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Magnetospheric Convection ?

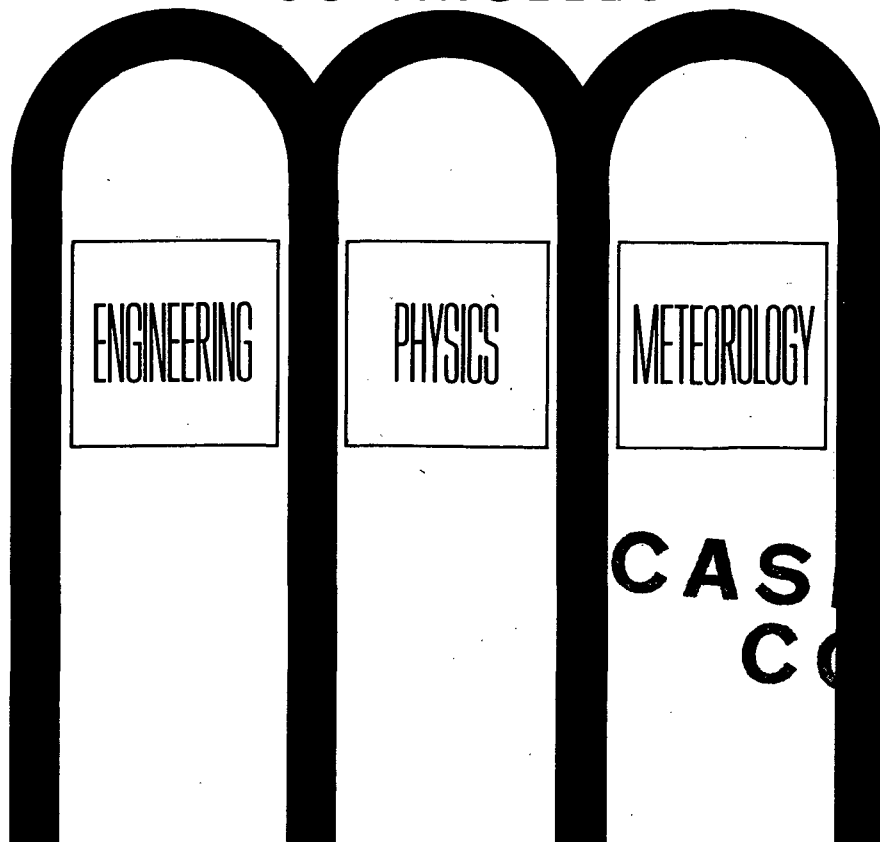
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October, 1972

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UNIVERSITY OF CALIFORNIA  
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# ABSTRACT

Following a southward shift of the interplanetary magnetic field, which implies enhanced reconnection at the nose of the magnetosphere, the magnetopause shrinks from its Chapman-Ferraro equilibrium position. If the convective return of magnetic flux to the magnetopause equalled the reconnection rate, the magnetopause would not shrink. Consequently, there is a delay in the development of magnetospheric convection following the onset of reconnection, which we ascribe to line tying by the polar cusp ionosphere. A simple model relates the dayside magnetopause displacement to the currents feeding the polar cap ionosphere, from which the ionospheric electric field, and consequently, the flux return rate, may be estimated as a function of magnetopause displacement. Flux conservation arguments then permit an estimate of the time scale on which convection increases, which is not inconsistent with that of the substorm growth phase.

## INTRODUCTION

In 1961, Axford and Hines proposed that a general circulation of magnetic flux tubes and plasma within the magnetosphere would account for the observed patterns of electrical currents in the polar cap and auroral oval ionospheres. Historically, then, the first indication of the existence of magnetospheric convection stemmed from its interaction with the ionosphere. Axford and Hines also suggested that convection could be driven by viscous coupling of solar wind momentum to the magnetosphere. In the same year, Dungey (1961) proposed a morphologically equivalent model of convection, which, however, was driven by magnetic field line reconnection at the nose of the magnetosphere. Dungey's model predicts open field lines in the geomagnetic tail, and since averaged over long periods of time, dayside reconnection can not reduce the total magnetic flux of the geomagnetic dipole, a second magnetically neutral reconnection region is required in the geomagnetic tail. In 1964, Axford estimated the steady convection rate resulting from viscous coupling at the magnetopause. In the same year, Petschek (1966), using his model of the magnetic annihilation rate estimated the convection rate resulting from reconnection at the nose of the magnetosphere. This last estimate was subsequently incorporated into a steady state model of convection (Levy, Petschek, and Siscoe, 1964). Both estimates of the convection rate provided energy inputs from the geomagnetic tail to the inner magnetosphere sufficiently large to power magnetic storms. While it was thereby evident that either steady convection estimate could account for magnetic storm and auroral energetics, the infrequent occurrence of magnetic storms indicated that convection approached their calculated rates only infrequently. Moreover, the great temporal variability of auroral activity, just then organized by the concept of the auroral substorm, (Akasofu, 1964) had one possible interpretation in terms of unsteady convection. At that time, it was unclear, however, whether substorms were

strong nonlinear local ionospheric responses to small changes in magnetospheric boundary conditions, or whether they truly involved unsteady motions of magnetospheric scale. It gradually became clear experimentally that substorms involve the whole magnetosphere.

Convection, nevertheless, produces a geomagnetic tail (Axford, Petschek, and Siscoe, 1965), which since its discovery (Ness, 1965) has never disappeared. The continuous existence of the geomagnetic tail argues that there should always be a finite convection rate on the average. This made it worthwhile to continue theoretical exploration of the consequences of steady state convection models. Nishida (1966) and Brice (1967) then proposed a generally accepted model of the plasmopause (Carpenter, 1966) based upon the action of steady convection upon cold plasma escaping from the ionosphere. Petschek and Kennel (1966), Kennel (1969) and Vasyliunas (1969) argued that strong diffusion electron precipitation would produce a sharp inner edge to the plasma sheet electron distribution (Vasyliunas, 1968). They considered only steady convection and neglected the self-consistent interaction with the enhanced auroral oval ionosphere produced by the electron precipitation. Finally, steady state convection has been the subject of nearly all numerical investigations of convection.

The strength of viscous coupling has yet to be determined experimentally. One test which would be made is to choose times when the solar wind field is quiet and northward, and correlate magnetospheric disturbances and polar cap electric fields with variations in the dynamic pressure of the solar wind. Thus, the absence of viscously driven convection has not been demonstrated. On the other hand, the reconnection model has had two simple yet definitive tests. Lin and Anderson (1966) interpreted their observations of direct entry of solar flare electrons into the high latitude geomagnetic tail as evidence for open field lines. Fairfield and Cahill (1966) found a distinct

correlation between southward shifts in the magnetosheath field and polar cap and substorm disturbances. Since then, a long series of investigations have confirmed this conclusion (see Arnoldy (1971) and the references therein). Thus these experimental tests of the reconnection model of convection all necessarily involved unsteady convection. This paper addresses itself theoretically to an idealization of the above experimental tests of reconnection. Namely, we will ask how rapidly is enhanced convection established within the magnetosphere following a sudden southward shift of the magnetosheath magnetic field.

Steady state convection models need not grapple completely with the problem of self-consistency between the convective flow and the conditions imposed upon it at its boundaries, the magnetopause and the ionosphere, since in steady state, convection must always adjust to the imposed reconnection rate. In time-dependent convection, it is precisely the rates at which these boundaries are adjusted and adjust the flow which should determine that rate at which convection is established. Since a rigorous mathematical treatment of self-consistent time dependent convection is still beyond us, we limit our objective to a search for a simplified model which incorporates as clues for, and constraints upon, our theoretical reasoning the evidence provided by observations of substorms, which now definitely appear to be the consequence of enhanced reconnection, and therefore, enhanced convection. In particular, we will find it illuminating to ask what other phenomena follow upon enhanced reconnection besides enhanced convection. From these observations, we will abstract a highly simplified model of time dependent convection, whose simplicity itself precludes a detailed discussion of substorms in all their variability. Even with this limited objective, it has proven difficult to be completely self-

consistent conceptually, and so where necessary we will use phenomenological arguments to fill in gaps in our theoretical understanding. Furthermore, we will consciously maximize the role of the ionosphere, for example, by closing magnetospheric currents through the ionosphere when faced with a choice of closure paths which is not settled by phenomenology or theory. If a consistent pattern emerges from this procedure, then a model of convection involving close coupling with the ionosphere will at least be a reasonable possibility.

Cauffman and Gurnett (1971) and Gurnett and Frank (1972) have found that polar cap convection electric fields are generally enhanced prior to substorm breakup. Mozer (1971) has observed a gradual temporal increase of the westward electric field in the night side auroral oval prior to the development of the enhanced westward electrojet. In the one case in which solar wind data was available, the slow increase in ionospheric electric field followed a southward shift of the magnetic field, in accordance with theoretical expectation. In addition, the magnetosphere undergoes a series of coherent configurational changes on the same time scale as the electric field buildup. Aubry, Russell and Kivelson (1970) observed, following a southward shift of magnetosheath magnetic field, that the magnetopause migrated slowly inwards and the geomagnetic tail field increased on the same time scale. A breakup followed this sequence of events. Since the solar wind dynamic pressure did not change during this time interval, Aubry et al. (1970) concluded that the magnetopause shrinkage was a direct consequence of reconnection and subsequent transport of magnetic flux to the geomagnetic tail. Although Aubry et al. (1970) reported a single event, there has now accumulated evidence which indicates that this sequence of events may be typical. Even earlier, Meng (1970) had found statistically that the magnetopause lies closer to earth at disturbed times. During the magnetic storm of November 1, 1968, OGO-5 observed the polar cusp to move

equatorward following southward shifts of the solar wind field, and to return poleward following northward shifts (Russell, et al., 1971). In a similar vein, Akasofu (1972 a,b) has found that the intensity of substorms on the night side is proportional to the equatorward displacement of the dayside polar cusp auroral arcs. Camidge and Rostoker (1970), Fairfield and Ness (1970), and Russell et al. (1971) have observed that the geomagnetic tail field increases prior to substorm breakup. Aubry and McPherron (1971) found that the geomagnetic tail field increases followed southward solar wind field shifts. The plasma sheet has also been observed to thin at these times (Hones, 1970; Hones et al., 1971). In addition, the night side auroral oval migrates equatorward prior to breakup (Snyder and Akasofu, 1972).

Since they both have the same time scale, we adopt the point of view that changes in magnetospheric structure are inherently coupled to the time-development of convection, and furthermore, that understanding the configurational modifications should begin with an understanding of the observed magnetopause shrinkage. In a previous paper (Coroniti and Kennel, 1972b), we argued that if dayside magnetopause shrinkage were the controlling configurational change, then the observed magnetotail changes could be accounted for, both qualitatively and semi-quantitatively, using a simple flaring tail model and assuming that the tail changes on time scales long compared with the Alfvén travel time across and along the lobes of the tail. If these arguments are correct, the fundamental question becomes "Why does the magnetopause shrink in response to enhanced reconnection in the absence of changes in solar wind dynamic pressure?"

Aubry et al. (1970) argued that the magnetopause shrank because flux was peeled away and added to the geomagnetic tail. On the other hand, Mozer's (1971) electric fields measure an enhanced convective return to flux towards the dayside magnetopause during the same general time interval following



enhanced reconnection. If this flux return rate equalled the field cutting rate, then the magnetopause would not shrink. Since it does shrink, we are forced to conclude that the field cutting rate exceeds the flux return rate, at least initially. Consequently, the question "Why does the magnetopause shrink?" reduces to "Why are the two flux rates out of balance?" An alternative point of view is that after the onset of enhanced reconnection, there must be a delay for the establishment of a self-consistent convection return rate in balance with the reconnection rate. That there should be a delay is not surprising. For example, there will certainly be magnetohydrodynamic wave propagation delays associated with communicating changes in boundary conditions at the magnetopause to the internal flow.

A complete self-consistent theory of time dependent convection would include the interaction of convection with all magnetospheric boundaries. However, since the Alfvén propagation time to the distant tail is very long, the initial response of convection to enhanced reconnection should involve primarily the near earth magnetosphere and its boundaries, the magnetopause and the ionosphere. If the ionospheric conductivity were identically zero, there would be no interconnection of the ionosphere with convection. However, the mid-latitude dayside ionospheric conductivity is never zero. In the high-latitude polar cusp, whose equatorward edge is now considered to be the boundary between open and closed field lines on the dayside, hot magnetosheath electrons are observed to precipitate into the ionosphere (Heikkilä and Winningham, 1971; Frank, 1971). Therefore, on dayside polar cusp field lines, where tangential stress is exerted from field cutting, there will be an enhanced ionospheric conductivity (Kennel and Rees, 1972). Furthermore, convection carries hot electrons from the plasma sheet through the inner magnetosphere to the magnetopause. These electrons precipitate to the atmosphere and thus produce an enhancement of the ionospheric conductivities in the auroral oval. Hence, wherever convection goes, there will

be enhanced ionospheric conductivity.

In general, the convection electric field will drive both Hall and Pedersen currents in the ionosphere. At least the direct Pedersen current must have its source in space, either in the magnetosphere or on the magnetopause. In addition, spatially inhomogeneous ionospheric conductivity profiles might require closure of Hall currents in space. Divergences of ionospheric and magnetospheric current systems must be coupled by field-aligned currents. In general, the magnetospheric sources for these currents require plasma stress gradients since the magnetospheric plasma is collisionless. A minimum requirement for a self-consistent description of convection is that the divergence of the ionospheric currents be consistent with the magnetospheric current systems, or equivalently the magnetospheric stress gradients. Since configurational changes are implied by changes in magnetospheric and magnetopause currents and stresses, the hypothesis that configurational changes, intensifications of field-aligned current systems, and convection enhancement are related is reasonable.

We now will outline qualitatively how the changes in dayside magnetopause boundary conditions following enhanced reconnection may be communicated to the rest of the magnetosphere and ionosphere. The demand for magnetic flux created by enhanced reconnection must launch a wave from the reconnection region which propagates throughout the magnetospheric cavity. This wave, which signals the change in magnetopause boundary conditions, initiates an enhanced flux return in its wake. Since the flow speed behind this wave exceeds that ahead, it has the character of a rarefaction wave. Since any time dependent reconnection rate could be resolved into a series of step changes in reconnection, the time development of convection could also be so resolved; in particular, each step in reconnection rate would radiate a step rarefaction wave. If the plasma pressure within the

magnetosphere and also the ionospheric conductivity could be neglected, then the rarefaction wave would be an interchange mode propagating at the Alfvén speed. The  $\partial E / \partial t$  polarization currents in the wave front would accelerate the plasma and field lines to the required flux return rate (Tamao, 1972). The accelerated convective flow could propagate thereafter to the magnetopause without dissipation. Such a wave could in fact propagate as a sharp impulse. However, on closed field lines within the magnetosphere, the plasma pressure is usually not negligible and consequently there will also be a finite ionospheric conductivity bounding the convecting field lines. In this case the wave would resemble the MHD slow rarefaction wave which must now adjust not only the convective flux return rate but also the plasma stresses necessary for self-consistency with the induced ionospheric currents. Whereas it is conceivable that for times short compared with an Alfvén travel time along the lines of force, the slow wave could impulsively accelerate the plasma and field lines in space without affecting convection in the ionosphere, for times longer than the Alfvén communication time, enhanced convection requires a changed stress gradient in space to overcome the ionospheric dissipative drag. Ionospheric dissipation requires an energy input to maintain steady convection in the wake of the wave. Since the ultimate source of energy is the magnetopause and the boundary conditions it imposes on the stress gradients within the magnetosphere, maintenance of line tied convection requires good communication with the magnetopause. We expect this to be reasonable only when the time-scale for convection is longer than the Alfvén travel time along the lines of force, so that connection with the ionospheric boundary conditions is established, and also longer than the fast MHD wave travel time across the magnetospheric cavity, so that pressure and stress changes can be communicated throughout the cavity and to the magnetopause. The fact that the torsional Alfvén wave propagation time to the

ionosphere and the fast MHD wave time across the magnetosphere are comparable indicates that if the ionospheric boundary conditions are regulating the development of convection, then it must also be that the necessary configurational changes involve the whole front side of the magnetosphere. These arguments lead us to view the establishment of convection by the slow rarefaction wave to be equivalent to magnetospheric configurational changes.

Of course, the rarefaction wave establishing convective flux return must propagate into the distant plasma sheet. Here, however, the relation between plasma sheet configurational changes and the establishment of a convective return of flux is less clear. It seems likely that the connection with the ionosphere is less intimate, due to long length of the field lines. In the high  $\beta$  region of the plasma sheet, the propagation speed of a slow wave along the magnetic field is the Alfvén speed, so that the wave propagation time and the Alfvén time to the ionosphere become comparable. Hence the intimate connection between convection and the ionosphere may no longer exist.

Our understanding of when, where, and how, reconnection takes place in the geomagnetic tail is sufficiently vague, even during steady state conditions, much less in time-dependent situations, that the crucial question "how much tail flux is reconnected during the establishment of convection? cannot be answered with any assurance. There are at least two possibilities: that the tail reconnection rate doesn't change until the slow wave has propagated to the pre-existent tail neutral line to notify this reconnection region of the change in flow boundary conditions, or that the topology of the plasma sheet changes in such a way that a new tail reconnection region can be formed. The observations that the nightside auroral oval does not expand to high latitudes until late in the substorm are not very conclusive in this regard, for they do not preclude the possibility of reconnection prior to breakup which does not involve

significant plasma heating. Furthermore, if the tail neutral line is distant, there could be significant delays between the onset of dissipative heating in the tail, and the appearance of the heat over the nightside auroral oval ionosphere. The establishment of the appropriate tail reconnection rate is of course essential to the creation of a completely steady convection pattern.

Given good coupling to the ionosphere and magnetopause via Alfvén and fast wave communication, a reasonable first attempt to understand the time development of convection begins by imagining the flow configuration within the magnetosphere - but not the magnetotail - to evolve through a sequence of nearly steady states, each one of which is consistent with its instantaneous ionospheric and magnetopause boundary conditions. Such a quasi-steady state implies that if it were possible to estimate the flux return rate, consistent with the boundary conditions, anywhere in the convection pattern, this estimate could be reasonably valid throughout the inner magnetosphere. Furthermore, the flux return rate should be throttled at that region where by whatever combination of ionospheric drag and magnetospheric stresses, there tends to be produced the minimum flux return. Since the ionospheric electric field must be curl-free to a high degree of approximation, all convection flow streamlines must be closed in the ionosphere. Consequently, the anti-sunward flux transport rate over the polar caps must equal the sunward convective flux return rate through the auroral oval. Thus, the  $\text{emf}$  across the polar cap  $\psi_{pc}$  measures the flux return rate,  $c\psi_{pc}$ . When the convective flux return rate, as measured by  $c\psi_{pc}$ , is less than the reconnection rate at the nose of the magnetosphere, there will be a transport of flux to the geomagnetic tail. However, the increase in tail flux is measured by changes in the area of the polar caps and not by the ionospheric convection rate. Furthermore, when the tail flux increases with time, the  $\text{emf}$  taken around one lobe of the tail

should exceed that across the corresponding polar cap ionosphere; of course the difference between the two emf's is accounted by time dependent magnetic configurational changes.

Clearly, the emf across the ionosphere and that across any surface which intersects all the convection streamlines in the magnetosphere or magnetotail must eventually come into balance. The key question is how long it takes to establish a steady state. In this paper, we relate the dayside magnetopause displacement to the electric field in the polar cusp ionosphere, and consequently to the flux return rate. Flux conservation arguments then permit an estimate of the time scale on which a steady state is approached. This time scale depends primarily upon the polar cusp ionospheric Pedersen conductance and the size of the magnetosphere.

#### LINE TIED MAGNETOPAUSE

The establishment of an enhanced eastward convection field in the polar cap ionosphere requires enhanced field-aligned currents into the ionosphere on the dawn side and out of the ionosphere on the evening side of the polar cap ionosphere, much of which will flow through the high conductivity polar cusp. The task ahead of us is to estimate, from a given magnetopause displacement, the current which as a result flows into, through, and out of the ionosphere. This, together with the estimated conductance of the polar cusp ionosphere, will yield the instantaneous ionospheric electric field as a function of magnetopause displacement, which in turn provides an estimate of the convective flux return to the magnetopause. If the flux return rate to the magnetopause is less than the flux reconnection rate, the magnetopause will continue to shrink until an appropriate balance is reached.

Let us first consider the configuration of surface currents on an ideal Chapman-Ferraro magnetopause. The Chapman-Ferraro solution assumes no internal convection, and consequently, no interaction with the ionosphere. Therefore the surface currents all must and do close on the magnetopause in this model. When tangential stresses, convection, and dissipation are added to this picture, these currents are no longer restricted to close on the magnetopause, but can close via internal magnetospheric currents; for example, tail magnetopause currents close through the neutral sheet. Similarly, ionospheric currents across the polar cap are also a possible closure path, which bears the same topological relationship to the magnetopause currents over the polar caps as the neutral sheet currents do to the tail magnetopause currents. This makes it plausible that one source of ionospheric currents can be divergences of the surface currents on the magnetopause.

A combination of observational and theoretical arguments suggest that divergences of dayside magnetopause surface currents could accompany the development of convection. Consider the topological changes in the magnetosphere following enhanced reconnection. Observationally, the magnetopause shrinks without a significant change in the magnetic field jump across it. Consequently, the line current density per unit meridional length remains roughly constant, while the length of the field lines connecting to the magnetopause diminishes. Thus the total current carried by the dayside magnetopause between the polar cusps decreases. G. Atkinson has suggested to us that this current diminution provides the dominant current feeding the ionospheric line tying circuit. During reconnection events, observation indicates that the tail magnetic field strength increases. Therefore the tail magnetopause currents and those over the polar cap magnetopause must increase to contain the increased tail field. In a Chapman-Ferraro magnetosphere, the dayside magnetopause currents are fed entirely by, and close the polar cap and tail magnetopause currents. Here,

however, when the dayside current decreases and the polar cap magnetopause current increases with time, it seems plausible that some of the extra current required to contain the enhanced magnetotail field could be available to flow through the polar cap ionosphere. In the absence of detailed solutions for the magnetospheric configuration, it is impossible to state what fraction, if any, of the magnetopause currents actually flow through the ionosphere. However, in this section, we assign to the ionosphere the diminution in day-side magnetopause current and ask whether or not this leads to a reasonable relation between the magnetopause displacement and convection rate. If it does, then a relationship between ionospheric line-tying and magnetopause displacements remains a plausible hypothesis.

The total current per unit meridional length of the magnetopause, integrated over the thickness of the magnetopause, is  $\frac{c\Delta B_{CF}}{4\pi}$  in cgs units, where  $\Delta B_{CF}$  is the magnetic field jump across the magnetopause. If we take the effective meridional length of the magnetopause to be  $R/2$ , the radius of curvature of a dipole line of force which intersects the geomagnetic equator at the instantaneous nose radius  $R$ , then the total magnetopause current  $I_M$  carried between the polar cusps is approximately

$$I_M = \frac{c\Delta B_{CF}}{8\pi} R \quad (1)$$

The magnetopause has been observed to shrink without a significant change in  $\Delta B_{CF}$  (Aubry et al., 1970), which is consistent with the fact that the dynamic pressure of the solar wind remains unchanged during many reconnection events. Consequently, the dominant change in the total magnetopause current  $\delta I_M$  stems from a change in the meridional length of the magnetopause; therefore we may estimate



$$\delta I_M = + \frac{c \Delta B_{CF}}{8\pi} Dr \quad (2)$$

where  $D$  is the nose radius prior to the onset of enhanced reconnection, and  $R = D(1 + r)$ . Equation (2) is probably most trustworthy when  $r$  is reasonably small, since we have implicitly assumed that the changes in shape of the magnetopause following reconnection are reasonably small. We will take  $\delta I_M$  as an estimate of the line-tying currents flowing through the two polar cusp ionospheres.

Let us now turn to the configuration of currents flowing in the polar cusp ionospheres. The equatorward edge of the polar cusp appears to be the boundary between open and closed field lines (Gurnett and Frank, 1972). We expect that the convection electric field  $E_I$  will be tangential to the equatorward boundary of the dayside polar cusp, corresponding to  $\underline{E}_I \times \underline{B}$  convection normal to this boundary. Since  $E_I$  must be curl-free to a high degree of approximation, the ionospheric electric field on closed field lines equatorward of the polar cusp boundary will equal that in the polar cusp. Consequently, computation of  $E_I$  within the polar cusp is equivalent to computing the flux return rate to the magnetopause. The total current  $I_p$  flowing through the polar cusp is roughly

$$|I_p| \approx \sum_p E_I W \approx \frac{\sum_p \phi_p W}{\ell} = \frac{\sum_p W}{c \ell} \dot{\Phi}_R \quad (3)$$

where  $\sum_p$  is the Pedersen conductance,  $W$  is an effective width of the polar cusp conductance enhancement taken in the approximately North-South direction,  $\phi_p$  is the electric potential taken around the effective longitudinal length of the dayside conductance enhancement, and  $\dot{\Phi}_R$  is the flux return rate to the magnetopause.

Assuming that half of the magnetopause current increment  $\delta I_M$  flows through each polar cusp ionosphere, and equating  $-\delta I_M/2$  to  $I_p$  leads to an expression for the flux return rate  $\dot{F}_R$  as a function of magnetopause displacement:

$$\dot{F}_R = -\frac{c^2 \ell \Delta B_{CF}}{16\pi W \sum_p} D r = -\dot{F}_* r \quad (4)$$

where  $F_*$  is a characteristic flux return rate which parametrizes the efficacy of line-tying. Since  $\dot{F}_*$  decreases with increasing  $\sum_p$ , increased line-tying implies that increased magnetopause shrinkage is required to produce a given flux return rate  $\dot{F}_R$  in this model.

If we could relate the total closed magnetic flux  $F_c$  to the instantaneous nose radius  $R$ , then its time derivative  $\dot{F}_c$  could be related to the time rate of change of the nose radius,  $\dot{R}$ . Then since the rate of change of closed flux must equal the difference between the flux return rate  $\dot{F}_R$  and a given reconnection rate  $\dot{F}_0$ ,

$$\dot{F}_c = \dot{F}_R - \dot{F}_0 \quad (5)$$

we would then have an equation for  $\dot{R}$ , and from (3) and (2), also for the time development of the convection electric field.

In principle, the total closed flux is the total dipole flux minus the open flux in the two polar caps. Clearly a part of  $\dot{F}_c$  is determined by the tail reconnection rate, whose relationship to the instantaneous magnetopause reconnection rate is unclear, as we discussed in the introduction. However, another part of  $\dot{F}_c$  does depend upon the reconnection at the nose of the magnetosphere. By the propagation arguments contained in the introduction, the reservoir of flux confined in the dayside magnetosphere, and perhaps in the portions of the nightside near to the Earth, should most immediately respond to changes in the magnetopause reconnection rate.

Consequently, we will estimate the flux in the dayside magnetosphere. If we model the dayside magnetopause as a hemisphere with radius  $R$ , then the total flux confined within is

$$F_c = \gamma \mu \pi (1/R_E - 1/R) + \frac{\mu \pi R^2}{D^3} \quad (6)$$

where  $\mu$  is the Earth's magnetic moment and  $R_E$  is one Earth radius; the second term in (6) is the confined Chapman-Ferraro flux due to magnetopause surface currents which produce a uniform perturbation field throughout the cavity in this model. We have, in accordance with observation, assumed this perturbation field,  $\mu/D^3$ , to remain unchanged when the magnetopause moves from its initial position  $D$ . The factor  $\gamma$  in front of the first term of (6) represents the possibility that we must include some nightside closed magnetic flux in the estimate of  $F_c$ . Consequently, we expect  $\gamma$  to be somewhat larger than one and probably less than 2. The time rate of change of closed flux is consequently

$$\dot{F}_c = \mu \pi \left[ \frac{\gamma \dot{R}}{R^2} + \frac{2R\dot{R}}{D^3} \right] \quad (7)$$

For lack of better information,  $\gamma$  was assumed constant. Therefore, combining (4), (5) and (7), we arrive at an approximate equation for the magnetopause displacement

$$\frac{\mu \pi}{\dot{F}_* D} \left[ \frac{\gamma}{1+r^2} + 2(1+r) \right] \dot{r} + r = - \frac{\dot{F}_0}{\dot{F}_*} \quad (8)$$

To explore the physical consequences of (8), we assume small magnetopause displacements,  $r \ll 1$ , and normalize the time to the characteristic time

$$\Delta = \frac{(\gamma+2)\mu\pi}{\dot{F}_* D} \quad (9)$$

whereupon, (8) reduces to

$$\frac{dr}{d\tau} + r = - \frac{\dot{F}_0}{\dot{F}_*} \quad (10)$$

where  $\tau = t/\Delta$ .

The steady state solution of (10) with a finite reconnection rate  $\dot{F}_0$  leads to a magnetopause displacement  $r = -\dot{F}_0/\dot{F}_*$ ; consequently, the assumption  $r \ll 1$  implies that (10) will be valid only for reconnection rates  $\dot{F}_0/\dot{F}_* \ll 1$ . For an arbitrary  $\dot{F}_0(\tau)$ , the solution of (10) is

$$r(\tau) = -e^{-\tau} \int_0^{\tau} d\tau' \frac{\dot{F}_0(\tau')}{\dot{F}_*} e^{\tau'} \quad (11)$$

where  $r(0) = \dot{F}_0(0) = 0$ . We note from equation (4) that the flux return rate  $\dot{F}_R(\tau) = -\dot{F}_* r(\tau)$  is trivially derivable from (11). Equations (4) and (10) indicate that the steady state flux return rate equals the reconnection rate.

A definitive calculation of the time development of magnetospheric convection involves explicit knowledge of the precise relationship between the reconnection rate integrated around the magnetopause,  $\dot{F}_0$ , and the parameters of the solar wind upstream of the bow shock. However, southward shifts of the solar wind magnetic field are at least broadly related observationally to enhancements in  $\dot{F}_0$ . Often, the solar wind magnetic field is observed to shift southward abruptly and remain southward for times long compared to the Alfvén propagation time across the magnetosphere and the magnetosheath flow time around the nose of the magnetosphere. Furthermore, when reconnection is suddenly enhanced, we would expect an increased flux of magnetosheath electrons to precipitate into the dayside polar cusp ionosphere. Since the ionospheric structure comes into equilibrium with the precipitation flux on time scales of a few minutes (Kennel and Rees, 1972), a time comparable with the Alfvén communication time, in calculating the effects of line-tying upon the development of convection, we may therefore assume a steady ionospheric conductivity. Therefore, as an illustrative example, we will assume a step function reconnection rate given by  $\dot{F}_0(\tau) = \dot{F}_0 [\theta(\tau) - \theta(\tau - \bar{\tau})]$

where  $\theta(\tau) = 0$ ,  $\tau < 0$ ,  $\theta(\tau) = 1$ ,  $\tau > 0$ , where reconnection has been assumed to cease at  $\tau = \bar{\tau}$ . In this case, (11) reduces to

$$r(\tau) = \dot{F}_0 / \dot{F}_* (1 - e^{-\tau}), \quad 0 < \tau < \bar{\tau} \quad (12a)$$

$$r(\tau) = \frac{\dot{F}_0}{\dot{F}_*} (1 - e^{-\bar{\tau}}) e^{-(\tau - \bar{\tau})} \quad \bar{\tau} < \tau \quad (12b)$$

From equations (4) and (12), we see that the maximum flux return rate  $\dot{F}_R = \dot{F}_0 (1 - e^{-\bar{\tau}})$ ; consequently the duration of the reconnection event  $\bar{\tau}$  must exceed unity in normalized units for significant stimulation of internal magnetospheric convection. Should  $\bar{\tau}$  be very large, the flux return rate would asymptotically approach the reconnection rate.

The present model indicates that after reconnection ceases, convection continues and consequently the magnetopause would re-expand on the same time scale it contracted until a Chapman-Ferraro equilibrium is re-established. Physically, this represents the assumption that internal convection is still driven by the decrement in Chapman-Ferraro current arising from the inward magnetopause displacement which flows through the polar cusp ionosphere. As the magnetopause re-expands, the decrement decreases until the convection field is reduced to zero. However, several effects not included in the above model might alter the physics of the relaxation of the magnetosphere to a zero convection state. For example, if the dayside polar cusp magnetic field lines were suddenly closed, magnetosheath electrons might no longer have as free access to the polar cusp ionosphere as before. The ionospheric conductances would decay on time scales of a few minutes following a sudden reduction in magnetosheath electron precipitation flux. If the Chapman-Ferraro decrement must still flow through the ionosphere, the reduction in conductance implies that the convection

electric field should increase rapidly, whereupon the magnetopause might pop out. Should it pop on Alfvén time scales, then we would expect a strong rarefaction wave to be launched tailward, which could provide a further but temporary enhancement of convection elsewhere in the magnetosphere. On the other hand, the Chapman-Ferraro decrement could be shunted to a different closure path. Clearly, the return to a slowly convecting magnetosphere requires that the magnetic flux transported into the geomagnetic tail by dayside field-cutting be reconnected again in the tail, but our ignorance of the factors regulating tail reconnection prohibits us from defining a precise sequence of events. For example, should tail reconnection continue after dayside field-cutting ceases, then the earthward tail flow might act as a piston driving convection to the magnetopause.

To evaluate whether or not line-tying of the magnetopause could produce a significant delay in the enhancement of internal convection, we must estimate the characteristic flux flow rate  $\dot{F}_*$  and its associated time scale  $\Delta$ . First we estimate  $\Delta B_{CF}$  at the nose of the magnetosphere as  $2B_0/D^3$ , where  $B_0$  is the equatorial surface geomagnetic field. The line tying currents must flow in the polar cusp ionosphere at least over the local time region in which reconnection occurs at the magnetopause. The dependence of the local time region of reconnection upon upstream magnetosheath flow and magnetic field parameters is an unsolved problem. However, since most currently available reconnection theories (Petschek, 1964; Yeh and Axford, 1970) predict flow speeds towards the magnetopause the order of the Alfvén speed or less, it seems reasonable that reconnection could be most efficient when the magnetosheath flow does not carry the field lines very far before they reconnect. Consequently, we estimate the reconnection region to lie between the Alfvénic points in the magnetosheath flow, typically located  $\pm\pi/4$  radians from the noon-meridian. Thus, the effective length of the dayside

polar cusp is approximately  $\pi/4\xi_0$ , where  $\xi_0$  is the radius of the polar cusp. For  $\xi_0$ , we take 1200 km, corresponding to polar cusps at  $78^\circ$  geomagnetic latitude. According to observation (Gurnett and Frank, 1972), the width W of the polar cusp is typically 200 km corresponding to  $2^\circ$  geomagnetic latitude. Choosing  $D \approx 10 R_E$ , and normalizing  $\Sigma_p$  to 10 mhos, we find

$$\dot{F}_* \approx \frac{6 \times 10^{13}}{\Sigma_p^*} \text{ maxwells/sec} \quad (13)$$

where  $\Sigma_p^*$  is measured in units of 10 mhos. A flux equal to  $\dot{F}_*$  would create a  $\frac{600}{\Sigma_p^*}$  KV emf across the polar cap. Using the same estimates, we find for the characteristic time  $\Delta$

$$\Delta \approx 660 (\gamma + 2) \Sigma_p^* \text{ seconds} \quad (14)$$

We argued that  $\gamma$  should lie between 1 and 2; if we take  $\gamma = 1.5$ , then  $\Delta \approx 40\Sigma_p^*$  minutes.

Kennel and Rees (1972) have estimated the conductance enhancements expected from the precipitation of magnetosheath electrons into the polar cusp ionosphere. Assuming the precipitation fluxes were isotropic in pitch angle, and consequently equal to those in the magnetosheath, they found that normal solar wind and magnetosheath plasma energy densities lead to Pedersen conductance enhancements of 10-15 mhos on the noon meridian, which considerably exceeds the conductance of the normal polar cap ionosphere. Should there be resistive heating of electrons due to magnetic field annihilation on these field lines, the conductance enhancements could conceivably exceed their estimates. Since the Hall conductance enhancement produced by magnetosheath electron precipitation is small,  $\approx 2-3$  mhos, it is consistent to use only the Pedersen current in the above calculation.

Since the magnetosheath electron heat flux should decrease away from the stagnation point at the nose of the magnetosphere, and since the estimate for  $\dot{F}_*$ , eq. (13), at best represents an average over the whole dayside reconnection region,  $\int_p \approx 5$  mhos is probably a better estimate for the

present purposes. In this case,  $\dot{F}_*$  represents a 1.2 mV emf, and the convection response time  $\Delta \approx 20$  minutes. Gurnett and Frank (1972) have observed that the emf across the polar cap is the order of 200 kV. Taking  $\dot{F}_0$  to correspond to a 200 kV emf, then from (10) and (13) the corresponding magnetopause displacement  $r \approx 1/6$ , which for  $D = 10 R_E$ , implies a  $1.5 R_E$  inward displacement, which is not inconsistent with observation (Aubry et al. 1970).

In this model, the flux return rate and the field-cutting rate are out of balance ( $\dot{F}_R < \dot{F}_0$ ) for times the order of  $\Delta$  following a sharp onset of reconnection. Consequently, a finite increment of flux  $\delta F_T$  is added to each lobe of the geomagnetic tail during this time. The rate of change of tail flux  $\dot{F}_T$  is given by

$$\dot{F}_T = \dot{F}_0 - \dot{F}_R \quad (15)$$

Since  $\dot{F}_R = -\dot{F}_* r(\tau)$ , we may use equation (12), with  $\bar{\tau} = \infty$  for simplicity, to arrive at

$$\dot{F}_T = \dot{F}_0 e^{-\tau} \quad (16)$$

whereupon, integrating  $\dot{F}_T$  with respect to time, we find

$$\delta F_T = \dot{F}_0 \Delta (1 - e^{-\tau}) \quad (17)$$

Equation (17) indicates that the increment of tail flux scales as  $\dot{F}_0 \Delta \approx 2.5 \times 10^{16}$  Maxwells for  $\dot{F}_0$  corresponding to 200 kV emf and  $\Delta = 20$  minutes. A typical flux in each lobe of the tail might be  $5 \times 10^{16}$  Maxwells. Therefore, for convection potentials as large as 200 kV, the relative flux increment in each lobe a time  $\Delta$  after the onset of field-cutting could be the order of 33%. The areas of the polar caps should increase accordingly.

For the model of the flaring tail developed by Tverskoy (1968) and Spreiter and Alksne (1969), the combination of inward magnetopause displacement and tail flux addition should increase the flaring of the tail and therefore



its magnetic field strength. If the linearized adiabatic estimates of Coroniti and Kennel (1972b), based upon the above flaring tail model, may still be used for  $r \approx -1/6$  and  $\delta F_T/F_T \approx 1/3$ , then the relative increase in geomagnetic tail field would be  $\leq 70\%$ . The tail field has been observed to increase by roughly this amount on time scales the order of  $\Delta$  following southward shifts in the solar wind magnetic field (Aubry and McPherron, 1971).

Thus, we conclude

- (1) The changes in geomagnetic tail configuration which may be inferred from the observed tail field increases are consistent with the observed inward displacements of the dayside magnetopause and the necessarily associated transfer of magnetic flux to the tail.
- (2) In this model, these coupled changes in magnetospheric configuration following southward shifts of the solar wind magnetic field are consistent with a delayed development of internal convection which is regulated by ionospheric line-tying in the polar cusp.
- (3) The slow development of the convection electric field is also consistent with Mozer's (1971) observations of the monotonic buildup of a westward convection electric field in the nightside auroral oval ionosphere prior to substorm breakup. This in turn is consistent with a slow development of polar cap and auroral oval current systems prior to substorm breakup (Oguti, 1968; McPherron, 1970). The field-aligned current systems feeding the ionosphere should also develop on the convection time scale. If the north-south current components in the dayside polar cusp ionosphere are also fed by field-aligned currents, the transverse magnetic field fluctuations observed at 1100 Km altitude by Zmuda, et al. (1970) are explainable in terms of typical convection electric fields and conductance enhancements in the polar cusp (Kennel and Rees, 1972).

## DISCUSSION

It is tempting to speculate upon several other possible consequences of the model outlined above. For example, conventional models of the dayside magnetopause place the noon-meridian neutral line at a geomagnetic latitude of  $82^{\circ}$ , whereas the polar cusp is typically observed at latitudes of  $78^{\circ}$  and below. N. M. Brice has suggested to us that this discrepancy could be accounted for by the magnetopause shrinkage required by convection. Furthermore, we can argue that during magnetic storms, the magnetopause displacement could be very large. Since enhanced solar wind energy densities imply enhanced Pedersen conductivity in the polar cusp, and the large solar wind velocities and magnetic field strengths observed during magnetic storms imply that reconnection when it occurs, will lead to large convection potentials, perhaps the observations of magnetopause crossings at the  $L = 6.6$  geostationary orbit could be accounted for in this way.

Even though we considered explicitly only the idealized situation of a single rapid enhancement of field-cutting at the nose of the magnetosphere, similar physical arguments ought to apply if the field-cutting rate has a more complex temporal variation. Thus, for each change in the field-cutting rate, ionospheric line-tying should require magnetospheric configurational changes to accompany enhancements of internal convection. We have implicitly assumed throughout this paper that the field-cutting rate integrated over the nose of the magnetosphere bears a one-to-one relationship to the solar wind magnetic field direction. In this case, the variability of the solar wind field which is often observed (Coleman, 1966) could lead to variations in the field-cutting rate. However, even if the solar wind field should be relatively steady, the magnetosheath field could be variable (Greenstadt,

et al., 1967 ). Moreover, the field-cutting rate may not respond uniformly to changes in magnetosheath field direction and could indeed be dependent upon the ionospheric conductivity. The ionospheric conductivity enhancements depend at least upon the properties of the magnetosheath electrons, and their accessibility to the ionosphere, and both may in turn be reconnection dependent. The locations of the maximal reconnection regions could vary, and in particular the change in magnetopause shape accompanying enhancement of internal convection could alter the integrated reconnection rate. Finally, the basic reconnection process could be locally unsteady even for uniform ionospheric, flow and magnetosheath field conditions (Aubry et al. 1971). Given all these possibilities for transient variations in the reconnection rate, and given the slow response time of internal convection, it could be argued that the most likely state for convection is an unsteady one. Falthammar (1965), Cornwall (1968, 1972), and Birmingham (1969) have pointed out that unsteady convection electric fields can drive the radial diffusion of energetic particles trapped within the magnetosphere. Since ionospheric line tying forces a transient response on time scales  $\Delta$  of internal convection to changes in the solar wind boundary conditions, the spectrum of electric field variations driving radial diffusion from this source should diminish for Fourier components with periods less than  $\Delta$ . If substorm breakups involve electric field enhancements on the short Alfvén communication time, then the net radial diffusion coefficients could involve components with periods much less than  $\Delta$ .

Although we have referred to substorm phenomenology for evidence supporting the point of view developed in this paper, we have deliberately refrained from explicit theoretical discussion of the structure of substorms, because of our conviction that time dependent convection should be placed in a more general context. Now, however, we must come to grips with the problem of substorms,

and, in particular, substorm growth phase. The difficulty with growth phase is that it has been observed to have a variable duration. Some breakups are observed to occur as much as one to two hours following a southward solar wind magnetic field shift (Aubry et al., 1970; McPherron, 1970). On the other hand, there can be triggered substorm breakups which take place so far as one can tell on the fast Alfvén response time following an external solar wind perturbation (Tsurutani and Meng, 1972). The distribution of growth phase durations may well be continuous between these two limits. This suggests an interesting experimental investigation in which the duration of the growth phase is certainly related to solar wind conditions, but also to the previous state of the magnetosphere. For example, do isolated substorm growth phases differ from those occurring in a sequence during magnetic storms, and, do the first and last substorms during magnetic storms have different growth phases?

One reason why the individual substorms in a sequence could differ one from another may be the intensification of ionospheric neutral winds by enhanced convection (Fedder and Banks, 1972). The neutral winds develop on time scales of several hours following the turn-on of a steady convection electric field. For a steady imposed electric field, the neutral winds would asymptotically approach the plasma drift velocities in the ionosphere, which has the effect of reducing the ionospheric conductivities. Within the context of the present calculation, intensified neutral winds reduce the convection enhancement time scale  $\Delta$ . Should  $\Delta$  become comparable with the Alfvén communication time along the lines of force, line tying would no longer inhibit the development of convection. When the reconnection rate varies on time scales short compared to that for the decay of the neutral wind system, the neutral winds can drive an induction electric field which tends to preserve the convection pattern

during those periods when reconnection is inoperative. Thus, if the repetition rate between substorms is sufficiently rapid - as it appears to be - after a sequence of substorms, ionospheric line tying does not inhibit magnetospheric convection, but drives it. Since the time scale for the creation of a fully developed neutral wind system is comparable to typical durations of magnetic storm main phases, we therefore expect significant differences between the first substorm of the main phase and those deep in the main phase. Since well into the main phase convection might be predominantly neutral wind induced, we would expect more or less continuous substorm activity which is less tightly coupled to changes in the solar wind boundary conditions and to the changes in magnetospheric structure.

Present experimental evidence and theoretical arguments strongly suggest to us that, where definable, the substorm growth phase corresponds to an enhancement of magnetospheric convection, and must be associated with changes in magnetospheric configuration. One difficulty with defining more precisely from the arguments in this paper the duration of growth phase stems from the lack of a precise definition of the breakup which terminates it. The key question is whether something qualitatively different happens during breakup that does not occur during growth phase. From the theoretical point of view, this implies asking whether or not there is a phase change, from the slow development of convection during growth phase, to rapid convection enhancements on the Alfvén time scale during breakup. Observationally, such a phase change would be manifested in a rapid inward convection of plasma and magnetic flux coupled with a rapid change in the structure of the geomagnetic tail. Indeed Cummings, et al, (1968) and McPherron et al. (1972a) have found changes in geomagnetic tail fields on Alfvén time scales during some substorm breakups. Other observational indicators of substorm breakup include auroral

arc intensifications and motions, general enhancement of electron precipitation over the nightside auroral oval, and rapid southward shifts in the ionospheric electric field. From our theoretical point of view, it is unclear whether these phenomenological indications could not also occur during the growth phase as well as during breakup. Since we interpret growth phase as a simple enhancement of convection, and since all these phenomena should be coupled to convection, we suspect this to be the case. The relationship between these ground based phenomena and rapid Alfvén time scale convection enhancements observed directly in the magnetosphere remains to be clarified. Since the ionosphere should be decoupled from Alfvén time scale changes in convection and configuration, defining these complex observational relations may prove to be difficult.

To specify the duration of growth phases, one must define not only what a breakup is observationally but also, under what conditions a breakup occurs. For example, Atkinson (1967), Soop and Schindler (1972) and McPherron et al. (1972b) have all suggested that breakup results from the rapid creation of a new magnetic reconnection region in the near tail. In this case, breakup would occur when the tail configuration has evolved to the threshold for reconnection instability. On the other hand, Coroniti and Kennel (1972a) have pointed out that electrojet enhancements, one index of breakup, could occur when the westward convection electric field in the nightside auroral oval ionosphere arrives at a certain threshold intensity. Should this change in ionospheric boundary conditions destabilize parts of the geomagnetic tail, then we could argue that breakup requires a threshold convection field. Parks et al. (1971) have suggested that breakup is triggered by a rapid enhancement of electron precipitation, followed by a subsequent tail field collapse. In this case breakup depends critically on the particle populations arriving at the thresholds for microscopic plasma instabilities.

A recent paper by Burch (1972) considerably clarifies the problem of SSC triggered breakups. Therein, he shows that while the magnitude of the enhancement of the solar wind dynamic pressure implied by the magnitude of the SSC is an important factor in triggering breakup, a necessary condition for triggered breakup is that the solar wind magnetic field have a southward component and consequently that a substorm growth phase be in progress. Thus, it appears that SSC's trigger, not an inordinately rapid growth phase, but the mechanism leading to breakup.

Even if we understood breakup, there remain uncertainties with this model as to the duration of growth phase. For example, our estimate of the current flowing through the polar cusp ionosphere as the decrement in Chapman-Ferraro magnetopause current must be regarded as uncertain. Even if we had a procedure by which the current flowing through the ionosphere could be computed self-consistently with the structure of the magnetosphere, there remains the possibility that the fraction of the magnetopause currents fed to the ionosphere could depend upon the state of the magnetosphere prior to the onset of reconnection, and so vary from event to event. Furthermore, the other numerical factors which went into estimating  $\Delta$  are uncertain. Finally, we must remember that  $\Delta$  is an estimated response time for convection enhancements, and that the observed time scale for the development of convection could exceed  $\Delta$  when the solar wind magnetic field direction is variable.

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