressure from ionospheric ions correlates well with AU and poorly with AL during the growth phase. The near-Earth portion of the upward Harang currents westward and earthward of the Harang electric field reversal should close via the eastward electrojet (AU). (Note that M-I coupling was included in the MHD simulations by Hesse and Birn [1991], however, the runs did not include mass exchange with the ionosphere which could affect ion distributions along field lines.) The azimuthal periodicity in auroral luminosity prior to onset noted by Elphinstone et al. [1993] could be indicative of azimuthal structure of ballooning as discussed by Roux et al. [1991]. Global ballooning might be analogous to coronal mass ejections (CMEs) and flares. The CME (global ballooning?) is observed to

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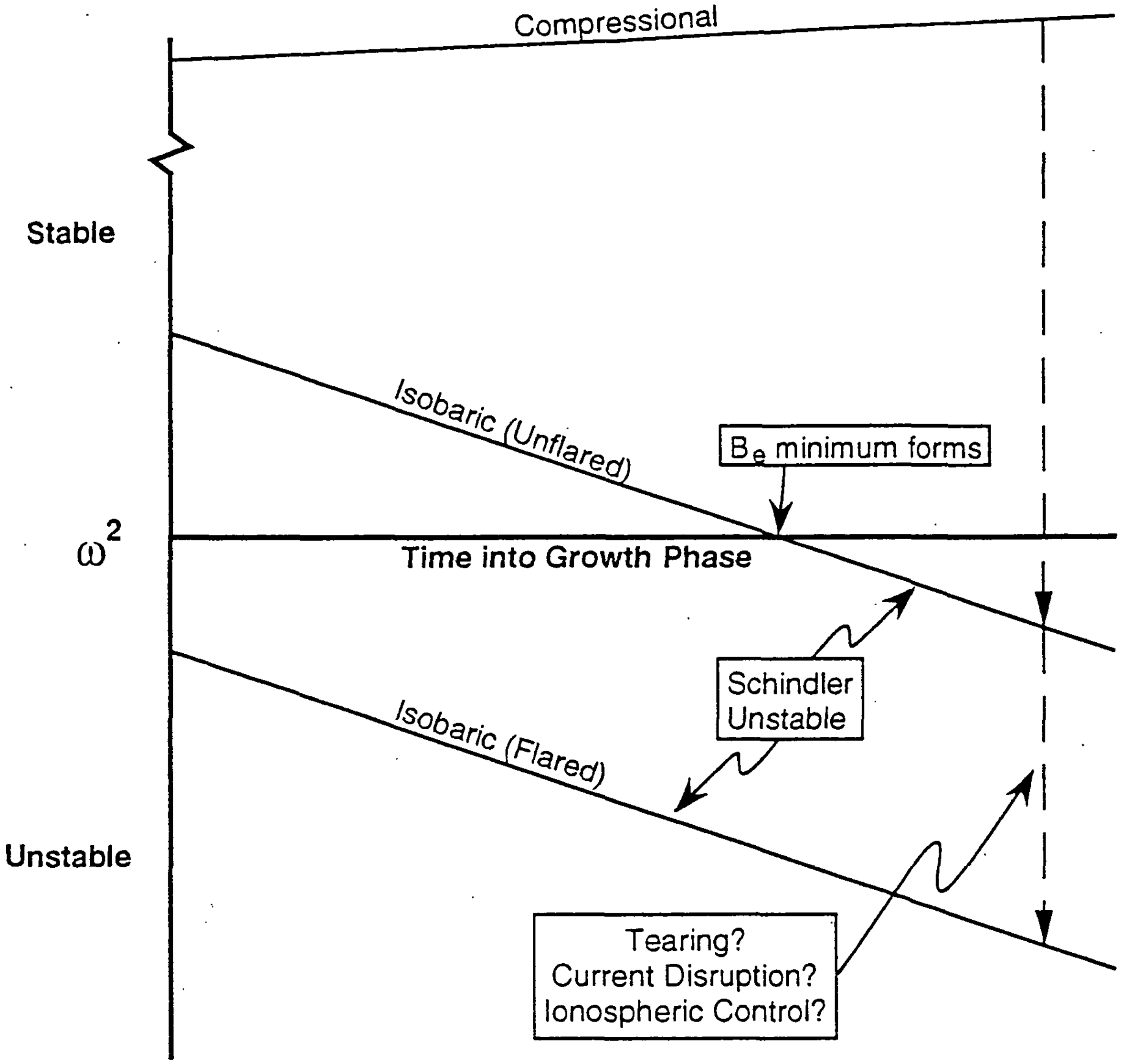
Compressional
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Time into Growth Phase
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Current Disruption?
Ionospheric Control?