Are we on the right approach to solve the substorm problem?

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Abstract: It is time to have a serious appraisal on the correct approach to solve the substorm problem, bearing in mind as to what happened with continental drift some four decades ago. We must deal in 3-D, not 2-D (the basis of the reconnection model). We must ascertain the source of energy, $\mathbf{E} \cdot \mathbf{J} < 0$, for the dissipation associated with reconnection. We must close all currents to treat cause vs effect, i.e. $\mathbf{E} \cdot \mathbf{J} < 0$ vs $\mathbf{E} \cdot \mathbf{J} > 0$. We need to face some harsh realities.

Key words: magnetic reconnection, viscous interaction, substorms.

1. Introduction

After five decades of observations and theoretical research the mechanisms for the interaction of the solar wind with the magnetosphere are far from being resolved. Two mechanisms have been proposed long ago in 1961, magnetic reconnection by Dungey [10], and viscous interaction by Axford and Hines [1]. The process of magnetic reconnection was sketched in the x, z noon-midnight meridian plane, while viscous interaction uses the x, y equatorial plane, both in 2-D. Importance of three dimensions is beyond doubt; still, the difficulty in conveying that idea on 2-D paper seemed to be overwhelming. I first discuss magnetic reconnection on the dayside since the conditions there are easier to resolve, then the substorm problem.

2. Magnetic reconnection (MR)

An X-line, or reconnection line, appears on the dayside [10]; this is clearly the case for a southward IMF in view of topological considerations. The magnetic field direction in the equatorial plane near noon meridian has to go from southward (IMF) to northward (Earth's dipole) in a continuous fashion, so that somewhere it must go through zero. There is an X-line in the magnetotail as well [10]. In fact, there should be an X-ring around the entire magnetosphere in 3-D; the X-lines are the intersection of this ring with the meridian plane. The conditions are modified for any other choice of the IMF but the physics is clearer for the southward case. The analysis in the x, z noon-midnight meridian plane has been widely used in research on magnetic reconnection, both dayside and nightside, even in the presentation of substorm data.

2.1. Reconnection is defined in 2-D

Figure 1 shows a hatched box around the X-line with the *assumed spatially constant* electric field; curl $\mathbf{E}$ is zero *by definition* as an initial condition. The plasma moves toward the X-line from both sides by $\mathbf{E} \times \mathbf{B}$ drift. The only possible outflow is toward open magnetic field lines (one foot in the IMF, the other in the ionosphere). The magnetic field lines from the X-line indicate the separatrix surfaces, S1 going to the IMF, S2 to the geomagnetic field. One definition of reconnection that is commonly used was well stated by Sonnerup [34] as:

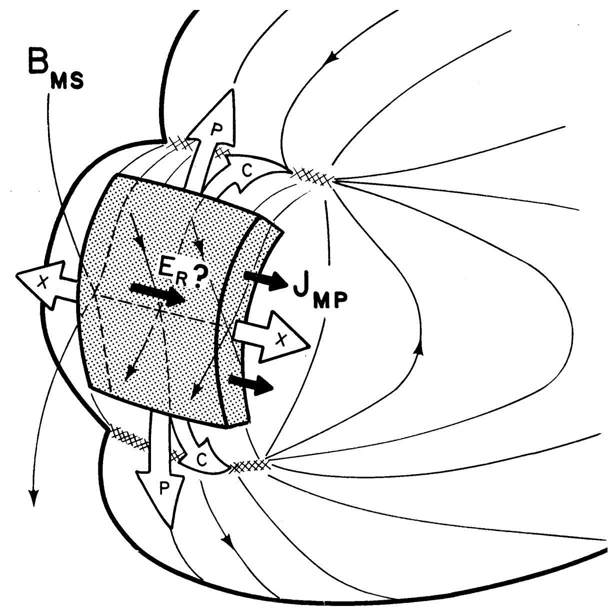

Fig. 1. Plasma moving toward the X-line at the magnetopause from both sides with the assumed spatially constant electric field; curl **E** is zero as an initial condition. The only possible outflow is toward open magnetic field lines. The magnetic field lines from the X-line indicate the separatrix surfaces, S1 going to the IMF, S2 to the geomagnetic field.

> "any plasma process with a non-zero component along the X-line separating magnetic fields from two different sources. $\cdots$ No plasma physics has been introduced into the above discussion but it is the presence of a highly conducting plasma that assures that the condition $\mathbf{E} \cdot \mathbf{B} = 0$ is satisfied everywhere except at the separator."

The above definition was viewed as being quite general and broad, non-restrictive. This in spite of the requirement "the condition $\mathbf{E} \cdot \mathbf{B} = 0$ is satisfied everywhere except at the separator", this implying that essential plasma physics must be used

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in the explanation (see Section 4.3.4). In contrast to the outflow with MR on open magnetic field lines, the low latitude boundary layer extends to closed field lines.

MR has led to considerable research for over the past four decades. Birn et al. [3, p.3718] summarized the results of a coordinated study in the Geospace Environmental Modeling (GEM) program. "The key conclusion of this project is that the Hall effect is the critical factor which must be included to model collisionless magnetic reconnection." These authors continue with an important stipulation:

> "The conclusions of this study pertain *explicitly* to the 2-D system. There is mounting evidence that the narrow layers which develop during reconnection in the 2-D model are strongly unstable to a variety of modes in the full 3-D system."

2.2. Anomalous resistivity

The constant electric field did pose a significant problem, that of maintaining an electric field when the Lorentz force vanishes at the X-line. An anomalous resistivity seemed to be a requirement in the so-called diffusion region [31]. This is still unresolved, prompting an article by Coroniti, *Turbulent Dissipation: Reality or Myth* [8]. In spite of this warning, the reconnection model continues to be in 2-D. The manner in which the electric field is handled in the theoretical work is commonly stated as follows [30]:

> "We divide the problem into two parts. One part concerns the specification of the electric field inside the diffusion region. The process which gives rise to this electric field should be studied with the aid of kinetic theory. This topic is poorly understood at present and seems to depend on the particular situation being considered. We therefore prescribe the reconnection electric field as an input parameter, i.e., a given function along the reconnection line, which is directed along the y axis. This allows us to investigate the large-scale consequences of an arbitrary functional behavior of the reconnection rate, which forms the second part of the problem. Strictly speaking, of course, we should solve these two parts self-consistently."

2.3. Source of energy dissipated by MR

In reconnection theory only the dissipation is considered, an electrical load with $\mathbf{E}\cdot\mathbf{J} > 0$ (current parallel to the electric field). In 2-D it is not possible to discuss the source of this energy, to search for another region in space where $\mathbf{E}\cdot\mathbf{J} < 0$ in the same current circuit. It is very important to develop a model of a substorm in 3-D for this reason alone. This has been echoed by Siebert and Siscoe [32]:

> "The result has the profound consequence that if there is a segment of a closed current tube in which energy is being dissipated (for example, in magnetic reconnection), and thus $\mathbf{J}\cdot\mathbf{E}$ is positive, there must exist another segment of the [current] tube in which $\mathbf{J}\cdot\mathbf{E}$ is negative so as to exactly compensate for the dissipation segment in the closed line integral of I."

In the case of the Dungey model of the magnetosphere there is a dynamo with $\mathbf{E}\cdot\mathbf{J} < 0$ over the lobe magnetopause (the current being in the dusk-dawn direction with the assumed dawn-dusk electric field); this could, in principle, deliver energy in the steady state by the magnetopause current to the reconnection region with $\mathbf{E}\cdot\mathbf{J} > 0$ (both dayside reconnection but also nightside reconnection within the magnetotail). Thus the source of energy for dayside reconnection is not upstream, as suggested by steady state reconnection defined in two dimensions, with the inflow of magnetic energy to power dayside reconnection, but it is instead a dynamo over the lobes. However, there are questions for the reality of this location of the dynamo, e.g., the northward direction of the magnetic field (see Figure 3), travel time for the energy, and several more.

2.4. Definition of Magnetic Reconnection

The definition of reconnection [34] seems to be quite general; however, it is *fatally deficient* in that it does not address the essential quantity: curl **E**. This does not mean that the state of interconnection between the geomagnetic field and the interplanetary magnetic field can not change, but it does mean that the advocated process is not relevant to such changes. Only the following term is concerned with magnetic energy:

$$\iiint_{vol} \frac{\mathbf{B}}{\mu_0}\cdot\frac{\partial\mathbf{B}}{\partial t}d\tau = \frac{d}{dt}\iiint_{vol}\frac{B^2}{2\mu_0}d\tau \qquad (1)$$

The wrong term was used, and still is, in Poynting's theorem for the reconnection problem [17]. By this simple, yet fundamental, argument it can be concluded that magnetic reconnection, as presently understood, and practiced, is unphysical.

2.5. Interconnection of magnetic fields

The above volume integral has been used in [17] for analysis of plasma transfer events (PTE, considered in the next section). True reconnection is accomplished only by the electromotive force through which energy can be interchanged with stored magnetic energy. By Faraday's law

$$\nabla\times\mathbf{E} = -\partial\mathbf{B}/\partial t \qquad (2)$$

we see that curl **E** is vital to deal with changes in the magnetic field. Such a curl is not included as an initial condition in Figure 1 because the electric field is assumed to be spatially constant, thus no curl. This is obvious in the integral form:

$$\varepsilon = \oint \mathbf{E}\cdot\mathbf{dl} = -d\Phi^M/dt \qquad (3)$$

where ϵ is the electromotive force (Φ^M is the magnetic flux through the contour). The sense of the electric field is different on the two sides of the magnetopause [16]; a finite value for the line integral over any closed path that includes the magnetopause means a finite electromotive force. Energy can be extracted from the magnetic field; the induction electric field acts as intermediary.

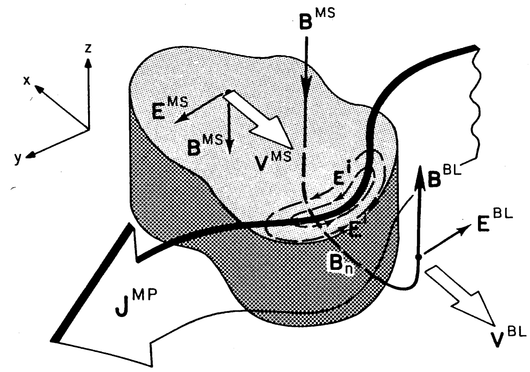

Fig. 2. A localized plasma cloud impacting the magnetopause current sheet. With it's assumed excess momentum it distorts the current, a localized meander, causing an induction electric field as indicated, everywhere opposed to the current perturbation by Lenz's law. The plasma response depends on the conductivity; in a collisionless plasma the Pedersen conductivity vanishes, but the field-aligned conductivity is very high, denoting a dependence on the interplanetary magnetic field (IMF).

3. Viscous interaction (VI)

I accept the view that the existence of the boundary layer inside the magnetopause (LLBL) is crucial to the physics of the magnetosphere [7, 11, 15, 22, 23]. The boundary layer flow is so massive that it can generate its own electric field by a polarization current for continued anti-sunward flow. At great distances (some 100 R_E downstream from the earth) the dawn and dusk boundary layers become joined together, and the magnetotail from there is essentially just boundary layer plasma, on closed magnetic field lines, all traveling tailward with no return flow [33, 37] (see Figure 4).

It is a dynamo with $\mathbf{E} \cdot \mathbf{J} < 0$, energy going from the plasma to the electromagnetic field. This is the viscous interaction that Axford and Hines [1] had sought. When they proposed their process they had little idea as to the responsible mechanism for the effective viscosity [private communication by Hines, 1985]. The LLBL had not been discovered.

3.1. Faraday's law and electromotive force (emf)

Figure 2 shows a cloud of magnetosheath plasma impacting the magnetopause current. It is assumed that the magnetic flux tube extends in the z-direction; nevertheless, the figure is essentially three dimensional: $x - z$ to show the magnetic topology, and $x - y$ to show curl $\mathbf{E}$ with finite dimension in the y-direction. The induced electric field shown follows from elementary electromagnetic theory; the assumed motion of the magnetopause, an earthward meander of the magnetopause current, will create and induction electric field, with a finite curl [17].

3.2. The total electric field

The electric field shown in Figure 2 is only the induction electric field. It is likely that the local plasma can modify this field, for example by charge separation to create an electrostatic field if the normal component of the magnetic field is finite. Briefly, the plasma response depends on the local conductivity, or rather, the tensor conductivity in the gyromagnetic medium. A collisionless plasma has a Pedersen conductivity that is very low. On the other hand, the direct conductivity along the magnetic field is very high. Thus we expect that the actual electric field at the magnetopause depends on having a finite B_n at the magnetopause. The electric field two sources:

$$\mathbf{E} = -\nabla\phi - \partial\mathbf{A}/\partial t \tag{4}$$

The electrostatic field is conservative, while the induction is solenoidal. A localized induction electric field is forced upon the plasma, not an electrostatic field. It is entirely local, opposed to the current perturbation by Lenz's law.

3.2.1. Motion of the magnetopause with $B_n = 0$

We need to consider 2 cases regarding B_n. If $B_n = 0$ the plasma cannot respond by charge separation, and no electrostatic field is created. The magnetosheath flow is tangential to the magnetopause as observed in [25] with low shear.

3.2.2. Response of the plasma: B_n *is finite*

The plasma response changes dramatically with an open magnetosphere. If there is a normal component of the magnetic field through the current sheet $\mathbf{E}^{ind}$ can polarize the plasma along B_n causing an electrostatic field tangential to the MP. We see that this $\mathbf{E}^{es}$ will drive the SW plasma into the current sheet, in the reconnection frame [25].

On the other side, since both $\mathbf{B}$ and $\mathbf{E}$ reverse, the electric drift $\mathbf{E} \times \mathbf{B}$ will be also earthward. Plasma transfer is created.

3.3. Plasma transfer event (PTE)

There is no question about the reality of a plasma transfer event (PTE); observations come from a variety of sources beginning with the rocket results of Carlson and Torbert [6] (see the reviews in [17, 21, 23, 38]).

In summary, there are two complementary processes: polarization electric field, which does not depend on the movement of the magnetopause itself, and induction electric field due to magnetopause erosion, which does. Lemaire and Roth [21] used electric energy of the plasma, i.e. plasma in motion, in a process they called impulsive penetration (IP), based on the pioneering work by Schmidt [28, 29]. I used a different process, that of tapping magnetic energy with the induction electric field in a complete current circuit [17].

A finite B_n is crucial to the PTE. This process was seen by C3 of the Cluster mission [19].

3.4. Low latitude boundary layer (LLBL)

The LLBL is earthward of separatrix S2, on closed field lines [11, 12, 13]. This layer *completely insulates* the plasma mantle on open field lines from the plasma sheet. Plasma flow must still be tailward; it is strong flow of a hefty plasma, ($n \sim 1 - 5\ cm^{-3}$ [37], delivering ion/electrons of about $\sim 10^{27}/s$). Since this is mostly $\mathbf{E} \times \mathbf{B}$ flow it is necessary to maintain an electric field on closed field lines; this is accomplished by a polarization current (preceding section). The polarization current has to move charges against the field, so that it must be a dynamo with $\mathbf{E} \cdot \mathbf{J} < 0$.

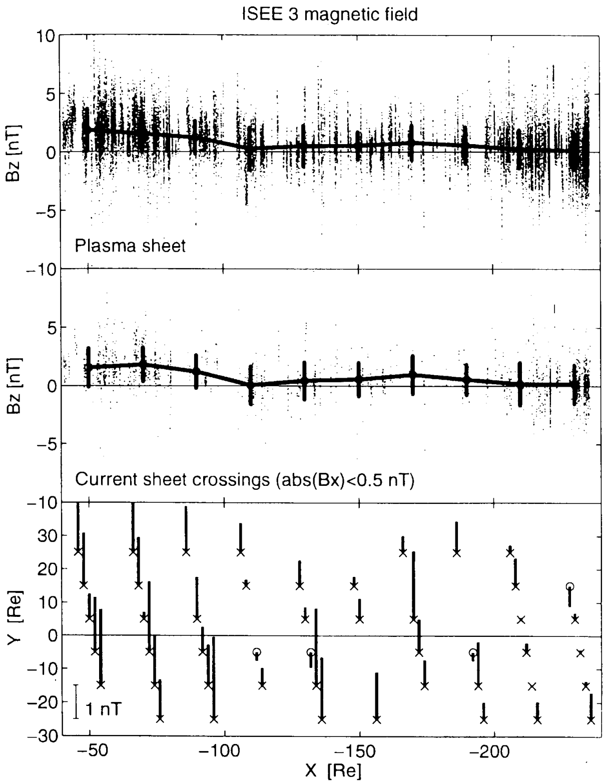

Fig. 3. Top: Plasma sheet B_z as a function of X in the anti-sunward direction. The averages ($20R_E$ bins) and variances are shown with heavy lines. Middle: Plasma sheet B_z at current sheet crossings ($|B_X| < 0.5$ nT). The averages and variances are shown. Bottom: A quasi-three-dimensional view of the B_z at the plasma sheet. The vertical bars indicate the average B_z, the scale is given in the lower left hand corner [26] .

4. The substorm problem

A magnetospheric substorm is a transient process of energy storage, release, and dissipation. For the past 40 years many substorm models have been put forward but none can completely explain the various phenomena of substorms. According to Vasyliunas, "Explaining the sudden onset of the expansion phase of magnetospheric substorms has proved to be one of the most intractable problems in magnetospheric physics to date" [36]. Baker et al. noted: "$\cdots$ fundamental issues remain to be resolved. Why, for example, is the magnetosphere stable most of the time, and why do substorms occur just when they do? What allows the violation of the frozen-flux constraint necessary for an efficient energy release by reconnection in the course of substorms?" [2].

4.1. The setting

Several spacecraft have explored the magnetotail as far as 220 R_E; [26] have used ISEE-3 to evaluate the z-component B_z as shown by Figure 3. They found that it was positive (northward) in the average values, using all the data in the top panel, but also in the current sheet. It did not reverse as it should have according to the Dungey model.

4.2. The far tail is a dynamo

It was found that at 180 R_E the plasma flow was tailward, implying an electric field that was from dusk to dawn [33, 37]. Since the current was dawn-dusk in view of the extreme tail-like shape, the conclusion is that $\mathbf{E} \cdot \mathbf{J} < 0$ (see Figure 4).

4.2.1. Exit at the distant magnetopause

All that plasma must exit the closed field line region that is apparent in Figure 3 beyond several 100 R_E to the right in Figure 4 [14] . Perhaps the process is similar to a PTE event on the dayside.

4.2.2. The dip in B_z at 120 R_E

Something strange happens just beyond 100 R_E; it appears to be where the plasma sheet boundary (PSBL) is located. The dip in B_z at 120 R_E could be caused by a cross-tail current separating the plasma sheet (with earthward flow) with the LLBL (with tailward flow).

4.3. Substorms begin near midnight

A substorm is initiated by a growth phase which feeds particles and energy into the plasma sheet. The plasma supplies this energy by a dynamo in the LLBL where $\mathbf{E} \cdot \mathbf{J} < 0$: the plasma particles release energy to the electromagnetic field. In contrast to this is a region where $\mathbf{E} \cdot \mathbf{J} > 0$: here the particles are accelerated and energy is dissipated, as in auroral arcs, in auroral electrojets, in the hypothesized 'reconnection' region.

4.3.1. Trigger phase

This important activity is localized in the plasma sheet at first during a trigger phase, reaching into the distant boundary layer somewhat later. In fact, we have known for a long time that a breakup usually starts on an equatorward arc; therefore, we must look in the inner plasma sheet ($10 - 20$ R_E) for the trigger mechanism.

We have proposed [18] that the appropriate instability to trigger a substorm is a tailward meander in the equatorial plane of the strong current filament that develops during the growth phase. From this single assumption follows the entire sequence of events for a substorm.

4.3.2. Motion becomes chaotic

The particle acceleration mechanism in the plasma sheet is curvature drift with a dawn-dusk electric field, leading to the production of auroral arcs. Eventually the curvature becomes so high that the ions cannot negotiate the sharp turn at the field-reversal region, locally, at a certain time [9]. The particle motion becomes chaotic, causing a local outward meander of the cross-tail current.

4.3.3. Electromotive instability

An induction electric field is produced $\mathbf{E}^{ind} = -\partial\mathbf{A}/\partial t$, by Lenz's law. An outward meander with $B_z > 0$ causes $\mathbf{E} \times \mathbf{B}$ flow everywhere out from the disturbance; this reaction is a macroscopic instability which we designate the *electromotive instability*.

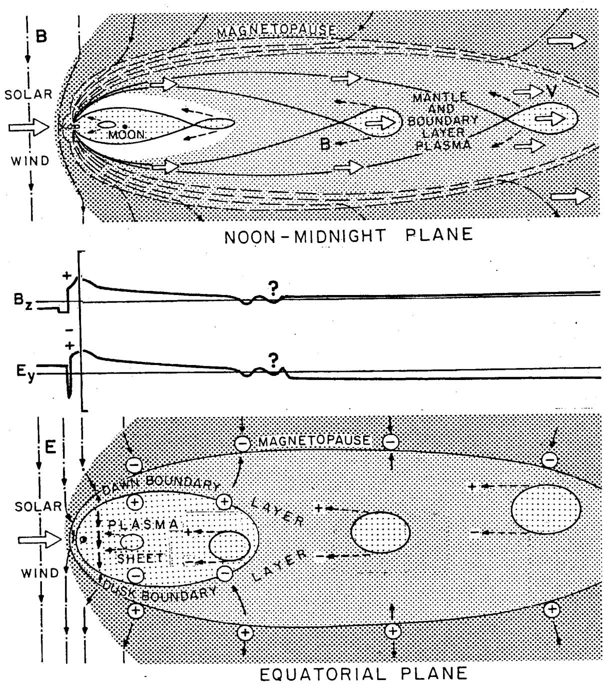

Fig. 4. Two views of the magnetosphere, noon-midnight median (top) and equatorial (bottom). The low latitude boundary layer is a dipole layer with negative and positive charges for a southwrd IMF. The dawn and dusk layers come together at 100 to 150 R_E. Middle: the profiles of the magnetic field B_z and the electric field E_y are based on spacecraft data. During substorms plasmoids may be created near the Earth, propagating tailwards. Within the plasma sheet they proceed against the normal earthward flow, but they coast with the tailward flow farther out.

4.3.4. The response of the plasma

The response of the plasma to the sudden formation of an induction electric field $\mathbf{E}^{ind} = -\partial \mathbf{A}/\partial t$ is through charge separation and a scalar potential, $\mathbf{E}^{es} = -\nabla\phi$. Both types of electric fields have components parallel to **B** in a realistic magnetic field. For MHD theory to hold the net $\mathbf{E}_\parallel$ must be small:

$$\mathbf{E}_\parallel = \mathbf{E}_\parallel^{es} + \mathbf{E}_\parallel^{ind} \sim 0 \tag{5}$$

This usually seems to happen because MHD often does hold, but not always. The requirement “the condition $\mathbf{E}\cdot\mathbf{B} = 0$ is satisfied everywhere except at the separator” (section 2.1) does imply some essential plasma physics.

4.3.5. Formation of field-aligned currents

Part of the response is the formation of field-aligned currents producing the well-known substorm current diversion. This is a direct result of a strong $\mathbf{E}_\parallel^{ind}$ (the cause) needed to overcome the mirror force of the current carriers; this enables charge separation to produce an opposing electrostatic field $\mathbf{E}_\parallel^{es}$ (the effect). Satellite data confirm the reality of a strong $\mathbf{E}_\parallel$ in the plasma sheet by counter-streaming of electrons and ions [20], and by the inverse ion time dispersion, up to several 100 keV [27].

4.3.6. Free energy of the stressed magnetotail

However, with zero curl, the electrostatic field $\mathbf{E}^{es}$ cannot modify the emf $\varepsilon = \oint \mathbf{E}\cdot d\mathbf{l} = -d\Phi^M/dt$ of the inductive electric field $\mathbf{E}^{ind}$; the charge separation that produces a reduction in the parallel component $\mathbf{E}_\parallel$ must enhance the transverse component $\mathbf{E}_\perp$. The *enhanced transverse component* will lead to strong flows perpendicular to the magnetic field depending on the solenoidal electric field (e.g. bursty bulk flows).

4.3.7. Plasmoid may be created

On the tailward side of the developing plasmoid the dusk-dawn electric field with $\mathbf{E}\cdot\mathbf{J} < 0$ will cause tailward motion of the plasma; a plasmoid may be created. It will move in the direction of least magnetic pressure, tailward. A dynamo is a necessity since the plasmoid has to proceed against the earthward flow within the plasma sheet. This may require that field aligned currents reach into the polar caps, observed to exist as far as 80^o. Once it gets into the LLBL beyond 100 R_E it can coast along with little resistance.

4.3.8. Electric field near the emerging X-line

It is likely that an emerging X-line will develop; this will depend on the strength of the dynamo. On the earthward side the enhanced dawn-dusk induction electric field with $\mathbf{E}\cdot\mathbf{J} > 0$ will cause injection into the inner plasma sheet, repeatedly observed at moderate energies up to 50 keV.

4.3.9. Acceleration to high energies

This same electric field near the emerging X-line will accelerate particles non-adiabatically to moderate energies. With high magnetic moments in a weak magnetic field, electrons (ions) can benefit from gradient and curvature drift to attain high energies (by the ratio of the magnetic field magnitude) in seconds (minutes) [4, 24].

5. Problems to be resolved

There is always a strong inclination for a body of professionals to oppose an unorthodox view. In the case of continental drift Sir Edward Bullard [5] summarized his own view:

> “Clearly it is more prudent to keep quiet, to be a moderate defender of orthodoxy, or to maintain that all is doubtful, sit on the fence, and wait in statesmanlike ambiguity for more data (my own line till 1959).”

as quoted by David Stern [35]. Here we must recognize some essential points as follows.

5.1. The far tail is a dynamo with $\mathbf{E}\cdot\mathbf{J} < 0$
5.2. Plasma must exit at the distant magnetopause
5.3. Consequences of the current between PS and LLBL
5.4. Cause(s) of the trigger phase
5.5. Limited response of the plasma, $\mathbf{E}^{ind} = -\partial\mathbf{A}/\partial t$ vs $\mathbf{E}^{es} = -\nabla\phi$
5.6. Plasmoid and flux ropes are created
5.7. Sources of electric field near the emerging X-line
5.8. Acceleration to high energies, still unresolved

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