The dependence of magnetospheric topology and convection (including night-side reconnection) on the average magnetic flux transfer rate

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Abstract: The average transfer rate of magnetic flux into the tail is determined, to a good approximation, by dayside reconnection. The topology and behavior of the magnetosphere adjusts to maintain the same average return transfer rate from the tail to the dayside, despite ”obstructions” resulting from energetic plasma in the system and the conductivity of the ionosphere. It follows that there is an average topology and behavior corresponding to each constant dayside reconnection rate. We may expect that evolution toward a new average topology is important in triggered substorms and growth phases. We focus on earthward flux transfer through the plasma sheet, initially for a constant dayside reconnection rate. It is hard to see how it maintains the appropriate average value, unless it is controlled by a collaboration of both the lobe (upstream) and the near-earth (downstream) boundaries. The same is true for reconnection in the tail since it determines flux transfer rates. It is proposed that lobe pressure provides a stressed plasma sheet in which the onset of reconnection is most likely if there is a strong earthward $\mathrm{E} \times \mathrm{B}$ convection on the earthward side of a possible X-line site. For the nearest-earth neutral line, this corresponds to a strong earthward $\mathrm{E} \times \mathrm{B}$ component in the dipole-like region. For MHD models, this occurs at midnight. For models with energetic ions, it occurs at the Harang discontinuity, for the following reasons. The upward current at the Harang suggests that energetic ions are drifting westward off flux tubes in the Harang, resulting in an energy difference between the west and east sides. This difference in ion energy would be expected to produce an $\mathrm{E} \times \mathrm{B}$ convection cell with an earthward component in and east of the Harang and an outward component west of it. Thus reconnection onset is most probable in the tail at the local time of the Harang. However, reconnection provides positive feedback by adding energy to the earthward $\mathrm{E} \times \mathrm{B}$ convection. Instability would be expected (essentially driven by energy from both reconnection and the interchange/ballooning motion). This explains non-triggered substorms. Turning to time-dependent dayside reconnection, we suggest that triggered substorms are essentially the same as non-triggered, except that there is more energy input to the convection cell by the ions. The reduction in dayside reconnection requires additional outward $\mathrm{E} \times \mathrm{B}$ convection of energetic ”shielding” ions west of the Harang. Conversely, an increase in dayside reconnection requires inward convection of the shielding ions, and hence a reduction of the Harang convection. It is expected that reconnection onsets would be suppressed during growth phases.

Key words: substorms, reconnection, Harang.

1. Convection: fundamentals and some general considerations

We can define the rate of transfer of magnetic flux through any line as $\int E \cdot dl$. Conservation of the earth's magnetic flux then requires that the average transfer rates through the parts of the magnetosphere must be equal. The average value is imposed, to a good approximation, by the rate of transfer into the tail resulting from dayside reconnection.

The return transfer from the tail to the dayside must maintain the same average, despite the obstructing effects of energetic plasma and the conducting ionosphere. The obstructing effects include (Fig. 1): (1) compression of the plasma during earthward convection in the tail (in fact energy must be removed from tail-like flux tubes to resolve the pressure catastrophe: [3]); (2) ”shielding” of convection from the inner magnetosphere by energetic plasma in the earthward edge of the plasma sheet; (3) Ohmic dissipation in the ionosphere as flux is transferred from the nightside to the dayside in the dipole-like region (shielding plays a role by limiting the width of the convection channel requiring stronger electric fields for the same flux transfer rate). The topology of the magnetosphere must be consistent with closure of the currents, shown in Fig. 2, associated with the above obstructing effects. The currents include: (1) ionospheric current across the polar cap and dayside closing approximately one quarter of the region 1 Birkeland currents; (2) ionospheric closure of the remaining region 1 currents to region 2 currents, which then closes by near-earth plasma-sheet current across midnight from dawn to dusk; (3) cross-tail current. Observations and simulations (e.g. [5]) indicate that these currents increase with average dayside reconnection rate. Ionospheric currents increase (expected from Ohm's law), the plasma sheet approaches the earth with stronger near-earth currents, and the average amount of tail flux increases implying stronger cross-tail current.

Since dayside reconnection is an independent input parameter, it is useful to consider ”average” magnetospheres (topologies, currents, convection patterns) corresponding to each dayside reconnection rate. This average would be approached if reconnection remained constant for a sufficiently long time. (We do not assume the average is a steady-state, as it is for MHD models [5].) Changes in dayside reconnection would be

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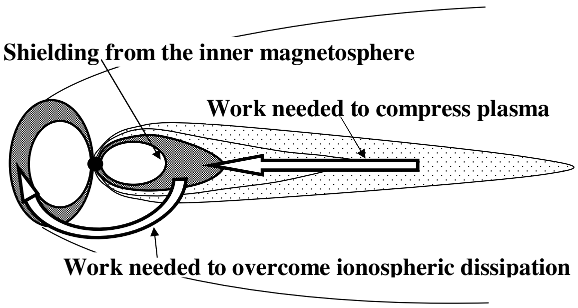

Fig. 1. Obstructions to the return flux transfer: (1) Work is required to compress plasma for earthward convection in the plasma sheet; (2) Convection of plasma into the inner magnetosphere is prevented by shielding; (3) Convection to the dayside is given by V=WE. The width of the channel, W, is decreased by shielding, requiring stronger E and increased dissipation.

expected to initiate evolution toward a new average topology with different amounts of flux in the tail and the nightside magnetosphere, and increases or decreases in the radial distance to the earthward edge of the plasma sheet. Some properties of triggered substorms and growth phases will be explained by these changes. In this paper we consider a model in which an

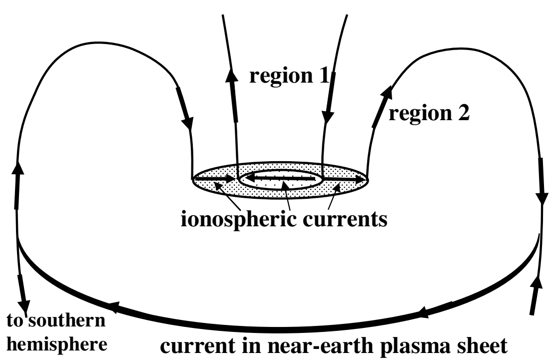

Fig. 2. A simplified illustration of currents associated with shielding and ionospheric closure, viewed from midnight above the equatorial plane. Other currents of obstructions include electrojets and cross-tail.

$\mathrm{E} \times \mathrm{B}$ convection pattern near the Harang discontinuity, driven by energy from the energetic "shielding" ions in the near-earth plasma sheet, provides boundary conditions which favour reconnection onset and non-triggered substorms. Triggered substorms are then essentially the same as non-triggered, but there is additional energy input to the convection pattern from the near-earth plasma sheet ions because their convection includes an additional outward component as the topology responds to a decrease in dayside reconnection. We therefore discuss the behavior for a constant dayside reconnection rate in some detail before considering how time-dependent dayside reconnection modifies the constant reconnection case. It is noted that the existence of non-triggered substorms has been questioned [8].

2. Magnetic flux transfer through the plasma sheet

It is useful to consider magnetic flux transfer from the tail lobes to the dayside as the two steps shown by the arrows in Fig. 1: from the lobes into the nightside dipole-like magnetosphere, and from the nightside to the dayside in the dipole-like magnetosphere. The first step is of greatest interest because of it relationship to substorms. We shall consider the second step only to the extent that it provides a boundary condition for the first. The properties governing step 1 of the flux transfer are illustrated in Fig. 3 The pressure catastrophe dictates that en-

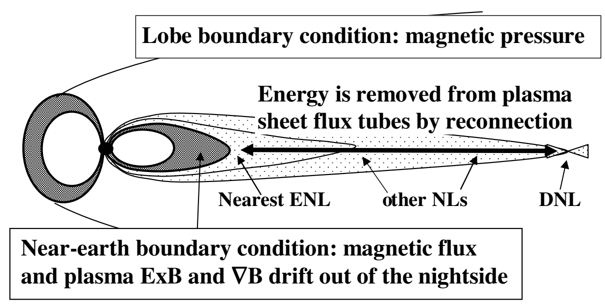

Fig. 3. Lobe and near-earth boundary conditions on magnetic flux transfer through the plasma sheet. In between the boundaries, energy is removed to overcome the pressure catastrophe. The nearest earth neutral line must produce flux tubes that can convect to the dayside at the appropriate average rate.

ergy must be removed from tail-like plasma sheet flux tubes to allow magnetic flux transfer into the nightside dipole-like region. It has long been believed that this occurs by reconnection, with energy travelling down the tail in the form of plasmoids. Recent observations [10] indicate that there are probably multiple, multiscale, reconnections throughout the plasma sheet, possibly involving self-organized criticality resulting in a behavior similar to avalanches on a sand pile [6].

Magnetic flux transfer in the tail has to proceed at the appropriate average rate. By analogy with similar systems, this requires that both the upstream boundary (the lobes) and the downstream boundary (the nightside dipole-like region) participate in controlling flux transfer and hence also reconnection. The analogies include compressible fluid-flow, in which flow through any part of the system depends on the pressures at the upstream and downstream boundaries; and even more relevant, transfer of sand by avalanches in the sand-pile analogue mentioned above. Avalanches can be triggered by adding sand to the top of the pile or removing it from the bottom since the slope of the surface depends on both boundary conditions.

A simple description of the role of the lobes in controlling flux transfer in the tail-like plasma sheet is that the transfer of magnetic flux into the tail increases the lobe pressure until, consistent with the pressure catastrophe [3], the plasma sheet becomes thin enough and sufficiently tail-like that the onset of reconnection at a neutral line can result in a decrease in magnetic energy. (In a thick plasma sheet, the downtail flow accompanying reconnection stretches closed field lines and increases the magnetic energy.) However, it is difficult to see how reconnection at the nearest earth neutral line produces flux which can convect to the dayside at the appropriate average rate, unless the near-earth boundary is also involved. A modification of this process is described below.

It has been argued that the outflow boundary conditions control reconnection in a tail-like configuration [1]. Both up-tail and down-tail magnetic flux transfer must be possible in a reference frame attached to the X line during reconnection. This suggests that, other factors being equal, reconnection onset is most probable at locations where dv/dx is a maximum before reconnection onset, where v is the component of $\mathrm{E} \times \mathrm{B}$ convection in the earthward direction. This condition is satisfied in two well-known and well-studied situations. First, for dayside reconnection, hydrodynamics indicates that the maximum divergence of the flow component parallel to the magnetopause is at the subsolar point, and hence reconnection would be expected to be at the subsolar point. Second, the condition is implicit in the onset described in the previous paragraph since $dv/dx > 0$ is required to produce a more tail-like configuration with a reduced normal component of B.

We are now in a position to discuss control of reconnection onset by earthward convection. As discussed above, increases in lobe pressure cause plasma sheet thinning, increased tail-likeness, and eventually reconnection. However, the nearer-earth boundary condition can increase or decrease v and hence dv/dx. Compare the situation in which earthward flow is completely blocked with one where there is a fast earthward flow. For the blocked case, the X line must move downtail faster and the tailward outflow speed must be greater, with the result that more work goes into stretching closed field lines. Hence reconnection onset is more likely if earthward outflow exists. Thus, earthward convection at the nearer-earth boundary can change dv/dx and control reconnection onset.

The above applies to both mid-tail and near-earth reconnection. Mid-tail reconnection can be controlled by nearer-earth flows, allowing avalanche-like behavior, as discussed later. At the nearest-earth neutral line, the uptail boundary is provided by the dipole-like region. Thus dv/dx would be a maximum and reconnection onset most likely at local times where the earthward component of $\mathrm{E} \times \mathrm{B}$ drift is a maximum in the outer dipole-like region. In an MHD magnetosphere, this occurs near midnight where convection is toward lower L values and then around dawn and dusk. We argue later that the inclusion of the curvature and gradient drifts of energetic ions places the maximum earthward component of $\mathrm{E} \times \mathrm{B}$ drift near the Harang discontinuity, and hence reconnection is most likely on tail-like field lines at the same local time as the Harang.

In summary of this section, observations indicate that multiple reconnection events, distributed throughout the plasma sheet, remove energy from flux tubes and result in earthward magnetic flux transfer. The boundary conditions are provided by the tail lobes and the nightside dipole-like region. Both boundaries must play a role in maintaining the appropriate average flux transfer rate. Reconnection is most likely to be initiated where dv/dx is a maximum, which for a nearest-earth neutral line is in the near-earth tail at the local time where the earthward component of $\mathrm{E} \times \mathrm{B}$ is a maximum in the dipole-like region. The maximum is at midnight for MHD models. Radar observations indicate an $\mathrm{E} \times \mathrm{B}$ component toward lower latitudes in and east of the Harang discontinuity [7]. Hence reconnection in the near-earth tail is expected and observed at the same local time as the Harang. Control of mid-tail reconnection by nearer-earth flows may lead to avalanche-like behaviour.

3. The near-earth boundary condition

For a population of monoenergetic ions, upward currents occur at particle boundaries where there is an increase in density and energy in going from east to west through the boundary [11], and magnetic flux transfer ($\mathrm{E} \times \mathrm{B}$ drift) is from west to east through the boundary. In simplest terms, ions are curvature and gradient drifting off magnetic flux tubes (defined as moving with the $\mathrm{E} \times \mathrm{B}$ drift). Similar behavior has been discussed for a more-general distribution, [9]. Since there is upward current at the Harang discontinuity, we associate it with a westward increase in number density and ion energy, and with eastward magnetic flux transfer in a reference frame moving with the Harang.

However, radar observations of the Harang ([7]) appear to indicate that the $\mathrm{E} \times \mathrm{B}$ flux transfer is in the opposite direction. The conflict can be removed in a time-dependent model of the Harang. Fig. 4 illustrates a model for times of no flux transfer into the dipole-like region (no reconnection). Properties include: 1) the Harang drifts westward with a velocity determined by the ions; 2) magnetic flux transfer is from west to east through the Harang because the ions drift westward in the $\mathrm{E} \times \mathrm{B} = 0$ frame, and 3) the total ion energy decreases on magnetic flux tubes while they are being transferred through the Harang from west to east.

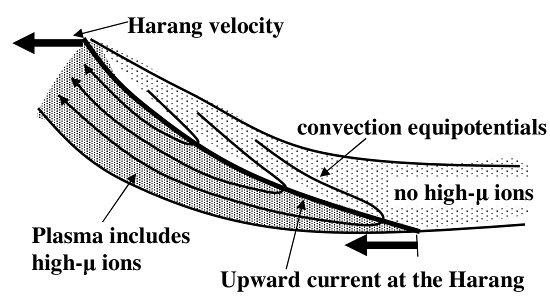

Fig. 4. Time-dependent model of the Harang: Upward current at the Harang closes to a drift current of high-μ ions in the magnetosphere. The Harang moves westward with the drifting ions with a velocity faster than the westward component of $\mathrm{E} \times \mathrm{B}$ drift. The decrease in energy (shielding) on flux tubes causes the convection pattern with a component toward lower L in and east of the Harang and toward higher L west of the Harang.

There is an important consequence of the above properties. The decrease in ion energy as flux tubes $\mathrm{E} \times \mathrm{B}$ drift through the Harang results in flux tubes with decreased ion energy (decreased shielding) on the east side. The resulting imbalance in radial stresses drives an $\mathrm{E} \times \mathrm{B}$ convection cell with a component toward lower L values in and east of the Harang, where the total ion energy is reduced, and a component toward higher L values west of the Harang where the ion-energy content of flux tubes is higher. Energy input to the convection cell comes from the difference between energy lost by outward-convecting ions and the energy gained by inward-convecting ions. The current system and convection are illustrated in Figs. 4 and 5 for times of no reconnection. Observational support for the above be-

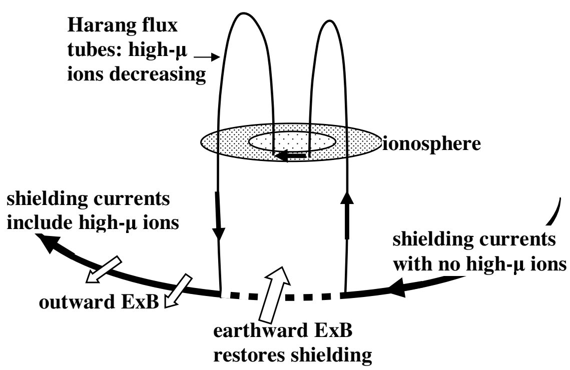

Fig. 5. The Harang-driven convection and its current system: The Harang moves westward as high-μ ions drift off flux tubes, causing an earthward $\mathrm{E} \times \mathrm{B}$ component until shielding is restored by the lower-μ ions and electrons. There is an outward $\mathrm{E} \times \mathrm{B}$ component west of the Harang which closes the convection streamlines (equipotentials). The system is a weak current wedge when there is no reconnection.

havior of the Harang is provided in a case study [7]. A Harang with a westward velocity of 1 km/sec was observed. The measured westward component of $\mathrm{E} \times \mathrm{B}$ drift was approximately half the Harang velocity, consistent with eastward magnetic flux transfer. The convection pattern shows the appropriate equatorward and poleward components of Fig. 4. The superposition of the Harang-driven cell on a large-scale two-celled convection offers an explanation of the observed eastward protrusion of the duskside convection cell near midnight.

4. Control of reconnection by Harang-driven convection

Figs. 4 and 5 illustrate the Harang-driven convection and current system in the magnetosphere at quiet times. The ion energy on flux tubes (shielding) is reduced as the Harang moves westward in the $\mathrm{E} \times \mathrm{B} = 0$ frame, resulting in an inward $\mathrm{E} \times \mathrm{B}$ drift component until the shielding is restored by energy increase of the remaining ions and electrons (which have lower values of the adiabatic invariants). The currents associated with the ion drifts are diverted to the ionosphere at local times where shielding is reduced. The inward $\mathrm{E}\times\mathrm{B}$ convection of dipole-like flux at local times of reduced shielding is closed by outward convection at local times of high shielding; that is west of the Harang.

It is now straightforward to relate the Harang-driven $\mathrm{E} \times \mathrm{B}$ convection to reconnection. The $\mathrm{E} \times \mathrm{B}$ drift to lower L values on dipole-like field lines at the Harang provides the conditions discussed earlier (dv/dx at maximum) that favor the onset of reconnection on tail-like field lines outside the dipole-like region. Thus, when near-earth reconnection is initiated, it would be expected to be at the local time of the Harang discontinuity.

However, reconnection produces stress changes that enhance the inflow at the Harang. This provides positive feedback, amplifying the Harang-driven convection shown in Figs. 4 and 5. The resulting instability is either an interchange or a ballooning instability with energy supplied by both magnetic field changes due to reconnection, and by the radial convection component of ions. The above offers an explanation of non-triggered expansions.

Now we can return to time variations of dayside reconnection and triggered substorms. A decrease in dayside reconnection requires increased $\mathrm{E} \times \mathrm{B}$ drift of the ions (west of the Harang) away from the earth, since shielding must decrease. This provides more energy input by ions to the Harang-driven convection cell of Figs. 4 and 5; that is more energy than for the non-triggered case. This results in a corresponding increase in the probability of reconnection onset at the Harang in the inflowing part of the convection cell. It offers an explanation of triggered expansions, and explains why the energy involved is greater for triggered substorms ([4]. It is consistent with a suggestion in [2] that the energy for triggered substorms comes from the convection of the shielding ions to higher L values.

Finally, there are a few additional properties of the model that should be noted: (1) The instability may involve east-west scales which are smaller than the Harang, since energy is available for a Harang-type convection cell wherever there is a westward increase in total ion energy. According to our earlier discussions there is a westward increase of total ion energy over most of the Harang. (2) An increase in the dayside reconnection rate is expected to produce electric fields that convect the shielding ions closer to the earth. The inward convection opposes the Harang-driven convection cell and would cause suppression of reconnection onset in the growth phase of substorms. (3) Since the Harang cell moves westward with the drifting ions, reconnection, after onset, would be likely to follow the motion as the expansion develops, consistent with westward travelling surges. (4) Fig. 5 illustrates that the sum of the ion currents and the westward electrojet should be constant over several hours of local time around midnight. At times when the westward electrojet current is comparable to the integrated region 2 current (one or two mega-amps), there is very little shielding in the magnetosphere. This suggests that the large increase in the conductivity of the ionosphere in substorms plays an important role in slowing down the earthward component of $\mathrm{E}\times\mathrm{B}$, and delaying the restoration of shielding.

5. Summary

Dayside reconnection transfers magnetic flux into the tail, and determines the average transfer rate, which must be the same through all parts of the magnetosphere. The return transfer to the dayside is obstructed by the plasma and the ionosphere. The topology of the magnetosphere adjusts to close the currents of these obstructions. It is useful to compare average topologies corresponding to different constant dayside reconnection rates. The average amount of magnetic flux in the tail and on the nightside increases with dayside reconnection rate, and the earthward edge of the plasma sheet moves closer to the earth. Growth phases and triggered substorms both involve topology change in response to increases or decreases in dayside reconnection rate. We focussed on magnetic flux transfer through the plasma sheet since this is related to substorms. Energy must be removed from flux tubes to resolve the pressure catastrophe. Observations indicate that multiple reconnections remove energy from flux tubes, reducing the energy content until they can convect to the dayside at the appropriate average rate. The appropriate average can be maintained only if both tail-lobe and near-earth boundary conditions play a role in controlling reconnection and flux transfer. It is proposed that reconnection onset is most probable at locations where and times when dv/dx, the uptail gradient of the earthward component of flow, is a maximum before onset. In the plasma sheet, dv/dx can be increased by a strong $\mathrm{E} \times \mathrm{B}$ earthward component at the earthward boundary of a region where other factors favor reconnection. This allows an avalanche-like process in the mid-tail with reconnection controlled by nearer-earth flows (which may themselves be the result of nearer-earth reconnection). At the nearest-earth reconnection site, the boundary condition is provided by the earthward component of $\mathrm{E} \times \mathrm{B}$ in the dipole-like region. In MHD models, this is a maximum at midnight. In the presence of energetic ion drifts, it is at the Harang discontinuity. A time-dependent model of the Harang discontinuity is presented in which it is the eastern limit of westward drifting highest-μ ions. The drift of high-μ ions off flux tubes at the Harang creates an east-west distribution of energy that is not in equilibrium. This causes a convection component toward lower latitudes at and east of the Harang and to higher latitudes at points west. These $\mathrm{E} \times \mathrm{B}$ components favor reconnection onset on tail-like field lines at the local time of the Harang. However, reconnection changes magnetic stresses so as to create a positive feed-back to the convection cell. The result is an interchange/ballooning instability with energy provided by both ion-drift and reconnection. This explains non-triggered substorms. Decreases in dayside reconnection require additional outward $\mathrm{E} \times \mathrm{B}$ drift of the shielding plasma west of the Harang. This enhances the Harang-driven convection and provides a boundary condition that is even more favorable for reconnection onset. Conversely, increases in dayside reconnection require inward $\mathrm{E} \times \mathrm{B}$ drift, which suppresses Harang-driven convection and reconnection during growth phases.

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