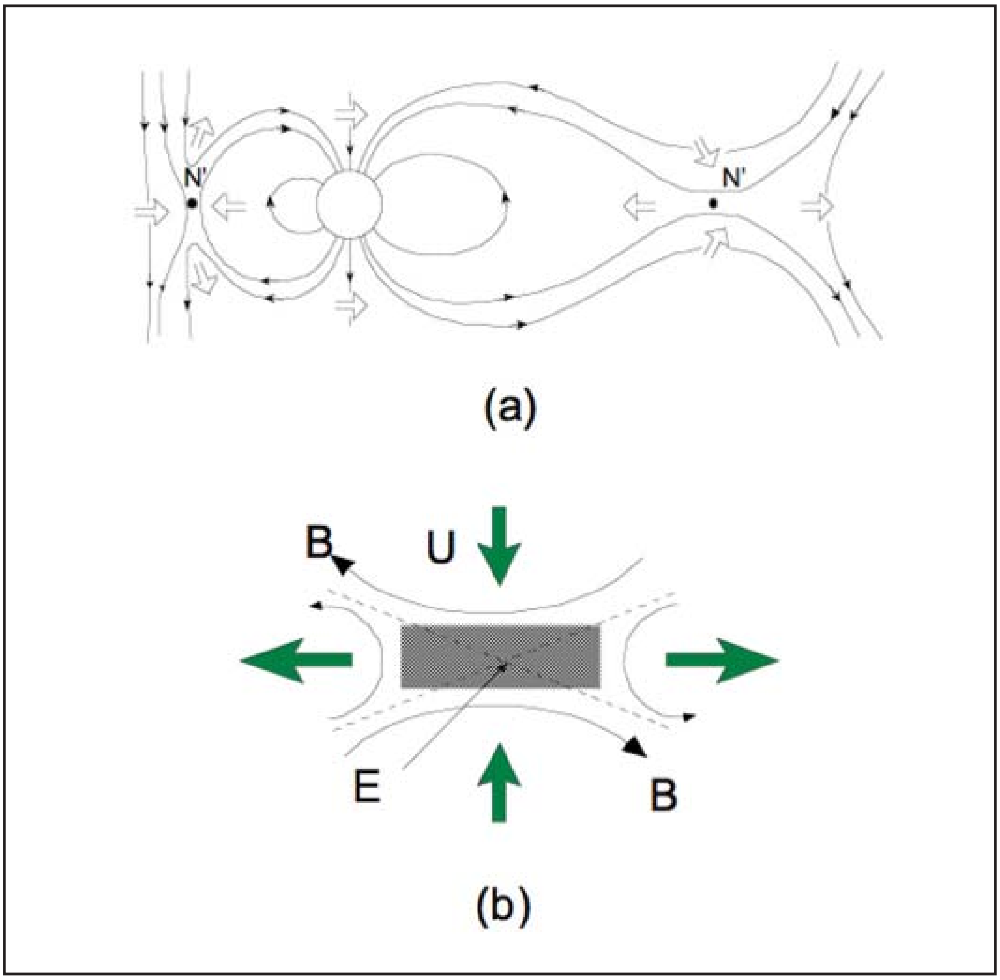
Proceedings of the Magnetic Reconnection Meeting

in Kiruna, Sweden, September 2002



Rickard Lundin and Rick McGregor
(editors)

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Swedish Institute of Space Physics
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Title page photograph:
Participants at the Magnetic Reconnection Workshop, September 2002, outside the Swedish Institute of Space Physics (IRF), Kiruna, Sweden (photographer: Torbjörn Lövgren, IRF).

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Preface

Magnetic reconnection/merging was introduced by by Jim Dungey in 1961 to explain the transfer of solar wind energy through the magnetopause and large scale convection in the magnetosphere. Magnetic reconnection was quickly adopted by many researchers in space plasma physics, but it also stirred up an intense controversy that remained for a long time. Among many of the contemporary critics were Hannes Alfvén, the founder of the concept "frozen-in magnetic field lines", a concept that formed the basis for the original thesis by Jim Dungey.

Magnetic reconnection has evolved extensively since the early 1960s and has become well recognized by most space researchers as an important plasma process capable of expeditiously converting large amounts of magnetic energy to both thermal energy and bulk acceleration of the plasma. However to say that the controversy is over and the intrinsic properties of magnetic reconnection are well understood is an opinion rather than the truth. Magnetic reconnection deals with a fundamental force-field in nature, the magnetic field, in a topological sense such that magnetic field lines from one source of the magnetic field may be tied to another source. Considering that the magnetic field is immaterial we have a problem in conveying the model to a general physics community.

Richard Feynman once provided the following definition of magnetism: "The fundamental magnetic effect is that a moving electric charge creates, in addition to the electric field, a magnetic field which acts to produce a magnetic force on a second moving charge". This definition, strictly tying magnetic fields to moving electric charges, implies a unique origin, or an ensemble of origins in a macroscopic sense. The magnetic effect is therefore not a free entity like the electric charge—there is no magnetic charge (div B = 0). Any process described by magnetic field topology changes must therefore correspond to topological changes of electric currents (moving electric charges).

The purpose of setting up a workshop in Kiruna in September 2002 was to enable proponents and opponents to confront and discuss all issues they find relevant to further the understanding of magnetic reconnection. Our goal was to analyse the existing findings critically and to find means of discriminating magnetic reconnection from other possible plasma physical processes because there is a risk that a ruling paradigm may gain so much momentum that it becomes obvious—and thus beyond criticism. Adequate use and understanding of magnetic reconnection is in my opinion essential for the respectability of space plasma physics within the science—and in particular the general physics—community.

The history of science is scarred with controversies, some of them taking a long time to settle while others quickly disappear in the realm of increased knowledge. Instantaneous suspicion and doubt is healthy while seeking the truth. On the other hand, progress in search of the truth in science also requires a certain amount of momentum or we would be stuck in a continuous debate. The blue ribbon for a healthy scientific field is criticism and careful scrutiny of existing paradigms. It is in my opinion a healthy sign that there are still knowledgeable critics in space plasma physics.

Rickard Lundin
Kiruna, August 2003.

Critcal Aspects of Magnetic Reconnection

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Abstract:

This report discusses critical aspects of magnetic reconnection, MR, focusing on the acceleration and deceleration of solar wind plasma at the magnetopause and inside the magnetospheric boundary layers. It discusses three major problems in the existing definitions and tests of MR. The first is related with the Walén test and the DeHoffman-Teller frame of reference. The second is that velocity enhancements during MR are not necessarily associated with plasma acceleration, suggesting a "focusing effect" – a conversion of thermal velocity to parallel bulk velocity. The third is related to an application of ideal MHD following MR. The break-down of ideal MHD is inferred from observations of plasma differential drift, indicating frequent departures from the frozen-in condition in the multiple-species plasmas of the boundary layer. The essence of this critical view is that one has to consider MR as a microphysical phenomena rather than a global phenomena, which is not to say that MR is not a process of global importance.

1. Introduction

Since Dungey (1961) proposed MR as a process for transferring solar wind energy to the Earth´s auroral zones, the distinguishing characteristics of MR have been discussed. The first evidence for MR in plasma data, acceleration at the magnetopause, was presented by Paschmann et al., 1979. The distinguishing characteristics of MR are considered to be plasma acceleration together with the existence of a normal magnetic field component at the magnetopause (rotational discontinuity), a D-shaped ion distribution having a low-energy cut-off at the Hoffmann-Teller velocity, and open magnetic field lines (as identified in the electron data e.g. Phan et al, 2001).

The objective of this report is: (1) To discuss plasma acceleration/deceleration at and inside the magnetopause and how that connects to the Earth´s ionosphere. (2) To analyze critically MR-events based on the Walén test and the DeHoffman-Teller frame (Sonnerup et at., 1987), and (3) To discuss the departure from ideal MHD frequently found in the magnetospheric boundary layer. Cluster CIS data is used to test the ion acceleration/deceleration properties at and inside the magnetopause. This will be combined with an investigation of the Walén test and the DeHoffman -Teller frame. Another important aspect of MR acceleration is the β-dependence (Paschmann et al, 1986), high velocity increases primarily observed for low β. A means of explaining the β-dependence is to infer mass-loading of the acceleration process in the magnetopause current sheet.

2. Observations of Magnetic Reconnection

One important characteristic of MR is the acceleration of ions at the magnetopause. Three cases with strong velocity increase (2-3 times the background ion velocity) inside as well as at the magnetopause are here used to show that an increase in bulk velocity is not necessarily associated with acceleration in the sense of plasma energization. Fig. 1 shows ion data from Cluster CIS where the total ion velocity reaches 370 km/s, well above the <100 km/s in the surroundings. Notice that the *velocity increase* is associated with an ion *density decrease*, the velocity increase being inversely proportional to the ion density (n). Perhaps somewhat surprisingly, the velocity increase is not associated with an increase of the ion energy (upper panel). This suggests that the velocity increase (Δv) is related to a ”flow confinement”, of the ion distribution rather than an acceleration. Finally we note that the velocity increase is associated with a decrease in plasma pressure and an increase in total magnetic field intensity (bottom panel). Considering the plasma pressure decrease and magnetic pressure increase in this case the overall dependence between Δv and n is very similar to the β-dependence reported by e.g. Paschmann et al, 1986.

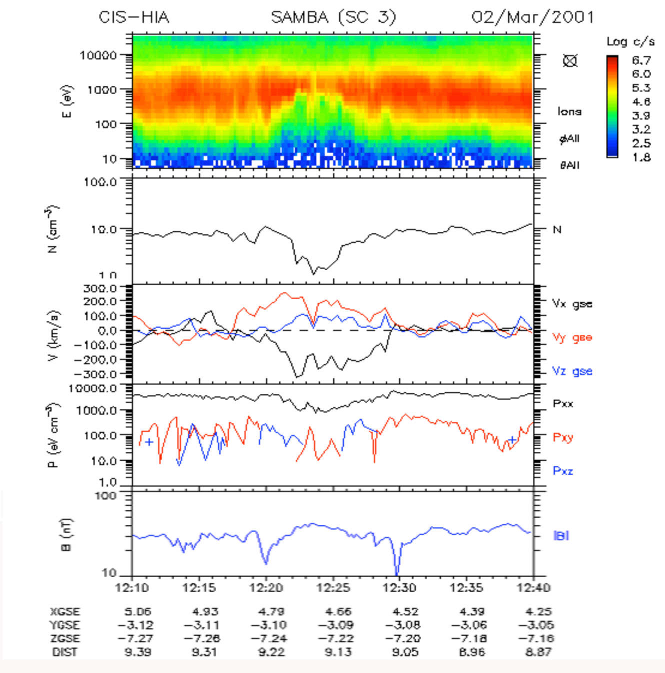

Fig. 1 Cluster CIS observation of a region with strong velocity increase, suggesting magnetopause reconnection.

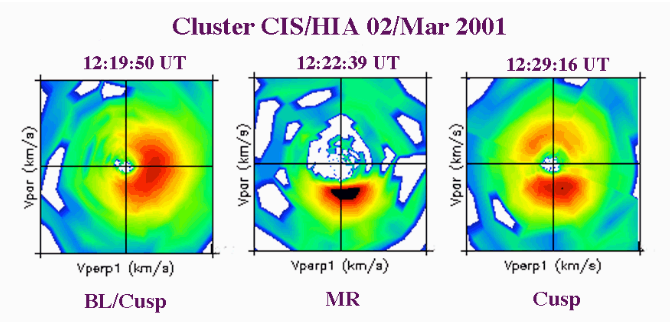

Fig. 2 Cluster CIS velocity distributions at, and on the borders (Cusp) of MR (see Fig. 1).

Fig. 2 shows a projection of the ion distribution in the parallel versus perpendicular (to B) velocity space. This illustrates again that there is no net increase in ion velocity, merely a confinement of the ion flux in the parallel direction and a corresponding decrease of flux in other directions, altogether leading to a net field-aligned flow velocity.

Before discussing the Walén test that suggests that a velocity increase results from MR, I will present an alternative test based on mass-loaded current sheet acceleration at the magnetopause. The test assumes that an electric field exists at the magnetopause with the same direction as the magnetopause current (E·J>0=>a load).

3. Magnetopause Plasma Acceleration

Consider a magnetopause layer of width several ion Larmor radii (fluid) and assume that the dynamo current is driven by the plasma inertia. This gives the following differential equation from Ohm´s law neglecting Hall currents for decelerating (solar wind) and accelerating (magnetopause) plasmas:

$$S_{xy}\sigma\left(E_{ind} - v_a B_n\right) = \frac{nm}{B_n}\frac{dv}{dt} \qquad (1)$$

where S_{xy} is a spatial parameter, σ is a phenomenological conductivity in the interaction region, v is the plasma velocity, E_{ind} is the induced electric field in the magnetopause current (j_{mp}), B_n is the normal magnetic field component at the magnetopause, and v_0 is the incident velocity in the z-direction of the acceleration region. Solving the equation gives:

$$v_a = v_0 + \frac{E_{ind}}{B_n}\left(1-\exp\left(-t/t_0\right)\right) \qquad (2)$$

$$\text{where:} \quad t_0 = \frac{n_a m_a}{B_n^2\, \sigma\, S_{xy}}$$

Notice that the velocity v_a in the equation above ranges from v_0 and $(v_0 + E_{ind}/B_n)$. A high density of the protruding plasma (n_a) and a small characteristic scale (S_{xy}) give: $t/t_0 \longrightarrow 0$ and $v_a \approx v_0$. This implies that acceleration is more effective when the plasma density is low and the magnetic field strength is high. A high plasma density effectively acts as *a mass-loading of the acceleration process*. More generally speaking the acceleration is more effective for: $t > t_0$.

A conclusion from the above considerations is therefore that acceleration is more effective in a low-beta plasma (Paschmann et al, 1986, Phan et al., 1996) as a direct consequence of mass-loading.

Returning now to the fluid-kinetic prediction, we have the following four requirements for MR at the magnetopause (e.g. Phan et al, 2000):

(a) The plasma acceleration must satisfy the Walén relation,

(b) The magnetic field normal to the magnetopause, B_n, must be non zero,

(c) The ion distribution must be D-shaped and have a low-energy cut-off at the Hoffmann-Teller velocity

(d) The electron distribution should show signatures of open field topology.

Notice that all four requirements focus on local properties associated with MR, rather than what happens next after MR. Before addressing ideal MHD and the motion of flux tubes the Walén relation will be considered.

4. Plasma Drift and the Departure from Ideal MHD

A general expression for the macroscopic ion flow velocity of ion species (mass m, density n, and electric charge q) implied from first order drift theory is:

$$\underline{v}_{\perp} = \frac{\underline{B}}{B^2} \times \left[-\underline{E} + \frac{m}{q}\frac{dv_0}{dt} + \frac{\nabla P_{\perp}}{qn} + \frac{(P_{\parallel} - P_{\perp})}{qn}(\underline{b}\cdot\nabla)\underline{b} \right] \quad (3)$$

where: $\underline{b} = \underline{B}/B$.

The electric drift is the only drift term that is species independent (mass, charge). All other terms are species dependent and/or spatial (pressure-, and magnetic field inhomogeniety) dependent. The plasma drift in the *convection frame of reference*, the frame of reference of the convective flow ($\underline{E} = -\underline{v} \times \underline{B} = 0$) is given by:

$$\underline{v}_a = \underline{v}_{\perp} - \underline{v}_E = \frac{\underline{B}}{B^2} \times \left(\left[\frac{m}{q}\frac{d\underline{v}_o}{dt} + \frac{\nabla P_{\perp}}{qn} \right] + \frac{(P_{\parallel} - P_{\perp})}{qn} (\underline{b}\cdot\nabla)\underline{b} \right)$$

The drift velocity in the convection-frame of reference may also be written:

$$\underline{v}_a = \underline{v}_A \times \frac{\sqrt{\mu_0 \rho}}{B^2} \left(\left[\frac{m}{q}\frac{d\underline{v}_o}{dt} + \frac{\nabla P_{\perp}}{qn} \right] + \frac{(P_{\parallel} - P_{\perp})}{qn} (\underline{b}\cdot\nabla)\underline{b} \right)$$

where $\underline{v}_A = \underline{B}/(\mu_0 \rho)^{1/2}$ is the Alfvén velocity, and ρ is the plasma mass density. For constant r, |B|, ΔB, n and pressure gradients this corresponds to:

$$\underline{v}_a = \underline{v}_A \times \left[C_1 \frac{d\underline{v}_o}{dt} + C_2 \nabla P_{\perp} + C_3 (P_{\parallel} - P_{\perp}) \right]$$

Notice that this expression describes additional drift terms that must be considered provided one attempts to find a frame of reference that singles out the parallel flow component of a plasma – e.g. the HT frame.

Let us now consider the above in view of the Walén relation (Sonnerup et al, 1987) given by:

$$\underline{v} - \underline{v}_{HT} = \pm (1-\alpha)^{1/2} \cdot \underline{v}_A$$

where $\alpha = (P_{\parallel} - P_{\perp})\,\mu_0/B^2$, and $\underline{v}_{HT}$ represents a motion in the DeHoffman-Teller (HT) frame of reference - e.g. convection along the magnetopause normal B.

The HT-frame is obtained from a set of measurements by determining the *minimum variance of the plasma drift velocity*, i.e.:

$$D = \langle |(\underline{v} - \underline{v}_{HT}) \times \underline{B}|^2 \rangle = \text{minimum}$$

The minimum variance of the drift velocity in the set of measurements gives the Hoffman-Teller velocity, $\underline{v}_{HT}$, in the

HT-frame (the frame of reference of convection).

However, as discussed above the plasma drift has three additional drift terms (besides electric drift) connected with the variance. The actual rest-frame is therefore given by:

$$\underline{v}_{HT} = \underline{v}_E + \underline{v}_a \qquad (4)$$

The drift term in the HT-frame, $\underline{v}_{HT}$, is only partly due to convection. A follow-on question is: can additional drift terms be comparable in magnitude to the electric drift? The answer is yes, as was already first implied some 15 years ago (Lundin et al, 1987) and recently also confirmed from Cluster data (Lundin et al, 2003). Fig. 3 illustrates this aspect from one of the three Cluster events. The figure illustrates the existence of three different ion populations: H^+ of solar wind origin, energetic O^+ and cold O^+, all three populations flowing/drifting in separate directions. Notice that a DeHoffman-Teller frame may be obtained for H^+ and the cold O^+ ions, but that only H^+ ions are streaming along the field lines while the cold O^+ remain at rest. The latter illustrates that the cold O^+ ions are unaffected by any field-aligned acceleration process on that flux tube.

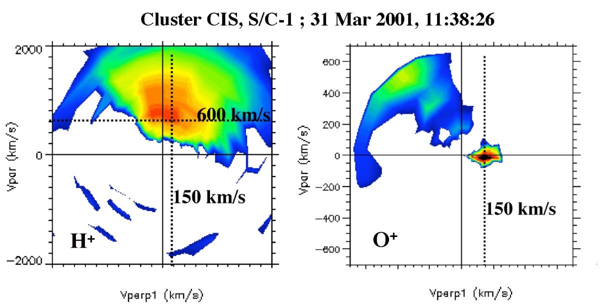

Fig. 3 Cluster CIS data illustrating the differential drift between energetic protons and "cold" O+ ions, the difference amounting to some 100 km/s.

On the basis of this one can argue that the minimum variance method of the plasma drift gives no hint of the physical effect that promotes the drift, it only determines an "average" drift vector in an "average" frame of reference - which is not just convection. Even more importantly, the experimental basis for suggesting that ions of different origin/species drift together in a common frame of reference (DeHoffman-Teller frame) is not justified in the most critical regions – where the plasma velocity is enhanced.

5. PTEs and FTEs

The discovery of Flux transfer events, FTEs, were first made on the basis of magnetic field signatures (Berchem and Russell, 1984). Later FTEs were also studied from the plasma point of view as plasma flowing in and out of the magnetosphere. FTEs are usually considered as regions with transient transfer of solar wind magnetic flux to the terrestrial magnetosphere. Heikkila (1982) argued that instead of magnetic flux it is plasma that is transferred, favouring the notion Plasma Transfer Events (PTEs).

Lundin (1989) proposed on the basis of ion observations near the magnetopause and at mid-altitude (Viking-data) that FTEs and PTEs may represent two "sides" of the same process, the latter (PTEs) mainly identified inside the magnetopause. On the other hand a lack of IMF Bz-dependence and the existence of "overlapping injections" in PTEs at mid-altitudes (Woch and Lundin, 1992) are characteristics not easily connected with FTEs. The existence of overlapping injections may be considered problematic for ideal MHD and convecting flux tubes since it implies several time-of-flight plasma events along one and the same flux tube. However an even more important departure from ideal MHD is that individual plasma populations may experience a completely different history along one and the same flux tube, as already discussed in the previous section. Fig. 4 shows that the $-\underline{v}\times\underline{B}$ ($\underline{E}$) of energetic (plasma sheet), injected magnetosheath, and cold (ionospheric) H^+ ions is clearly energy dependent. This demonstrates that whenever the plasma is not completely mixed and in thermal equilibrium, it may be subject to individual, force terms that depend not only on electric fields but also on inertia and gradients.

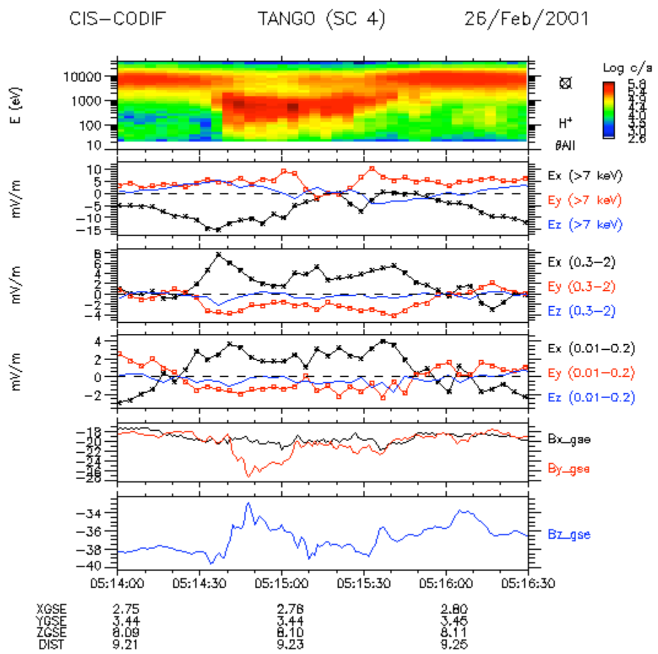

Fig. 4 Cluster CIS data of PTE illustrating a pronounced difference in $-\underline{v}\times\underline{B}$ ($\underline{E}$)*, for ions of different origin, thereby demonstrating the complexity of plasma forcing.*

6. The Magnetosphere-Ionosphere coupling

A final important aspect of MR is its coupling to the ionosphere. Since one of the requirements for MR is open field lines, it should be distinguishable from processes that occur on closed field lines. Open field lines imply that a motion or a force applied on a flux tube corresponds to a forcing, and a corresponding motion of the entire flux tube provided ideal MHD holds. On the other hand it is well known that forcing resulting in e.g. aurora and its connection to field-aligned currents occurs frequently, if not mostly, on closed geomagnetic field lines. A requirement is therefore that energy and momentum is transferred from open- (solar wind) to closed magnetic field lines. The electric field and current description first formulated by Alfvén (1958) meets more easily these requirements compared to the MR description.

The main power input in the MR description feeds into the polar cap potential where energy is tapped along the auroral oval on preferentially open field lines. However the Alfvén current description allows for a transfer of energy almost anywhere in the magnetosphere where it is generated by local dynamos/generators. The difference between the two descriptions boils down to two aspects: the dualism in physics (E,J versus B,V) and the morphological connection to the energy transfer regions. The first aspect may not be a problem provided the causal chain of events is properly tracked. However the second aspect is more serious because it implies that despite 40 years of *in situ* space investigations we have not yet reached a common understanding on the major causes of the acceleration regions connecting to the aurora oval.

7. Conclusions

The observations of ion differential drift in the magnetopause/boundary layer indicates that:

• The plasma motion frequently departs from ideal MHD, i.e. the plasma drift is species and energy dependent (equation 3).

• For the HT-frame of reference to be applicable one must add a drift term $\underline{v}_a$, depending on plasma pressure, anisotropies and inertia. The consequence of this is individual HT-frames for individual plasma species /populations.

• The Walén test requires a proportionality between Alfvén velocity and the velocity in the HT-frame. Provided a common HT-frame can be determined for the local plasma (no pressure gradients, inertia etc) the velocity change is in the parallel component, i.e.:

$$\Delta \underline{v}_{\parallel} = \pm k \cdot \underline{v}_A = \pm k \cdot \underline{B}/(\mu_0 \rho)^{1/2}$$

A successful Walén test as an indicator of field-aligned plasma acceleration also requires that:

$$\Delta E_{\parallel} \approx k\, m/2\, (\underline{v}_A)^2 = k \cdot B^2 / 2\mu_0 n$$

The parallel acceleration is then proportional to B^2 and inversely proportional to number density (n). For instance, a factor of 2 increase in velocity corresponds to a factor of 4 increase in energy. As discussed here an energization is not always observed together with a veclocity increase. A velocity increase without ion energization can be the feature that distinguishes MR from other plasma injection processes. Observations such as those in Figs 1-3 may be explained by a temporal opening of the magnetopause and a rapid expansion of magnetosheath plasma along terrestrial magnetic field lines.

MR as a process for plasma access and for converting electromagnetic energy ($\underline{E}_{ind}$) to kinetic energy in the magnetopause current sheet ($\underline{J}$), may take place whenever $\underline{E}\cdot\underline{J}>0$. However, for steady-state MR to drive global convection requires ideal MHD within magnetic flux tubes, a condition that frequently does not apply in the magnetopause boundary layers.

Another weakness of MR as a process with impact on the magnetosphere-ionosphere coupling is its inability to describe in a simple manner the magnetospheric current circuitry. This is particularly obvious for field-aligned currents connecting the ionospheric load region with the dynamos/ generators in the magnetosphere.

If one focuses on MR as an access mechanism, allowing for a bursty access of plasma into the magnetosphere, the injected plasma bulk flow instead represents a source of free (kinetic) energy. In this way the injected plasma will act as a dynamo/generator coupling to the ionospheric load (Fig. 5).

Recent Cluster data supports the idea of a ”bursty” injection of magnetosheath plasma elements into the dayside boundary layer. Whether the injection process is associated with impulsive penetration, IP, or MR remains to be seen, but the study by Lundin et al (2003) suggests frequent injections of plasma elements in the boundary layer almost independent of IMF. In summary the study by Lundin et al. (2003) suggests that PTEs:

• are frequently observed inside the dayside magnetopause,
• expand along as well as transverse to the magnetic field lines,
• are partially, or totally, embedded in energetic magnetospheric plasma,
• may be associated with substantial differences in ion flow and ion drift for individual ion populations (non-MHD properties, i.e. $\underline{E} \neq -\underline{v} \times \underline{B}$),
• are limited and highly variable in space and time, their properties varying on Cluster spacecraft separation distances (≈300 km),
• occur during all IMF conditions, with some preference for IMF $B_z>0$,
• have a magnetic signature (field-aligned currents) similar to FTEs.

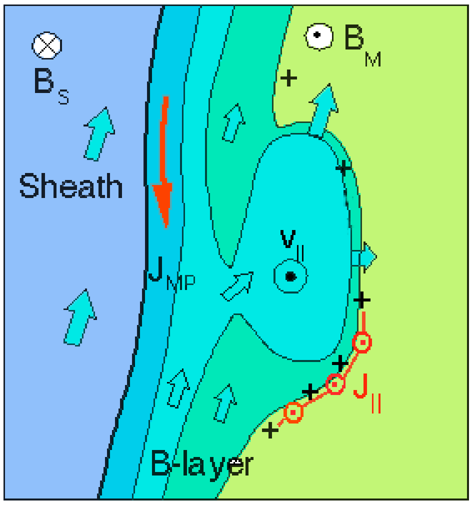

Fig. 5 Diagram of the PTE expansion in the boundary layer (along and perpendicular to B) generating electric fields and currents coupling to the ionosphere (via $J_{||}$).

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Report to Workshop on Magnetic Reconnection at Kiruna, Sweden, 18-20 September, 2002

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1. Introduction

Using the E,J paradigm [Heikkila, 1997b] we can discuss Poynting's energy conservation theorem (from Maxwell's equations, no other assumptions):

$$\iiint_{vol} E \cdot J d\tau = -\oint \frac{E \times B}{\mu_0} \cdot dS - \iiint_{vol} \varepsilon_0 E \cdot \frac{\partial E}{\partial t} d\tau - \iiint_{vol} \frac{B}{\mu_o} \cdot \frac{\partial B}{\partial t} d\tau \qquad (1)$$

Thus we see that there are three types of processes that are involved with solar wind – magnetospheric interactions corresponding to flow of electromagnetic energy to the reconnection load from 3 sources.

Reconnection theories consider the first source term on the right [Sonnerup, 1985]. Birn et al. [2001] summarized the Geospace Environmental Modeling (GEM) Reconnection Challenge project: "Magnetic reconnection is studied in a simple Harris sheet configuration with a specific set of initial conditions including a finite amplitude magnetic island perturbation to trigger the dynamics" and "The key conclusion of this project is that the Hall effect is the critical factor which must be included to model collisionless magnetic reconnection. 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."

Time-dependent terms occur only in the volume integrals, appropriate for local sources. These two terms specify the rate of increase or decrease of stored electric and magnetic energies, e.g. plasma in motion and changing electric currents. The first has been used by Lemaire and Roth [1978, 1991] and Lemaire [1985] for impulsive penetration (IP) across the magnetopause, a result of a polarization electric field [Schmidt, 1979], for low ß. It was also used by Lundin and Evans [1985] for the low latitude boundary layer just inside the magnetopause. The second volume integral has been used by Heikkila [1982, 1984, 1997a, 1998] for an analysis of plasma transfer events (PTE), considered next.

2. Time dependent interconnection of magnetic fields

To study *changes* in the magnetic field, *by definition*, we must consider *perturbation* electric currents, by Ampere's law. The initial condition for change in the state of interconnection must be a perturbation current δ**J** shown in Fig. 1 [Heikkila, 1998]. The possible reconnection electric field E^R is also shown. The perturbation is in the equatorial plane, div δ**J** = 0 to indicate current closure. A perturbation current in the clockwise sense produces southward magnetic field inside, replacing the northward geo magnetic field, i.e.

change in interconnection. Three dimensions are required to show both magnetic and electric field topologies; the topology of the magnetic field can have an X-line.

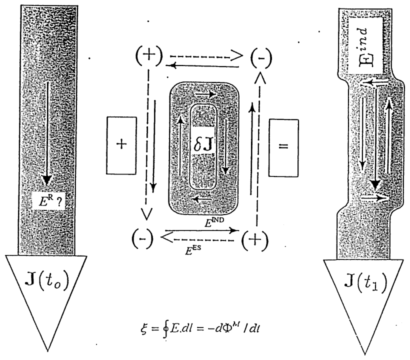

Fig. 1. The immediate cause of transient reconnection is a pressure pulse from the magnetosheath, an inward push by solar wind plasma associated with erosion [after Heikkila, 1998, Figure 10-13]. A possible reconnection field E^R is shown. In addition, Lenz's law states that an induction electric field is created to oppose any current perturbation everywhere given by ***E*** *= - ∂****A*** */ ∂t. A locally changing current distribution, a current meander, can be represented as shown, where the perturbation current δ****J*** *added to the former current at time t_0 produces the new current at time t_1. The line integral of this induction electric field around the current perturbation is the electromotive force that is associated with the perturbation. The result of a (partial) cancellation of $E_{||}^{IND}$ by $E_{||}^{ES}$ is a tangential electrostatic field E_t^{ES} directed oppositely on the two sides (Heikkila and Pellinen, 1977). The electrostatic field E_t^{ES} enhances E_t^{IND}, on both sides! The net effect can be an electric load* ***E.J*** *> 0 and a dynamo* ***E.J*** *< 0 within the current sheet, but that depends on a finite Bn at the magnetopause (rotational discontinuity).*

Magnetopause erosion

The immediate cause of transient interconnection is a pressure pulse from the magnetosheath, an inward push by solar wind plasma associated with erosion [Aubry et al., 1970]. The induction electric field (shown on the right within the current sheet) is forced upon the plasma, not an electrostatic field; it is entirely local, opposed to the current perturbation δ**J** by Lenz's law. This process can happen anywhere on the magnetopause (dayside, flanks, lobes), but also in the magnetotail for the initiation of substorms [Heikkila et al., 2001], and for solar flares [Heikkila, 1983].

The plasma tries to respond to this onslaught by charge separation (polarization) but the response is hindered by the magnetic field. Because *B*z is the dominant component of the magnetic field on either side of the magnetopause, the low Pedersen conductivity (≈0) for a collisionless plasma in the tangential *y* direction limits polarization of charge in that direction. Such is the case at the upper and lower edges of the imposed current perturbation in the case when the normal component of the magnetic field *B*n vanishes (corresponding to a tangential discontinuity). Here too we must use the Pedersen conductivity. In other words, if *B*n ≈ 0 the plasma cannot respond at all by charge separation to the imposition of the current meander. The induction electric field alone is the field that determines the motion of the plasma over the bumpy surface [Heikkila, 1982], which is everywhere tangential to the local magnetopause; this is the low shear case of Phan et al. [1994] shown in Fig. 2.

On the other hand, with a finite *B*n electron and ion mobilities are high along it. Now we can use the high direct conductivity; the plasma can polarize, cause vs effect. The plasma can try to cancel (or at least reduce) the normal component *E*n (now ≈ $E_{||}$). However, an electrostatic field can have no effect on the electromotive force of the induction field because its curl vanishes. Any reduction in the net $E_{||}$ in an arbitrary closed contour must involve enhancement of the perpendicular component $E_\perp$ at least somewhere around the chosen contour, otherwise the curl (emf) would be affected. "Whatever the distribution of the secondary field $\mathbf{E}^{ES}$, the resultant field has to remain finite and large enough to make the line integral finite and equal to $-d\Phi^M/dt$" [Heikkila et al., 1979, p.1386; equation 2 below]. The result of a cancellation (even partial cancellation) of $E_{||}^{\mathrm{IND}}$ by $E_{||}^{\mathrm{ES}}$ is a tangential *electrostatic* field $E_{\mathrm{t}}^{\mathrm{ES}}$, *in opposite senses*, on the two sides of the localized current meander. The electrostatic field $E_{\mathrm{t}}^{\mathrm{ES}}$ *enhances* the induction component $E_{\mathrm{t}}^{\mathrm{IND}}$, *including the reversal* (simply a property of vector fields). The high shear case of Phan et al. [1994] is the result (Fig. 2); this article merits the highest praise in bringing some order to the physics of the MP.

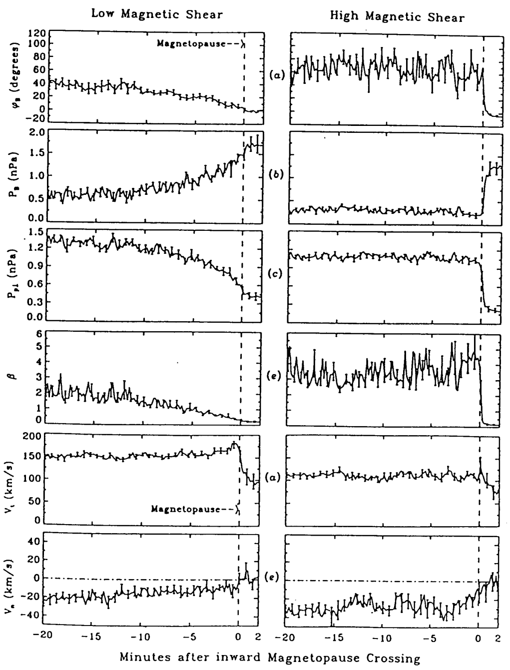

Fig. 2. Superposed epoch analysis of 13 low-shear (< 30°) and 25 high-shear (60°-180°) crossings of the magnetopause (Phan et al., 1994). The key time for the low-shear crossings was defined by the proton temperature change, while for the high-shear case by the maximum magnetic field rotation. The four panels at the top (from Fig. 9) are the magnetic field rotation angle, magnetic and perpendicular plasma pressures, and the plasma ß. The bottom two panels (from Fig. 12) are the tangential and normal plasma velocity components. These results clearly bring some order to physical processes at work in the magnetopause; they suggest that the normal component of the magnetic field through the magnetopause Bn must be finite for the high shear cases, corresponding to a rotational discontinuity.

Plasma transfer across the magnetopause

Now we recognize a crucial result: since both fields reverse the electric drift **E** x **B**/B^2 is unidirectional [Heikkila, 1997a]. Consequently, bursts of solar wind plasma can cross the magnetopause into the low latitude boundary layer as plasma transfer events (PTE), even onto closed magnetic field lines; this has been observed repeatedly by satellites [e.g. Woch and Lundin, 1992]. In another article Phan et al. [1997, p.19,894] noted: "other processes [besides reconnection] must be responsible for transporting plasma across the local MP, onto the closed field LLBL. [These] are rather general occurrences, irrespective of the IMF and the magnetic shear across the MP."

There is direct observational support for this model [Heikkila, 1997a]. Phan and Paschmann [1996] and Phan et al. [1996] studied conditions with high-shear crossings; they found significant structure within the magnetopause current sheet. Their profile of electron temperature is shown in Fig. 3 (after Fig. 6 in the referenced article). On the outer (left) side $T_{||}$ showed an increase of about 10%, signifying that **E.J** > 0 consistent with the reconnection process. However, this is followed by an impressive decrease in $T_{\perp}$ on the right, about 10-20% well above experimental uncertainties, before the large increase due to the hot magnetospheric component. This latter result is consistent with **E.J** < 0, signifying that the plasma supplies energy to the electromagnetic field, a pivotal result.

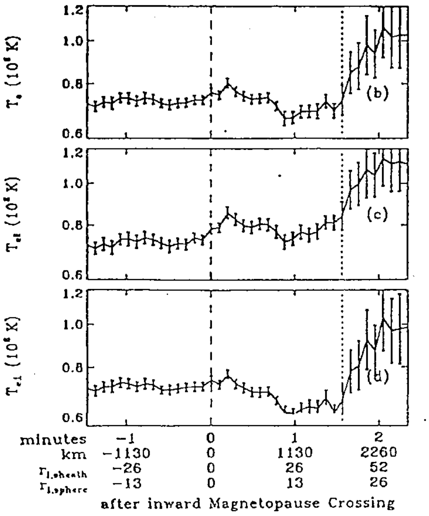

Fig. 3. Superposed epoch analysis for high shear of the parallel and perpendicular electron temperatures, very close to and within the magnetopause (after Fig. 6 in Phan and Paschmann, 1996; the current sheet is between the dashed and dotted lines). The heating and cooling effects are quite apparent in the $T_{e\,||}$ *and* T_{eperp} *curves that are brought about by the induction electric field enhanced by the plasma due to a finite* B*n. This is a pivotal result: it is consistent with an electromotive force needed for tapping magnetic energy.*

Poynting's theorem

The third term *must* be considered for time-dependent interconnection. In the integral form:

$$□ = \oint E.dl = □d□^{M}/dt \qquad (2)$$

where □ is the electromotive force (□^{M} is the magnetic flux through the contour). Energy can be extracted from the magnetic field; the induction electric field acts as the intermediary. The process may be regarded as Bohm diffusion into the low latitude boundary layer, independent of the X-line; there is no theoretical understanding of Bohm diffusion [Chen, 1984, p.190], as yet.

3. PTE model for Substorms and Solar Flares

A similar model is applicable to substorms in the magnetotail, and also for solar flares [Heikkila et al., 2001]; this is a case of spontaneous plasma transfer to a plasmoid traveling downtail (or solar escape).

Particle energization during growth phase

The main particle acceleration mechanism in the plasma sheet is curvature drift with a dawn-dusk electric field [Hines, 1963], leading to the production of auroral arcs. Eventually the curvature becomes so high, locally, that the ions cannot negotiate the sharp turn at the field-reversal region due to their higher mass and energy compared to the electrons [Delcourt and Belmont, 1998]. The ion motion becomes chaotic [Büchner and Zelenyi, 1989], causing a local outward meander in the equatorial plane of the strong cross-tail current that is developed late in the growth phase [Pulkkinen et al., 1991]. From this single assumption (event) follows the entire sequence of events for a substorm.

Induction electric field

An induction electric field is produced by Faraday's and Lenz's laws, $\mathbf{E} = -\partial \mathbf{A}/\partial t$, in a similar fashion to the dayside magnetopause but with different plasma conditions, e.g. initial and boundary conditions. An outward meander on closed field lines will cause **E**x**B** flow everywhere out from the disturbance: the release is explosive! This reaction is a macroscopic instability which we designate the *electromotive instability.* The response of the plasma is by charge separation and a scalar potential, **E** = □□□ . Both types of electric fields have components parallel to **B** in a realistic magnetic field.

Current diversion

Part of the response is the formation of field-aligned currents producing the well-known substorm current diversion [McPherron et al., 1973]. This is a direct result of a strong parallel component of the induction electric field (the cause:

solenoidal voltage difference) needed to overcome the mirror force of the current carriers; this enables charge separation to produce an opposing parallel electrostatic field (the effect: potential difference). Electron precipitation is associated with the westward traveling surge [Baumjohann, 1991; Kauristie et al., 1995] and the downward current on the morning side with -bands [Baumjohann, 1991].

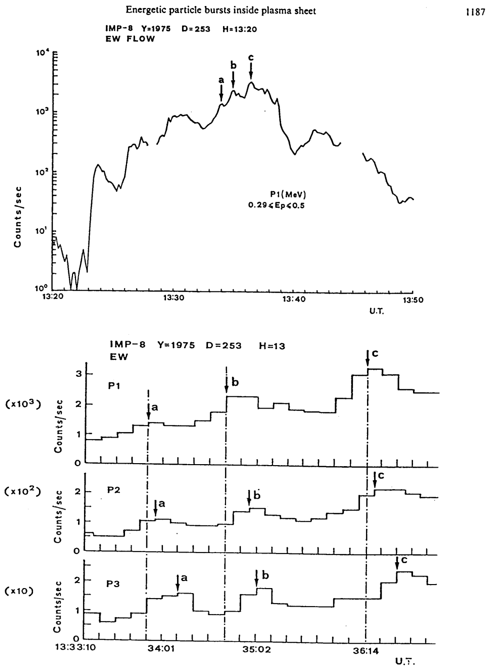

Fig. 4. (top) Measurements of the count rates of energetic protons (290-500 keV) during a long duration burst on day 253, 1975, as observed with IMP-8. (bottom)
Detailed measurements of the proton count rates in 3 channels, P1 (290-500), P2 (500-960), and P3 (960-2000keV), over a much smaller time interval. The counting rates show an inverse time dispersion: the low energy ions arrive first at the satellite before the high, difference of 10 to 20s. This is strong evidence for a sudden increase in the parallel component of the electric field $E_{||}$ at the location of the satellite (some 34 R_E down the magnetotail) with a voltage difference of more that 1 MV. Such a field must have dramatic consequences for the local plasma; this needs to be explored by spacecraft such as Cluster

Rapid acceleration to high energies

Satellite data confirm the reality of a strong parallel electric field in the plasma sheet by counter-streaming electrons and ions [Kirsch et al., 1977] up to several 100 keV. Fig. 4 shows the inverse ion time dispersion [Sarafopoulos and Sarris, 1988] also at high energies. As an example, if a disturbance of diameter of 20R_E (a developing plasmoid) has a rate of change of 1 nT in 1 minute the emf would be 200,000 volts. These two observations would be difficult to explain in any other way.

However, with zero curl, the electrostatic field cannot modify the emf of the induction electric field; the charge separation that produces a reduction of parallel E field must enhance the transverse component. The new plasma flow becomes a switch for access to the free energy of the stressed magnetotail. On the tailward side the dusk-dawn electric field with **E.J** < 0 (a dynamo) will cause tailward motion of the plasma and a plasmoid may be created; it will move in the direction of least magnetic pressure, tailward. On the earthward side the enhanced dawn-dusk induction electric field with **E.J** > 0 (an electrical load) is associated with injection of particles into the inner plasma sheet, repeatedly observed at moderate energies of 1-50 keV [Sauvaud et al., 1999].

This same enhanced 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 MeV energies (by the ratio of magnetic field magnitude) in seconds (minutes) [Bulanov and Sarorov, 1975; Pellinen and Heikkila, 1978].

4. Concluding remarks

Much has been learned about the dayside magnetopause, largely through the observational analysis by Phan and colleagues (some listed in References). The situation on the nightside has not been as rosy: "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" [Vasyliunas, 1998].

I submit that the wrong questions are being asked. Questions formulated in 2-D may seem nonsensical in 3-D. Indeed, the term *magnetic reconnection* was *defined* by Sonnerup [1985, p7] as *any plasma process with a non-zero component E^R tangent to the X-line* (in 2-D). "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 **E.B** = 0 is satisfied everywhere except at the separator." The ability to maintain such a field then becomes a crucial issue; this region has been called the diffusion region, a major stumbling block for reconnection theories. Neither the IP [Lemaire and Roth, 1978, 1991; Lemaire, 1985; personal communication] nor the PTE processes (3-D) [Heikkila, 1982, 1997a, 1998] involve such a field; in both cases the electric field is directly a result of Maxwell's equations.

"At the present moment [1982] it is fair to say that we have very little idea as to what actually happens at the magnetopause [or in the magnetotail]. Surely there is no doubt that there can be changes in the state of interconnection between the geomagnetic field and the interplanetary magnetic field. It is often said that this must imply [magnetic] reconnection. However, there seem to be two meanings of the word 'reconnection', a colloquial [physical] one and a mathematical [modeling] one. With the first, the above statement is a tautology; with the mathematical definition this is by no means so [it depends on the actual model, input conditions, boundary conditions, etc.]" [Heikkila, 1982].

"… The difference is never openly expressed, nor even appreciated. … True reconnection is accomplished only by the electromotive force through which energy can be interchanged with stored magnetic energy" [Heikkila, 1998, p.431].

What is still needed is a one-sentence definition of magnetic reconnection using the E,J paradigm, trying to embody the above remarks. Try this:

A change in the state of interconnection between the magnetic fields of two or more sources can be effected by a current meander of sufficient intensity.

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APPENDIX
Digression on the E,J paradigm

Since the E,J paradigm is not in common use in space plasma physics it is appropriate to discuss it here, however briefly (all textbook material).

The electric field

All vector fields in three dimensions are *uniquely defined* if their source densities (charge) and their circulation densities (perturbation current) are given functions at all points in space being zero at infinity, by Helmholtz's theorem [Panofsky and Phillips, 1962, p2]. The total electric field can be calculated by using potential functions ϕ and **A** as

$$\mathbf{E} = -\nabla\phi - \partial A/\partial t \qquad (3)$$

where the potentials are defined by

$$\phi = \frac{1}{4\pi\varepsilon_0}\iiint_{vol}\frac{\rho\, d\tau}{[r]} \qquad (4)$$

$$\mathbf{A} = \frac{\mu_0}{4\pi}\iiint_{vol}\frac{J\, d\tau}{[r]} \qquad (5)$$

The Coulomb scalar potential ϕ depends on the distribution of charge density ρ, while **A** is the vector potential defined by **A** = ∇ x **B** that depends on the current density **J**. The scalar potential has an arbitrary integration constant, while the vector potential has an undefined divergence $\nabla\cdot$ **A**. Both types of sources produce electric fields with both perpendicular and parallel components in a realistic magnetic field, a *key factor* for plasma physics. For MHD theory to hold the net parallel component must be small ($E_{||}^{ES} \approx - E_{||}^{IND}$); this usually seems to happen because fluid theory (MHD) often does produce correct results (but not always, especially in critical situations).

Equation 3 holds true in general, but various gauge conditions can be used to bring out the physics in various situations by defining a value for div **A**. The Lorentz gauge $\nabla\cdot\mathbf{A} = -1/c^2\,\partial\phi/\partial t$ "has the advantage of introducing complete symmetry between the scalar and vector potentials" [Di Bartolo, 1991, p.164], useful for treating electromagnetic waves. In the Coulomb gauge $\nabla\cdot\mathbf{A} = 0$ "the scalar potential is the instantaneous potential due to the charge density at time t; … the vector potential is expressed in terms of the transverse current $\delta\mathbf{J}_\perp$" [Di Bartolo, 1991, p.167]. The solution for ϕ, $E^{ES} = -\nabla\phi$, is a conservative field, irrotational, depending solely on the instantaneous charge distribution. The solenoidal part of the solution, $E^{IND} = -\partial A/\partial t$ (with retardation), is due to the transverse quasi-static perturbation current $\delta\mathbf{J}_\perp$, one with zero divergence, div $\delta\mathbf{J}_\perp = 0$ [Cragin and Heikkila, 1981]. The potential **A** is not affected by the free charge [Morse and Feshbach, 1953, p212]. The Coulomb gauge provides "for a more complete separation between 'longitudinal' [irrotational] and 'transverse' [solenoidal] fields than any other choice of gauge would allow" [Morse and Feshbach, 1953, 211]. This gauge is natural for plasma physics where it is possible to single out the electromotive force associated with tapping magnetic energy as distinct from the plasma response through charge separation.

There is a need for decomposing the electric field into potential and induction components. Use of the E,J paradigm (quite different from the usual B,V) is the key to solving the intractable problems in magnetospheric physics [Heikkila and Pellinen, 1977; Heikkila et al., 1979].

Applicability of circuit analysis to plasma physics

Jordan and Balmain [1968] had this to say about the derivation of circuit relations from field theory: “The electric circuit laws of Ohm, Faraday, and Kirchhoff were based on experimental observations and antedated the electromagnetic theory of Maxwell and Lorentz. Indeed, that theory was developed as a generalization from the simpler and more re+-stricted laws. It is interesting, but not surprising, then, to find that the circuit relations are just special cases of the more general field relations, and that they may be developed from the latter when suitable approximations are made. Nevertheless, the importance of the simple (and approximate) circuit relations should not be underestimated. With these beautifully simple relations the electrical engineer has been enabled to design and construct electric systems and circuits of amazing intricacy. Without the simplifying assumptions of circuit theory the vast power and communication networks of today would not have been possible, for the exact field solutions to many of the problems would have been of over-whelming complexity.” It goes without saying that similar complications do occur in space plasma physics. As an example, consider a battery connected to a resistor (Fig. 5): circuit analysis immediately yields the result $P_E = VI$. The Poynting flux yields the same result! In either case we *must* include the entire current loop, with both **E.J** < 0 and **E.J** > 0, dynamo and load, cause vs effect. The magnetopause current is closed with the dynamo over the lobes magnetopause; only a 3-D model can bring out this feature. This can be put into a more general form by employing vector identities [Heikkila, 1998].

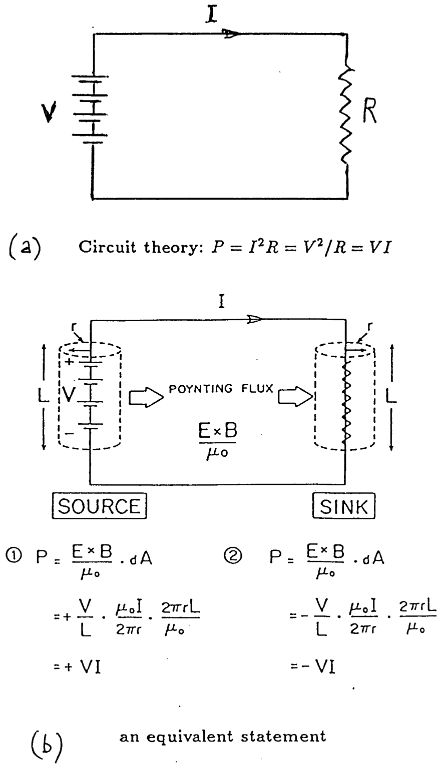

Fig. 5. A simple electric circuit in which a battery provides energy to a load resistor, magnitude VI. An equivalent statement is provided by the Poynting flux ***E*** *x* ***B*** *through a surface enclosing the load! In either case, the source of the dissipated energy is the battery. Similarly, there is a dynamo over the lobe magnetopause that can be the source of the energy dissipated in the dayside magnetopause, such as for the reconnection process. The magnetopause current is closed, with the dynamo over the lobes magnetopause; only a 3-D model can bring out this feature.*

Plonsey and Collin [1961] showed that lumped constant circuit elements C, L, and R can have generalized meaning in space. In terms of the energy stored in the electric field W_E, the magnetic field W_M, and the energy dissipation P_E, they are [Heikkila, 1988]:

$$\text{(a) } C = \frac{II^*}{4\omega^2 W_E} = \frac{4W_E}{VV^*}\,,$$

$$\text{(b) } L = \frac{4W_M}{II^*} = \frac{VV^*}{4\omega^2 W_M}\,,$$

$$\text{(c) } R = \frac{2P_E}{II^*} = \frac{VV^*}{2P_E} \quad (6)$$

where I*, V* are complex conjugates. Rostoker and Boström [1976], among others, have used these ideas showing that C, L and R have values commensurate with the large stored energy in the vast magnetosphere. The circuit approach allows us to do counting, oblivious to the dimensional concerns, related to cause and effect [Ramo and Whinnery, 1953, p207]. The ability of using various network theorems well known in the engineering community, such as superposition and Thevenin's theorems [Lorrain et al., 1988], can be of paramount importance, once it is recognized. If you do not start out by counting, you may never be able to succeed in the thinking exercise that follows the arithmetic.

However, circuit ideas do not replace plasma physics. "It should be said immediately that finding an electric circuit for a plasma problem does not provide for a complete description. Circuit analysis leads to a scalar equation, useful for comprehending energy relationships in a plasma, or cause and effect. Circuit equations are essentially linear; they contain no information about the forces at work in a plasma. Equations of motion are vector relationships that play no part in circuit theory. They do play a part in determining the appropriate circuit, a feat which requires good intuition" [Heikkila, 1988, 1997b].

Applicability of MHD

Applicability of fluid theory of plasma is quite limited at the magnetopause, or during substorms [Heikkila, 1997b]. MHD must use an equation of state to get achieve a complete set; equation of state is essentially a point function, while the plasma can communicate along magnetic field lines bringing information from distant regions [Clemmow and Dougherty, 1969, page 344].

It may be necessary to use the difficult integro-differential equations instead, or particle simulation. We must use these and other methods, even circuit analysis, to see whether the fluid theory of plasmas yields the correct answer to a given problem obeying Newton's laws and Maxwell's equations.

Magnetic Reconnection and Physical Concepts

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Abstract:

This report is an attempt to clarify the physical concepts on which fluid magnetic reconnection is based. It appears that the theoretical structure is not built on a solid foundation. The concept of Magneto-Fluid-Dynamic does not give rise to a unique physical process but leads to different models of magnetic reconnection resulting from the fine-tuning of the Generalized Ohm's law.

1. Introduction

Magnetic reconnection is widely admitted by most space researchers as an important *plasma process* capable of expeditiously converting enormous amounts of magnetic energy to both thermal energy and bulk acceleration of the plasma, and also for changing the global topology of the magnetic field (e.g., *Parnell* [2000]).

A precise *definition* of magnetic reconnection is not easy to give. But do we actually have to define what most space researchers consider as a *physical process*? The term *definition* by itself means that we are looking for an enumeration of characteristics, which helps the mind to construct a mental representation of an abstract object or process. A definition tells us nothing about the *realness* of the object or process we try to characterize (after all we can give a enumeration of characteristics to define a little green man living on Mars). We can however define *physical concepts* on which *physical processes* are based (for instance the physical process of *Joule heating* is based, amongst others, on the physical concept of *energy*). The characteristics of a physical concept confer it a *scale of usefulness*. The physical concepts with the highest scale of usefulness in physics are also the most fundamental ones: mass, space-time, energy, … As the quest for an understanding of the physical world is a difficult task it is not surprising that misleading physical and astronomical concepts were often introduced in science to explain observations of the real world: the erroneous concept of geocentrism dominated astronomy for more than a millennium while the concept of ether did not resist to the accurate observations made by Michelson and Morley in order to measure speed of the ether relative to Earth. Quite often these misleading concepts led to more and more complex models like those developed by Ptolemy to explain the motion of the planets. Ptolemaic astronomy was based on combinations of epicycles whose complexity increased each time a new observation contradicted the predominated model. When these erroneous concepts were abandoned the observations were not only correctly explained but the new models used to describe the underlying physical processes appeared simpler and aesthetically more elegant.

2. The physical concepts on which magnetic reconnection is based

To describe magnetic reconnection as a physical process one should clearly define the physical concepts on which reconnection is based. As there are only a limited number of concepts in physics one should avoid introducing new ones, or at least avoid introducing new ones with a weak value in the scale of usefulness.

Although there exists a kinetic approach to magnetic reconnection (e.g., *Hill* [1975], *Galeev et al.*, [1986]), most of the reconnection models are based on the concept that space plasmas behave like regular fluids and are well described under the Magneto-Fluid-Dynamic approximation. In this approximation the state of the plasma is represented by local macroscopic properties, which depend on position in space **r**, and on time *t*.

Magnetic reconnection also relies on the concept of magnetic field lines. It is useful to recall that field lines were used by Faraday to assist visualization of the magnetic force on small magnets (this is why these lines are sometimes improperly called *magnetic lines of force*). Nowadays field lines are used as a support to visualize the direction and strength of the magnetic field in space *under time independent conditions*. In space plasmas the *mathematical concept of field line motion* relies on its association with a flow field [*Newcomb*, 1958]. The time rate of change of the magnetic flux Φ piercing the closed curve $C(t)$ with local normal **n**, linked to a set of fluid elements moving with the velocity field **u** (which transports $C(t)$) is [*Scudder*, 1997]:

$$\frac{d\Phi}{dt}\Big|_C = -\iint_S \nabla\times(\mathbf{E}+\mathbf{u}\times\mathbf{B})\cdot\mathbf{n}\,dS$$

When the magnetic flux through any circuit "attached" to the fluid and moving with it remains constant in time, the flow field of the fluid is said to be *magnetic flux preserving*. Flow fields $\mathbf{V_1}$ are magnetic flux preserving if:

$$\nabla\times(\mathbf{E}+\mathbf{V_1}\times\mathbf{B}) = 0 \qquad (1)$$

while flow fields $\mathbf{V_2}$ satisfying the more restrictive condition

$$\mathbf{E}+\mathbf{V_2}\times\mathbf{B} = 0 \qquad (2)$$

are said to be *field line preserving*. In flows that are field line preserving fluid elements connected by a field line at some time remain so later on. Flows that are field line preserving are also magnetic flux preserving. Flow fields that are line preserving or only magnetic flux preserving are not necessarily the center of mass flow of the plasma ($\mathbf{U}$). Ideal MHD is a fluid representation of the plasma where the center of mass flow, $\mathbf{U}$, obeys equation (2). In this representation $\mathbf{U}$ is then a type of flow, which is both magnetic flux and magnetic line preserving. In ideal MHD it is possible to ascribe a velocity to the magnetic field lines since the velocity in equation (2) is field line preserving. In the real world the velocity of a magnetic field line can not be unambiguously defined and, therefore *is not a measurable quantity, so that it is, strictly speaking, meaningless to talk about it* (citation from *Newcomb* [1958], page 348).

Equation (2) represents only a portion of the difference between the ion and electron momentum equations. The generalized Ohm's law results from this difference and is obtained in the Magneto-Fluid-Dynamic approximation by treating electrons and protons as two independent fluids with their own number density (n_e and n_i) and own species-velocity ($\mathbf{V_e}$ and $\mathbf{V_i}$). These two fluids are coupled by a friction force equals to $-n_e m_e \nu(\mathbf{V_e}-\mathbf{V_i})$ for the electrons and, by action-reaction, to an opposite force for the ions [*Heyvaerts*, 2000]. Neglecting gravity the equations of motion of electrons (of charge -*e* and mass m_e) and protons (of charge *e* and mass m_i) can be written in the following form:

$$\mathbf{E}+\mathbf{V_e}\times\mathbf{B} = -\frac{\nabla\cdot\mathbf{P_e}}{en_e}$$

$$-\frac{m_e}{en_e}\left[\frac{\partial n_e \mathbf{V_e}}{\partial t} + \nabla\cdot(n_e \mathrm{V_e V_e})\right] + \frac{m_e \eta}{n_e e^2}\mathbf{j} \quad (3)$$

$$\mathbf{E} + \mathbf{V_i}\times\mathbf{B} = +\frac{\nabla\cdot\mathbf{P_i}}{en_i}$$
$$+\frac{m_i}{en_i}\left[\frac{\partial n_i \mathbf{V}_i}{\partial t} + \nabla\cdot(n_i \mathrm{V_i V_i})\right] + \frac{m_e \eta}{n_i e^2}\mathbf{j} \quad (4)$$

where $\mathbf{P_e}$ and $\mathbf{P_i}$ are ordinary pressure tensors, $m_e n_e \mathbf{V_e V_e}$ and $m_i n_i \mathbf{V_i V_i}$ are dynamic-pressure tensors, and $\mathbf{j}$ is the electric current density, $\mathbf{j} = -n_e e(\mathbf{V_e} - \mathbf{V_i})$, in the quasi-neutrality approximation.

The Generalized Ohm's law, which relates the electric field in the plasma to other field and plasma quantities, can be obtained with different levels of approximations (for details see chapter 12 in *Rossi and Olbert* [1970]). An approximate form is obtained by multiplying equation (3) by $-e/m_e$ and equation (4) by e/m_i and subtract. It simplifies in the limit of infinitely heavy protons ($m_e/m_i \to 0$) and in the quasi-neutrality approximation:

$$\mathbf{E} + \mathbf{U}\times\mathbf{B} \approx$$
$$\frac{\mathbf{j}\times\mathbf{B}}{en_e} - \frac{\nabla\cdot\mathbf{P_e}}{en_e} + \frac{m_e}{m_i}\frac{\nabla\cdot\mathbf{P_i}}{en_i} +$$
$$\frac{m_e}{n_e e^2}\left[\frac{\partial\,\mathbf{j}}{\partial\,t} + \nabla\cdot(\mathbf{Uj} + \mathbf{jU})\right] + \frac{m_e \eta}{n_i e^2}\mathbf{j} \quad (5)$$

The last term of the second member of equation (5) can be written to contain the "ordinary" Ohm's conductivity $\sigma = n_i e^2 / m_e \eta$ as $\mathbf{j}/\sigma$. The phenomenological frictional parameter η is usually calculated by the Fokker-Planck method of treating Coulomb collisions in a plasma. This approach is only valid when restricted to large-scale properties of the plasma larger than the Debye length and assumes 1) an infinitesimal smallness of the Coulomb interaction time Δt and, 2) a certain conditional smallness of the velocity changes occurring as a result of collisions in the time interval Δt. Because of the screening effect of the plasma the Coulomb interaction between two particles is actually limited to a range of the order of the Debye length, typically 1 m at the magnetopause, with typical particle velocities of 100 km/s, $\Delta t \approx 10^{-5}$ s, which is small enough in comparison with the various relaxation times of the system. The second condition is equivalent to the neglect of close Coulomb collisions. This condition is also satisfied since multiple scattering in the Coulomb interaction is much more important than single scattering. Besides the ohmic $\mathbf{j}/\sigma$ term there are additional contributions to the momentum exchange between protons and electrons called the thermal force emf that can be present even in the absence of a current density (for details see *Scudder*, [1997], page 251). These contributions are usually ignored.

The Magneto-Fluid concept implies that flow fields satisfying equation (2) describe super-conductor plasmas, in the electric sense of absolute zero resistivity (or infinite conductivity): this is the ideal MHD representation, a limiting case of the usual Ohm's law of MHD ($\mathbf{u}$ being the velocity field of the "fluid"):

$$\mathbf{E} + \mathbf{u}\times\mathbf{B} = \frac{\mathbf{j}}{\sigma} \quad (6)$$

The ideal MHD equation (2) also implies that there is no electric field component along the magnetic field direction. The generalized Ohm's law [equation (5)] shows that the preserving character of magnetic field line and magnetic flux not only requires the neglect of the ordinary ohmic dissipation term ($\mathbf{j}/\sigma$), but also implies that the contributions of the Hall electric field, pressure gradients and inertial terms cancel out. Broadly speaking magnetic reconnection involves loss of the line or flux preserving character of the plasma flow [*Scudder*, 1997] and may occur at places where the magnetized plasma locally develops strong field gradients and associated dissipative MHD motions. In the framework of the Magneto-Fluid-Dynamic magnetic reconnection may appear as a physical process with multiple facets. The physical process may differ from one situation to another depending on which term in the generalized Ohm's law plays the most important role in breaking down the ideal MHD condition. This is a situation quite similar to the Ptolemaic system: an additional epicycle (additional term in the Generalized Ohm's law) is added each time an observation contradicts a predominated model. The excellent review paper by Scudder [*Scudder*, 1997] shows that frequently the approximations made in Ohm's law are more those of convenience than physically justified. Furthermore the breakdown of ideal MHD is not a sufficient condition for magnetic reconnection to occur. For instance ideal MHD is obviously broken along auroral magnetic field lines where parallel pressure gradients and the unbalanced mirror force lead to the formation of parallel electric fields.

3. Open questions

For more than 40 years an extensive research has been made on magnetic reconnection. Despite the tremendous existing amount of literature on the subject many questions remain:

1. Most of the reconnection models assume the existence of a *diffusive region* where ideal MHD breaks down. The physical processes in this region are different for electrons and for ions. The microphysics in this region remains poorly understood.
2. The role of plasma beta is not clearly identified.
3. We know little about the *spark* that ignites magnetic reconnection [*Drake*, 2001]. Many mysteries persist, as for instance, the fact that in solar active regions the magnetic field can remain quiescent for a long time before releasing its energy (it is believed that magnetic reconnection is a universal physical process, therefore occurring also in the solar corona).
4. Does the magnetic shear play a role in the ignition process?
5. Steady-state models of magnetic reconnection at the dayside magnetopause have been developed in a 2-D geometry. They imply a uniform reconnection electric field, $\mathbf{E}$, aligned along a X-type magnetic neutral line, but also along the magnetopause current to allow for the heating and acceleration of the plasma. The question of maintaining such a $\mathbf{E}$-field remains open. Models of 3-D reconnection require the existence of *magnetic neutral points* and are still under debate [*Parnell*, 2000].
6. Transient magnetic reconnection must include the energy input from the time-dependent terms in the energy equation by appealing to Poynting's theorem, where $\mathbf{E} \cdot \mathbf{j}$ describes the net effect on or by the plasma [*Heikkila*, 1998].
7. Models for transient reconnection are still under development.

4. Signatures of magnetic reconnection

It is outside the diffusion region where ideal MHD is believed to hold that, until recently, signatures of magnetic reconnection have been looked for. This inquiry is based on tests to verify the Walén relation for a rotational discontinuity. It is important to note that the identification of a rotational discontinuity (RD) does not necessarily provide evidence for ongoing reconnection. RDs are frequently observed in the solar wind as one of possible MHD discontinuities without resorting to the context of reconnection. Furthermore WIND observations of directional discontinuities (DDs) in the solar wind have shown that DDs with small normal magnetic field can be regarded as the limiting case of tangential discontinuities (TDs) [*De Keyser et al.*, 1998]. Using a kinetic model of TDs [*Roth et al.*, 1996], *De Keyser and Roth* [1997, 1998a, 1998b] have demonstrated that, contrary to the general belief, plasma flows on both sides of a TD are not unconstrained. Indeed these authors have shown that, at the TD magnetopause, not all configurations of magnetic field vectors and magnetosheath velocity allow an equilibrium to exist and that there is a preference for a particular magnetic field rotation sense across the magnetopause. This study has demonstrated a north-south asymmetry of the rotation sense for high magnetic shear TDs: large positive (negative) rotations occurring predominantly in the northern (southern) hemisphere. It is interesting to note that the north-south asymmetry of the rotation sense for high magnetic shear TDs is the same as the one predicted by the electron whistler polarization theory for wide RDs [*Su and Sonnerup*, 1968]. Two other important conclusions of this study are worth emphasizing: the first is a better understanding of satellite observations showing that the magnetopause sometimes is in a TD state even in configurations where one would expect reconnection to occur, for instance in ≈180° magnetic shear cases; the second one is a demonstration that high-speed flows, regarded as the signature of magnetic reconnection, are also required for high magnetic shear TD equilibria.

5. Conclusions

When trying to clarify the physical concepts on which magnetic reconnection are based it appears that Magneto-Fluid-Dynamic is not the best framework for studying reconnection. One can attribute to this concept a weak *scale of usefulness* that may invalidate the whole theoretical structure. Fluid description of magnetic reconnection is like the Ptolemaic system where one hopelessly tries to fine-tune the Generalized Ohm's law to correctly explain puzzling observations. Space researchers have often disregarded early laboratory experiments showing that plasma streams injected perpendicularly to a magnetic field can cross the field by setting up a polarization electric field (e.g., *Baker and Hammel* [1965]). This polarization effect was explained theoretically by *Schmidt* [1960]. Schmidt's work is the basis of the model of impulsive penetration (IP) introduced by *Lemaire and Roth* [1978] and ultimately developed by *Lemaire* [1985]. Isolated magnetosheath-like plasma blobs have been observed in the boundary layer but a definitive experimental confirmation of the IP scenario requires at least two satellites. Favorable configurations of Cluster satellites could happen where the trajectory of the penetrating plasma blob would be "recorded" using a method developed by *De Keyser et al.* [2002].

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Challenge to the Traditional Magnetic Reconnection Hypothesis

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Abstract:

We suggest that there is an urgent need in magnetospheric physics to break the habit of using the quasi-steady reconnection hypothesis and to establish instead a three-dimensional and dynamical description for realistic physical processes occurring in active plasma regions. Nonlinear interactions of MHD wave packets and between MHD wave packets and the current sheets are proposed to be key physical processes occurring in active plasma regions. The nonlinear MHD wave mode conversion at a current sheet can be considered to be a model for three-dimensional Alfvénic reconnection. Such a new paradigm, involving the concept of wave-particle duality, may bridge the gap between cosmic plasma physics and modern physics.

1. Introduction

The discovery of quantum mechanics is one of the most important achievements of modern physics in the twentieth century, leading to progress and expansion in many areas of physics and technology. It has long since become manifest that the fundamental physical concepts in modern physics such as wave-particle duality must also pervade cosmic plasma physics (e.g., *Alfvén*, 1977; 1981).

The importance of replacing the classical paradigm with a new one capable of explaining novel complex plasma processes in the active plasma region has been repeatedly emphasized (e.g., *Alfvén*, 1977; 1981; *Fälthammar*, 1990, 1997).

Unlike passive plasmas, which carry little or no current and behave nearly classically, active plasmas carry a large current and involve strong localized and time-dependent plasma interactions (e.g., *Alfvén*, 1981; *Fälthammar*, 1997). Active plasmas are characterized by inhomogeneity in space, variability in time, and strong electric fields, including field-aligned electric fields (*Fälthammar*, 1997). The magnetopause and magnetotail current sheets and the auroral acceleration region are examples of active plasma regions (e.g., *Alfvén*, 1981).

Over the last forty years, most commonly accepted theoretical models of the solar wind-magnetosphere interaction are quasi-static, where time dependence is not emphasized (e.g., *Song and Lysak*, 2000, 2001 a,b). The classical standard magnetic reconnection (SMR) hypothesis (e.g., *Dungey*, 1961, Fig. 1a) is one typical example, only describing a large scale and quasi-steady process for a specific configuration (e.g., Fig. 1b). Despite its inability to account for the three-dimensional dynamical process occurring in the current sheets, the reconnection hypothesis has been broadly accepted as the leading theory and a popular framework for solar wind-magnetospheric interaction. The habit to use the quasi-steady reconnection hypothesis in dynamical cases seriously impedes the understanding of the solar wind-magnetosphere interaction and hinders the development of space physics in the context of modern physics.

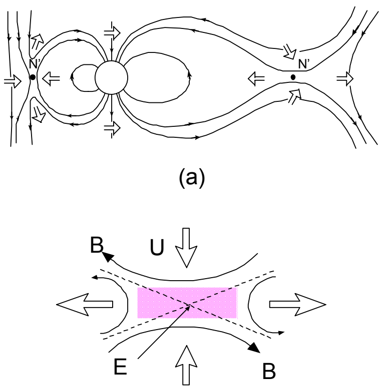

Fig. 1: (a) Dungey's reconnection model (after Dungey, 1961); (b) Schematic of standard reconnection (SMR) model.

The SMR hypothesis has been questioned and challenged by many scientists in the last few decades (e.g., *Alfvén*, 1977, 1981, 1983; *Lemaire*, 1977; *Lemaire and Roth* 1978; *Heikkila*, 1982, 1990; *Sonnerup*, 1984; *Akasofu*, 1985, 1998; *Schindler et al.*, 1988; *Song*, 1988, 1998; *Lundin*, 1989; *Sibeck et al.,* 1989; *Fälthammar*, 1990; *Lui*, 1991; *Woch and Lundin*, 1992; *Phan et al.,* 1994; *Song and Lysak*, 1994, 1995, 2001b; *Haerendel*, 1996; *Rostoker*, 1999). These challenges have enhanced our understanding of dynamical processes in active plasma regions.

We propose that the nonlinear interactions between (i) fast mode wave packets and the current sheets on the magnetopause and in the tail, and (ii) the incident and reflected shear Alfvén wave packets in the auroral acceleration region, are often the key physical processes occurring in these active plasma regions. These interactions may cause the localized breakdown of the frozen-in condition, allowing a further nonlinear MHD wave mode conversion (NWMC) to occur. The generation of a parallel electric field during NWMC may lead to the acceleration of charged particles and the formation of charge holes.

2. From the SMR hypothesis to the general magnetic reconnection (GMR) model

The SMR hypothesis (e.g., *Dungey*, 1961) asserts that the solar wind–magnetospheric interaction is not purely hydrodynamic, but also hydromagnetic; moreover, it emphasizes the importance of the break-down of the frozen-in condition in magnetospheric physics. The SMR model approximates an average qualitative description for many IMF controlled effects, such as the strong dependence of the geomagnetic activity on the IMF B_z component.

Despite the qualitative success of the SMR, there has been a lack of critical and careful examination of the fundamental theory based on observational facts. During the past few decades, many crucial observations of physical processes occurring in active magnetospheric plasma regions conflict with the SMR hypothesis, causing numerous controversies (e.g., *Alfvén*, 1977, 1981, 1983; *Lemaire*, 1977; *Lemaire and Roth* 1978; *Heikkila*, 1982, 1990; *Sonnerup*, 1984; *Akasofu*, 1985, 1998; *Schindler et al.*, 1988; *Song*, 1988, 1998; *Lundin*, 1989; *Sibeck et al.,* 1989; *Fälthammar*, 1990; *Lui*, 1991; *Woch and Lundin*, 1992; *Phan et al.,* 1994; *Song and Lysak*, 1994, 1995, 2001b; *Haerendel*, 1996; *Rostoker*, 1999). These issues are often ignored or overlooked (*Akasofu*, 1998), as their resolution inevitably requires a drastic paradigm shift. It is often difficult to challenge a "generally accepted" model, especially when offering alternative explications for previously explained physical phenomena.

It is obvious that the oversimplified SMR hypothesis describes only a quasi-steady state in a specific configuration, and is unable to provide a comprehensive description for a three-dimensional, time-dependent and localized dynamical process.

The GMR concept was proposed (e.g., *Axford*, 1984) and discussed in depth (e.g., *Schindler et al*. 1988; *Hesse and Schindler*, 1988), accounting for time-dependent and 3D phenomena not included in the SMR model. Although the GMR refers only to the localized breakdown of the "frozen-in" condition, the physical processes associated with a localized non-ideality could be numerous, where characteristics of plasma flows, changes in the magnetic structure, and the energy conversion after break down of the frozen-in condition differ.

It became evident in the course of the development of the SMR into the more realistic GMR that the scope of the reconnection concept to date is limited to the localized non-ideality. Neither SMR nor GMR elucidate the major dynamical processes occurring at the current sheets at the magnetopause or in the tail. The important task is then to understand the physical nature of the dynamical processes occurring at the current sheets.

3. From the quasi-steady models to dynamical treatment

3.1 Previous theories

Traditional theories of the SMR and the generation of the field-aligned current ($J_{||}$) and parallel electric field ($E_{||}$) are based on a convection picture that describes mainly large-scale, quasi-steady state phenomena (e.g., *Song and Lysak*, 1995).

Theoretically, a steady or quasi-steady description does not indicate cause and effect (e.g., *Song and Lysak*, 2001b). For example, noting that $\mathbf{E} = -\mathbf{u} \times \mathbf{B}/c$ does not mean "**E** causes **u**" or "**u** causes **E**" (see also *Parker*, 1996). The equation $B\partial(J_P/B)/\partial s \approx -\nabla_\perp \cdot (c\mathbf{B} \times \nabla P/B^2)$ does not imply "∇P generates $J_{||}$," since it does not describe the dynamics that produces the pressure gradient as well as $J_{||}$ in the first place.

The critical issue in the study of reconnection has been to find the mechanism to break down the frozen-in condition, often requiring existence of a parallel electric field (e.g., *Sonnerup et al.*, 1984; *Schindler et al.*, 1988). The mechanism has been recently emphasized by analyzing the generalized Ohm's law (e.g., *Drake*, 1995).

$$\mathbf{E} = \frac{4\pi}{\omega_{pe}^2}\frac{d\mathbf{J}}{dt} - \frac{(\mathbf{u}_i \times \mathbf{B})}{c} + \frac{\mathbf{J} \times \mathbf{B}}{nec} - \frac{\nabla \cdot \mathbf{P}_e}{ne} + \eta^* \mathbf{J} \tag{1}$$

where $\omega_{pe}^2 = 4\pi ne^2/m_e$, and $\eta^* = 4\pi\nu^*/\omega_{pe}^2$ are assumed. Here ν^* represents an average collision frequency between the electrons and the ions due to fluctuating fields and waves. If $J_{||} \approx -neu_e$ is assumed, the parallel component of the equation (1) is

$$E_{||} \approx \frac{4\pi}{\omega_{pe}^2}\frac{dJ_{||}}{dt} + \eta^* J_{||} - \frac{1}{ne}(\nabla \cdot \mathbf{P}_e)_{||} \tag{2}$$

Equation (2) is the momentum equation for the electrons in the parallel direction, which describes the $J_{||}$ generation. It can be rewritten as

$$\frac{dJ_{||}}{dt} \approx \frac{ne^2}{m_e}E_{||} - \nu_{ei}J_{||} + \frac{e}{m_e}\nabla_{||}P_e \tag{3}$$

From the generalized Ohm's law (Equation (2)), the generation of $E_{||}$ has often been considered as the result of the existence of anomalous resistivity ($E_{||} \approx \eta^* J_{||} \neq 0$), or the result of non-ideal effects, such as electron inertia ($E_{||} \approx (4\pi/\omega_{pe}^2)(dJ_{||}/dt)$) or electron pressure tensor ($E_{||} \approx -(\nabla \cdot \mathbf{P}_e)_{||}/ne \neq 0$). In fact, neither $E_{||} \approx \eta^* J_{||} \neq 0$ nor $E_{||} \approx -(\nabla \cdot \mathbf{P}_e)_{||}/ne \neq 0$ describes any causal relation, i.e., one cannot say "$\eta^* J_{||}$ or $-(\nabla \cdot \mathbf{P}_e)_{||}/n$ causes $E_{||}$" or vice versa. The generalized Ohm's law does not discuss what causes or generates $E_{||}$, i.e., $\partial E_{||}/\partial t$ (*Song and Lysak*, 2000a). The expression

$E_{\|} \approx \left(4\pi/\omega_{pe}^2\right)\left(dJ_{\|}/dt\right)$ describes only the generation of $J_{\|}$.

It must be emphasized that locally breaking the frozen-in condition is often a part of a three-dimensional dynamical process; therefore, it cannot be understood by analyzing only the generalized Ohm's law. A set of complete equations including Maxwell's equations and Newton's law for the ions and electrons is needed to understand the dynamical process (*Song and Lysak*, 2001b, see, section 3.2 in this paper).

Previous theories of $J_{\|}$ generation (e.g., *Hasegawa and Sato*, 1979; *Vasyliunas*, 1984) do not describe the dynamical processes that produce the $J_{\|}$ in time, i.e., $\partial J_{\|}/\partial t$ and the mechanisms that drag the vortex convection. The irreversible generation of the $J_{\|}$ filaments related to a localized breakdown of the frozen-in condition is excluded from the previous theories (e.g., *Song and Lysak*, 1995; *Song*, 1998).

In the quasi-steady models, the transfer of mass, momentum and energy from the solar wind into the magnetosphere often depends on either an ideal discontinuity assumption (e.g., *Lee and Roederer*, 1982; *Lee and Akasofu*, 1989) or dissipative terms, such as an anomalous bulk viscosity ν^*, an anomalous bulk resistivity η^* or some non-MHD terms related to the electron dynamics (e.g., *Drake*, 1995). These models describe basically passive physical processes, where transport properties are dissipative.

3.2 Time-dependent equations

The equation that describes the evolution of $E_{\|}$ is Ampere's law including the displacement current term, even though the magnitude of this term is often small (*Song and Lysak*, 2000a). However, discarding this term, we could not discuss how to generate and maintain parallel electric fields. From Ampere's law, we have

$$\frac{1}{4\pi}\frac{\partial E_{\|}}{\partial t} = \frac{c}{4\pi}\left(\nabla \times \mathbf{B}\right)_{\|} - J_{\|} \qquad (4)$$

From Equation (4) and the curl of Faraday's law, the generation of the total parallel current including the displacement current $J'_{\|} = J_{\|} + (1/4\pi)\partial E_{\mathrm{P}}/\partial t$ can be obtained as

$$\frac{\partial J'_{\|}}{\partial t} = -\frac{c^2}{4\pi}\nabla_{\|}\left(\nabla_{\perp}\cdot\mathbf{E}_{\perp}\right) + \frac{c^2}{4\pi}\nabla_{\perp}^2 E_{\|} \qquad (5)$$

The relationship between the total parallel current $J'_{\|}$ and perpendicular currents $\mathbf{J}'_{\perp} = \mathbf{J}_{\perp} + \left(1/4\pi\right)\partial\mathbf{E}_{\perp}/\partial t$ can be given by Gauss's law $\nabla\cdot\mathbf{E} = 4\pi\rho_e$ and the charge conservation equation $\partial\rho_e/\partial t + \nabla\cdot\mathbf{J} = 0$, i.e., $\partial J'_{\|}/\partial z = -\nabla_{\perp}\cdot\mathbf{J}'_{\perp}$. By using Newton's law and Maxwell's equations in the perpendicular directions, we obtain

$$\frac{\partial J'_{\|}}{\partial z} = -\frac{\varepsilon}{4\pi}\frac{d\left(\nabla_{\perp}\cdot\mathbf{E}_{\perp}\right)}{dt} - \nabla_{\perp}\cdot\left(\mathbf{J}_{\perp dia} + \mathbf{J}_{\perp vis}\right) \qquad (6)$$

where $\varepsilon = 1 + c^2/V_A^2$ is the perpendicular dielectric constant, $\mathbf{J}_{\perp dia} = (c\hat{\mathbf{b}}\times\nabla_{\perp}P)/B$ is the diamagnetic current and $\mathbf{J}_{\perp vis} = \rho\nu\nabla^2\mathbf{u}\times\hat{\mathbf{b}}/B$ is the viscous current. Equations (5) and (6) couple the dynamics of the system in the parallel direction to the perpendicular dynamics. The temporal and spatial derivatives of the parallel total current are related to $\partial\left(\nabla_{\perp}\cdot\mathbf{E}_{\perp}\right)/\partial z$ and $d\left(\nabla_{\perp}\cdot\mathbf{E}_{\perp}\right)/dt$, respectively. If we assume for simplicity that $\mathbf{u}_{\perp}\cdot\mathbf{J}_{\perp} \approx 0$, then $\nabla_{\perp}\cdot\mathbf{E}_{\perp} \approx -\left(B/c\right)\Omega_{\|}$, where $\Omega_{\|} = \left(\nabla\times\mathbf{u}\right)_{\|}$ is the parallel vorticity. Equations (5) and (6) can then be re-written as

$$\frac{\partial\left(J_{\|} + \left(1/4\pi\right)\left(\partial E_{\|}/\partial t\right)\right)}{\partial t} + \frac{c^2 k_{\perp}^2}{\omega_{pe}^2}\frac{\partial J_{\|}}{\partial t} \approx \frac{cB}{4\pi}\frac{\partial\Omega_{\|}}{\partial z}$$

(7)

$$\frac{\partial\left(J_{\|}+(1/4\pi)\left(\partial E_{\|}/\partial t\right)\right)}{\partial z}\approx\frac{\varepsilon B}{4\pi c}\frac{d\Omega_{\rm P}}{dt} \qquad (8)$$

where, again for simplicity, $\nabla_{\perp}\cdot\left(\mathbf{J}_{\perp dia}+\mathbf{J}_{\perp vis}\right)\approx 0$ is assumed. Equations (7) and (8) show that $\partial J'_{\|}/\partial t$ and $\partial J'_{\|}/\partial z$ are related to the spatial and temporal changes of the field-aligned vorticity ($\Omega_{\|}$). The generation of $E_{\|}$ or parallel potential drop ($V_{\|}$) can be analyzed by using the integrated forms of the equations (7) and (8), as well as by evaluating the ratio between $(1/4\pi)\partial E_{\|}/\partial t$ and $J_{\|}$ (*Song and Lysak*, 2000a).

In the following section, we describe a possible dynamical process that causes the generation of $J_{\|}$, $E_{\|}$ and the localized breakdown of the frozen-in condition.

4. MHD wave packet hypothesis and the physics in active plasmas

The MHD wave packet hypothesis was stimulated by the similarity between hydromagnetic waves and electromagnetic waves (*Song and Lysak*, 1994). Hydromagnetic waves can be considered to be an example of electromagnetic waves in a dielectric medium with a perpendicular dielectric constant given by $\varepsilon=1+c^2/V_A^2$ (*Alfvén*, 1942; *Alfvén and Fälthammar*, 1963). The intrinsic consistence of physical laws implies that a wave packet with particle-like properties may be associated with the MHD waves (*Song and Lysak*, 1994, 2000). The importance of wave-particle duality in cosmic plasma has been emphasized by *Alfvén* (1977).

In the past decades, the properties of MHD wave propagation have been well studied. However, the crucial properties to understand, in studying the nonlinear interaction between MHD wave packets, are the particle aspects of the waves, e.g., magnetic moment, angular momentum, and magnetic twist carried by MHD wave packets.

The structure of these MHD wave packets has been derived from the linearized MHD equations in the cold plasma approximation (*Song and Lysak*, 1994), but the generalization to a finite-β plasma is straightforward. The fields in these wave packets can be expressed as oscillator variables, which are conserved in the purely linear propagation of the waves and illustrate the structure of the localized wave packet corresponding to that wave mode. These electromagnetic "blobs" (wave packets) consist of (i) for the shear mode, loops of magnetic field and velocity field linked with filaments of $J_{\|}$ and vorticity for the shear wave packets; and (ii) for the compressional fast mode, current and vorticity loops with a compressional flow linked to a dipolar magnetic field and velocity flow. The consequence of the nonlinear interaction between the fast mode wave packet and the current sheet or between the shear Alfvén wave packets can be discussed by considering approximate conservation of the magnetic helicity (e.g., *Berger*, 1984) and angular momentum. A localized breakdown of the frozen-in condition is a necessary condition to allow a change in the linkage properties of the wave packets.

Fig. 2 shows a schematic picture of the magnetosphere indicating the active plasma regions where the dynamics of MHD wave packets is important. The fast mode wave, which carries energy and momentum across magnetic field lines, can be excited by an imbalance of forces across the magnetic field, e.g., a northward turning of the IMF. Fast mode wave packets will impinge on the current sheet before the large scale plasma flows and the associated convection electric field physically arrive at the current sheet.

The interaction between the fast mode wave packet and the current sheet can be considered to be the interaction between two compressional wave packets (Fig. 2a). Since a plasma attempts to evolve to a lower energy state while conserving the helicity (e.g., *Berger*, 1984; *Berger and Field*, 1984; *Taylor*, 1986; *Moffatt*, 1969), compressional wave packets tend to convert into shear Alfvén wave packets by twisting the magnetic field lines. The twisted magnetic structure radiates away as Alfvén waves carrying $J_{||}$ filaments (e.g., *Song and Lysak*, 1994; *Song*, 1998).

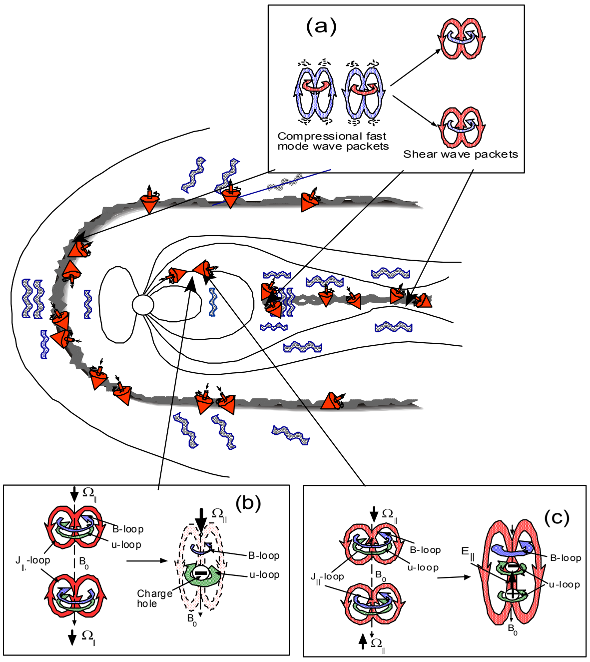

Fig. 2. Schematic description illustrating physical processes occurring in active magnetospheric regions. MHD wave propagation and the interaction between wave packets and the current sheet overlap on the large-scale convection picture. The small tops (in red) represent the shear Alfvén wave packets carrying $J_{||}$ filaments, which are generated by the interaction between the compressional fast mode wave packets (in blue) and the current sheets (Fig. 2a). The arrows of the small tops schematically represent the directions of the $J_{||}$ filaments carried by the shear wave packets. In the auroral particle acceleration region, the interaction between two small tops represent the interaction of incident and reflected shear Alfvén wave packets. Fig. 2b (2c) is for the case when the electric fields (the currents) of the reflected wave and the incident wave have the same direction, but their currents (the electric fields) have the opposite direction.

The impinging of fast mode wave packets on the current sheet can be described as the interaction between two adjacent flux tubes (Fig. 3a) or the interaction between current loops (Fig. 3b) on both sides of the boundary layer (e.g., the magnetopause). When two magnetic flux tubes having a relative velocity and carrying different magnetic fields interact ($t = t_0$ in Fig. 3a), the relative kinetic energy is converted into electromagnetic energy in the form of the inertial current filaments surrounding the two flux tubes. The current density in the small regions between neighboring loops of magnetic field becomes high and the current sheet becomes thin locally; thus, the breakdown of the frozen-in condition may occur. In particular, a large magnetic shear, a high kinetic energy carried by the compressional wave packet and the low plasma β would favor the onset of the localized non-ideality.

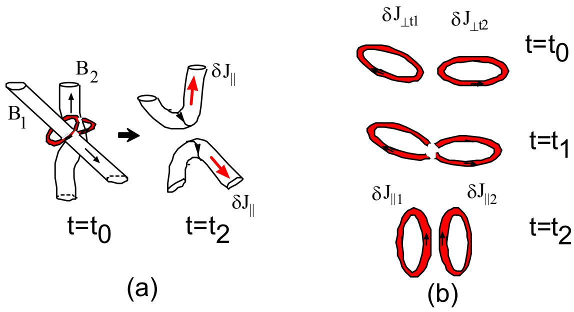

Fig. 3. The generation of local reconnection-related $J_{||}$ filaments is schematically illustrated as the results of the interaction of (a) two magnetic flux tubes or (b) two current loops.

The non-linear interaction between the incident and reflected Alfvén wave packets in the auroral particle acceleration region is also time-dependent and localized. This interaction process can convert magnetic energy into kinetic energy to generate a charge condensation (or a charge hole) (Fig. 2b), or convert the kinetic energy into electromagnetic energy to generate and support a parallel electric field (Fig. 2c), where the localized breakdown of the frozen-in condition is necessary. A detailed description of the wave packet interaction has been given in previous papers (e.g., *Song and Lysak*, 1994, 1995, 2000, 2001a; *Song*, 1998).

5. Breaking down of the frozen-in condition locally and reconnection rate

In the NWMC, space is divided into three regions (Fig. 4a): (A) small localized non-ideal regions marked by the red squares within the pink shaded region; (B) the NWMC regions (the pink shaded region in 4a and 4b); (C) the convection region, which is the large scale passive plasma region where the frozen-in condition is dominant. Ohm's law for the small regions A is $\delta_S \mathbf{E} = \delta_S \mathbf{R} \neq 0$, where $\delta_S \mathbf{R}$ represents a non-ideal term in small regions, which may be caused by, e.g., electron dynamics or kinetic effects. The fast "diffusion" in the region A serves only to release the topological constraints and to allow the NWMC and the radiation of shear Alfvén waves in region B to occur. The reconnection rate is related to the large scale, time-averaged electric field, which depends on the entry of the time-averaged magnetic flux $<\delta\Phi_B>$ into the interaction region (region B in Fig. 4a). If the length scale of the interaction region is L, the averaged **E**-field is $\mathbf{E}{=}<\delta\mathbf{E}>\approx -(1/c)\left(<\delta\Phi_B>/L(\Delta t)\right)$. During the NWMC, shear Alfvén waves are generated by twisting the magnetic flux tubes. The generation of electric field is related to the spatial and temporal changes of the field-aligned vorticity $\Omega_{\|}$ during the NWMC as seen in Equations (7) and (8).

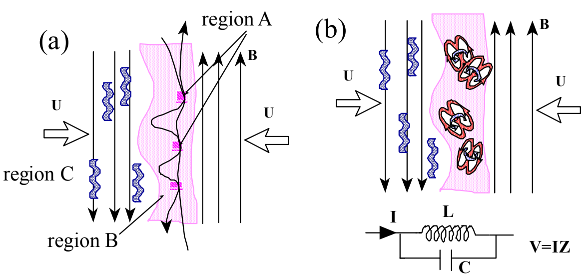

Fig. 4. (a) Schematic diagram illustrating physical processes occurring in different spatial regions during the NWMC. The regions A marked by the red squares are the fast "diffusion" region. The pink shaded region B is the NWMC region, and region C is the convection region (after Song and Lysak, 1994). (b) Circuit analogy of Ohm's law related to the generation of shear Alfvén wave packets, which form L/C loops corresponding to an impedance transport process.

6. MHD wave packet dynamics vs. SMR model

The physical processes described by the SMR model and by the MHD wave packet interaction model are very different. The former describes a convection-related passive physical process and the latter describes a three-dimensional Alfvénic dynamical process. The main differences between the two models can be briefly summarized as follows (see, *Song and Lysak*, 2001b). A more complete description will be given in future publications.

- ***Location of non-ideality sites*:**

In the SMR model, reconnection occurs around a neutral line, where magnetic fields have anti-parallel components. In the NWMC model, the interaction between fast mode wave packets and the current sheets occurs, not around a line, but over multiple-regions, where the threshold condition for localized breakdown of the frozen-in condition is satisfied. For example, breakdown of the localized frozen-in condition could occur in most part of the tail current sheet or the dayside magnetopause current sheet (see, Fig. 2). Localized non-ideality can occur even when there is no large-scale convection, or even in closed field regions.

- ***Local non-ideality, the erosion of the current sheet, and plasma reconfiguration***

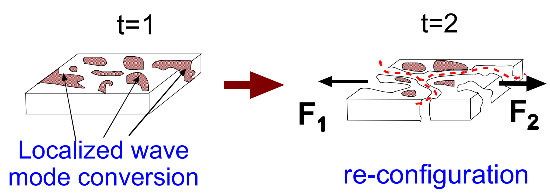

Fig. 5. Schematic description of local breakdown of the frozen-in condition and the erosion of the current sheet at t=1, and the reconfiguration of the current sheet at t=2.

In the NWMC, the local breakdown of the frozen-in condition, the erosion of the current sheet, and the reconfiguration of the magnetofluid are three distinct physical processes in space and time, although they are mutually related (Fig. 5) (*Song*, 1998). The NWMC associated with the localized non-ideality can occur over multiple regions of the current sheet, causing current sheet erosion (the regions in brown in Fig. 5). The reconfiguration of the current sheets is initiated by this collapse of the current sheet, but its subsequent evolution, i.e., characteristics of the plasma flow and the magnetic structure, depends on the resultant total force due to external conditions and interrelated plasma processes. For example, plasma flows could be in different directions on different sides of the red dashed curve in Fig. 5. But, the breakdown of the frozen-in condition does not occur only on this line.

- ***Driven nature:***

The threshold for the occurrence of NWMC is more directly associated with a strong current density and the kinetic energy carried by fast mode wave packets than with an antiparallel magnetic field topology. For example, at the magnetopause current sheet, the current density depends on external parameters, such as the IMF, solar wind dynamical pressure and plasma β.

Fast mode wave packets can be produced at the magnetopause by a force imbalance caused by a change in the IMF, e.g., a northward turning of the IMF, or a change in the dynamical pressure. In the tail, the substorm expansion onset may be caused by the interaction between fast mode wave packets and the near-Earth current sheet. These fast mode wave packets may either be transported from the magnetopause through the lobes, or may come from a force imbalance of the near-Earth current sheet due to a change of the magnetic topology in the tail.

The NWMC is thus a directly driven interaction process, controlled more by the external conditions than by the local dissipation processes.

- ***Energy conversion***

In the SMR model, the Poynting flux of electromagnetic energy flowing into the reconnection region is mainly balanced by the Joule heating and bulk kinetic energy of plasma flow. The NWMC process is a current dynamo process (*Song and Lysak*, 1989, 1992) that is related to the generation of $J_{\|}$ filaments, the radiation of shear Alfvén waves and the generation of $E_{\|}$. The generation of $E_{\|}$ becomes significant, for example, in low density cases (*Song and Lysak*, 2000a), where charged particles can be accelerated along field lines. The generation of Alfvén wave packets show an analogy to an AC circuit with inductors L and capacitors C. The energy balance in the interaction region becomes

$$
\begin{aligned}
&-\int\left(\frac{\rho U^2\mathbf{u}}{2}+\frac{c(\mathbf{E}\times\mathbf{B})}{4\pi}\right)\cdot d\mathbf{S} \\
&\approx\int\left(\frac{\mathbf{J}^2}{\sigma}+\frac{(\mathbf{J}\times\mathbf{B})\cdot\mathbf{U}}{c}\right)dV+\frac{\partial}{\partial t}\sum\delta W_{e-m}
\end{aligned}
\tag{9}
$$

where the last term on the right-hand side of the equation is the E-M energy associated with the shear Alfvén wave packet, including the kinetic energy carried by accelerated charged particles.

7. Discussion

The most standard reconnection model describes large scale, quasi-steady processes occurring in a specific configuration. The model emphasizes plasma convection as the main mechanism for plasma and magnetic transport through the magnetosphere. However, in active plasma regions, MHD wave packet dynamics becomes crucial. For example, during the impinging of fast mode wave packets on the current sheets at the magnetopause and in the tail, fast mode wave packets can be nonlinearly converted into shear Alfvén wave packets. This NWMC process is excluded from the SMR model, even when the effect of the electron dynamics or plasma kinetic theory are included in the model with a two-dimensional current sheet.

The NWMC processes occur commonly in active plasma regions. They play a key role in causing localized and time-dependent non-ideality, radiating shear Alfvén waves carrying $J_{||}$, generating $E_{||}$ and $V_{||}$, forming charge holes and causing charged-particle acceleration to high energy, and producing plasma heating.

At the magnetopause, this NWMC, as well as the transmission and reflection of the fast mode wave provides the mechanism, not only for transferring the mass, momentum and energy, but also for transferring angular momentum and rotational energy carried by the shear Alfvén wave packets.

The NWMC process can be considered to be a three-dimensional Alfvénic reconnection. However, the NWMC process is much different from the SMR process and includes more substantial contents. The MHD wave packet interaction model contributes to a much needed paradigm shift in the theoretical understanding of the physical processes occurring in active plasma regions.

The MHD wave packet hypothesis is able to account for a wider range of phenomena occurring in active plasma regions. Further detailed examinations of the MHD wave packet hypothesis are necessary to understand the nature of physical processes occurring in active plasma regions.

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Distinguishing the Reconnection from the Other Plasma Injection Phenomena across the Separatorix

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Abstract:

Various mechanisms of solar wind (SW) injection to the magnetosphere are reviewed from a reconnection viewpoint and a non-reconnection viewpoint. While the former is strongly related to the magnetospheric view with field line, the latter raises a new view using the equi-strength (equi-|B|) line of the magnetic field. Since the vector information completes only by both its strength and direction, both views are necessary to distinguish one mechanism from the other mechanisms. Classification of the different physical mechanisms inherently requires the examination of the causality chain, which is rooted to the very basic laws of physics by, e.g., Newton, Faraday, Ampere and Thermodynamics. Although one does not have to worry the causality in solving the closed set of ideal MHD, plasma injection takes place where ideal MHD is violated, and it is wise to go back to the original causality chain in non-ideal cases. The causality relations of the frozen-in condition are examined by introducing the new equal sign "/=" which keeps the physical causality instead of "=". Applying the dayside mechanisms of plasma flow across the separatrix to the magnetotail phenomena, it is suggested that the triggering mechanism of the sporadic energy release in the nightside such as the plasmoid formation (or formation of the x-line) is not necessarily unique, and that the sporadic energy release can even be the result of the plasma injection from the tail lobe to the plasma sheet.

1. Introduction

To understand reconnection, it is important to distinguish it from other plasma phenomena which are superficially similar to reconnection. In other words, we must understand the physical differences of various mass/momentum transfer mechanisms, rather than claiming that all of them are caused by a single phenomenon — reconnection.

After Woch and Lundin [1991, 1992] first reported the transient magnetosheath plasma penetrations into the dayside CPS [Winningham et al., 1975] based on Viking observations, various types of direct solar wind (SW) injections into the dayside CPS have been reported [Potemra et al., 1992; Yamauchi et al., 1993; Sandahl et al., 1997; Stenuit et al., 2001]. Solely for the Viking observation, we found quite a variety of bulk plasma transfer phenomena from the magnetosheath to the inner magnetosphere [Yamauchi et al., 2003]. Most of these events are transient ones through a limited but finite area of dayside magnetopause within a very short time. The variety of the injection signatures indicates that mechanisms responsible for these injections are also various, and a simple classification as reconnection does not give any insights into the physics of these phenomena although they are all classified as morphological reconnection, i.e., bulk plasma passing across the separatorix of the magnetopause. The variety of the injection forms is also found in the cusp region [Yamauchi and Lundin, 1994, 2001], and hence it is important to list as many models as possible, although very conceptional, that can deal with such non-ideal behaviour of plasma.

To understand the various mechanisms, it is useful to list the necessary or sufficient conditions for plasma injections in each mechanism. Here, condition means a set of all physical parameters. For example when we draw the magnetic field, we draw only the field lines (this means the magnetic field direction). This is not enough to describe the magnetic field condition because such drawings do not give the strength information explicitly and because the vector information can only be completed with direction and strength. Then the obvious question is why do we not draw equi-strength (equi-|B|) lines of the magnetic field or magnetic pressure? We always need both views in illustrating the magnetospheric boundary configuration. The difference between these two views is directly related to an argument for reconnection: which of the x-type configuration or the vanishing magnetic field is more important?

One more point I discuss in this paper is the causality chain of the reconnection and the other mechanisms. Although one need not care about the cause and effect terms when we solve the closed set of MHD equations, the reconnection and other important plasma phenomena mentioned above appear as the break down of the ideal MHD. Then one must be careful in describing the causality chain of these phenomena because the basic laws of physics (by Newton, Faraday, Ampere, and Thermodynamics) are all cause-effect relations (with time arrow). In this sense the mathematical equals sign is insufficient in describing the causality relations, and hence I introduce a new sign which is nearly the equals sign but can keep the causality relation. By examining the MHD equation from the causality viewpoint, we might find a clue to understanding the physical cause of the reconnection and other plasma phenomena.

Finally, I try to project my discussion of dayside to the nightside. The existence of the various mechanisms of bulk plasma flow crossing the dayside separatorix suggest that similar processes may take place between the tail lobe and the plasma sheet.

2. Various models

Table 1 summarizes the currently proposed plasma mass/momentum transfer mechanisms across the magnetopause [Yamauchi et al., 2003]. The listed mechanisms are just conceptional categories, and each mechanism on the list has several variations.

There are several classes of injection mechanism from the causality viewpoint: large-scale instability of the magnetopause current sheet allows the inflow of plasma (classic reconnection); spatial/temporal pulse of high dynamic pressure makes a magnetic hole in the magnetopause; the plasma does not care about the magnetic field at all near the neutral region where the magnetic energy is very weak compared to the plasma energy or wave energy (weak-|B| effect = finite gyroradii effect, yet morphological reconnection); or kinetic/wave effect plays the major role so that particles may soak through the magnetopause (diffusion). In addition we have mechanisms that transfer only momentum but not mass (e.g., Kelvin-Helmholtz (KH) instability). The above classes are also closely related to the MHD approximation, pressure balance (Chapman-Ferarro (CF) and image dipole) approximation, aerodynamic approximation and kinetic approximation. These classes and approximations are listed in the first and second columns of Table 1.

The third column in Table 1 lists the magnetic field configuration. Any bulk mass flux transferring from the magnetosheath to the magnetosphere drags the SW magnetic field, which will finally be connected to the magnetospheric magnetic field. In this sense the bulk plasma injection and the "morphological" reconnection are the same thing. Hence we must distinguish such simple topological magnetic connection between the magnetosheath and the magnetosphere from the specific process (driven by the instability of the electric current system) that makes such "open" field-line connection and eventually the particle mixture. We call the former "morphological reconnection".

It is also worth noting that the global MHD models or simulations with reconnection provide no more than the rough global configuration and rough location of major singular region where MHD most probably breaks down under the name of "diffusion region," "sash," or "turbulent boundary layer" [Savin et al., 1998; Siscoe et al., 2001], but that the nature of such singular region is unknown and in this sense the physics of reconnection is unknown too. The SW plasma injection problem in the MHD frame is how to adjust/understand the MHD singular region by non-MHD consideration as well as adding extra singularities. As mentioned in the introduction, the observations indicate that the singularity is not unique. It is probably not the simple "diffusion" region that the original reconnection model assumes.

Table 1. Various SW injection mechanisms [modified from Yamauchi et al., 2003)

Mechanism	Type: Causality	Type: Approximation	morphological reconnection?
diffusion	diffusion	kinetic	no
viscous-like interaction	friction	kinetic	no
KH instability	KH	MHD	no
drift at minimum-B (passive particle hole)	weak-|B|	kinetic	no
sporadic large-scale reconnection (classic)	reconnection	MHD	yes
smooth large-scale reconnection (with rotational discontinuity)	reconnection	MHD	yes
sporadic and patchy reconnection (FTE)	reconnection	MHD	yes
plasma breaking-in against weak-|B|*1	pressure change	CF	yes
impulsive penetration by pressure pulse	pressure change	CF	yes
indentation at minimum-B (classic)	weak-|B|	aero	yes
mass loading deceleration (Laval Nozzle)	weak-|B|	aero	yes
turbulence in magnetic cavity (active particle hole)	weak-|B|	kinetic	yes

Note: *1) The weak-|B| means infinitesimal large gyroradius as the zero order approximation.

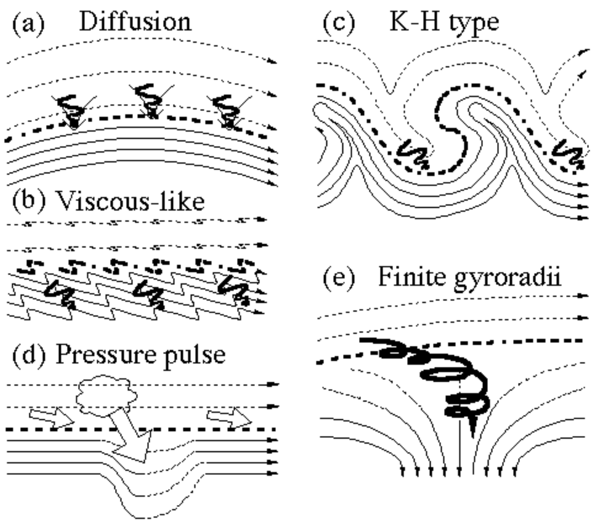

Fig. 1 Various non-reconnection SW injection mechanisms in the illustration frame using magnetic field lines (see Table 1). [Yamauchi et al., 2003]

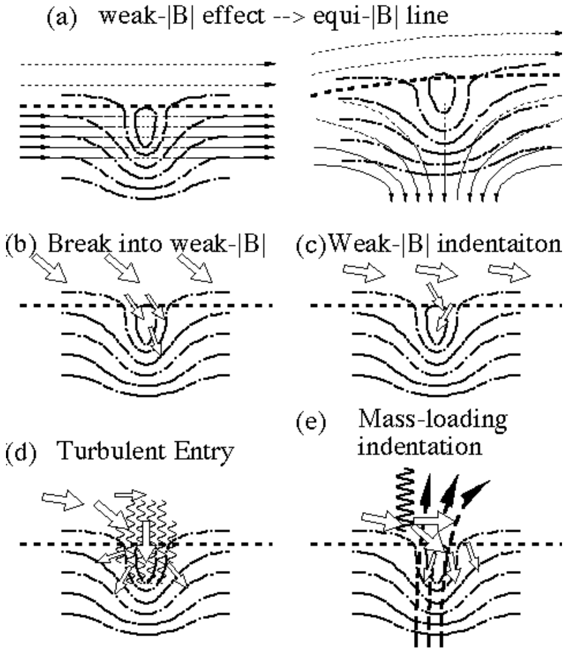

Fig. 2 Various non-reconnection SW injection mechanisms in the illustration frame using equi-|B| lines (see Table 1). [Yamauchi et al., 2003]

Let us look over the non-reconnection processes in Table 1. Figs 1 and 2 illustrate them. Fig. 1 uses the traditional way of drawing the magnetic field (in 2-D) to illustrate the configuration, while Fig. 2 uses equi-strength (equi-|B|) lines for the illustration.

Diffusion (Fig. 1a) and viscous-like interaction (Fig. 1b) have already been discussed for nearly 40 years using finite gyroradii effect, waves, and turbulence [e.g., Treumann, 1997; Thorne and Tsurutani, 1991], but they are not quite related to the bulk plasma transfer. Direct drift entry has also been discussed [Cole, 1974] but this requires larger gyroradii than the magnetopause thickness (Fig. 1e), and it is difficult to apply to the non-cusp transient bulk SW injections. The KH instability (Fig. 1c) is a kind of viscous-like interaction but can be formulated in MHD [e.g., Miura, 1995] and during the final stage when the morphological reconnection takes place during the solar wind mass entry to the magnetosphere.

Direct penetration of the SW plasma may occur when the plasma simply overcomes the magnetic barrier in a local scale. Morphological reconnection takes place as a result of the penetration. Such injection is a natural mechanism in the cusp magnetic neutral region (Fig. 2b). If the penetration takes place transiently at a non-cusp local region (i.e., |B| is no longer weak) because of the temporal excess of the SW dynamic pressure (Fig. 1d), it is called the plasma transfer event or impulsive penetration [e.g., Lemaire, 1977]. This event still prefers local minimum of |B| which can be caused by any instabilities of the magnetopause. In this sense the impulsive penetration is somewhat difficult to distinguish from the KH instability or the reconnection from the magnetospheric observation only.

Transient magnetosheath plasma injection can also be triggered by instability of local x-type magnetic field (strong current sheet), and this is called the reconnection-induced plasma injection or FTE [Russell and Elphic, 1979; Shi et al., 1988]. During

FTEs, the local magnetic field configuration determines the plasma motion whereas the plasma motion draws the magnetic field during the impulsive penetration.

There might be another way to cause the transient SW injections by locally/ transiently weakening the magnetic barrier of the magnetopause. Local enhancement of turbulence (Fig. 2d) [Haerendel et al., 1978; Savin et al., 1998] and local plasma indentation (Fig. 2c) [Spreiter and Summers, 1967] are good candidates for the positive feedback to decrease the local magnetic pressure by the wave pressure (Pondremotive force) or plasma density pressure. Both elements have originally been considered near the cusp, but the same physics might be applicable to the other magnetopause region.

The local plasma indentation may also be caused by the mass loading deceleration of the SW (Fig. 2e) [Yamauchi and Lundin, 1997], while the ion escape itself forms the local minimum-|B| by its thermal pressure. The mass loading indentation make a positive feedback of weakening the magnetic barrier because the ion escape prefers minimum-|B|. Extending this idea, one can easily consider the weakening of |B| by "counter pressure pulse," i.e., plasma exchange initiated by the pressure pulse of the magnetosphere. Since we know that the ionospheric ion escape (and turbulence) is very localized, it is possible that a small-scale but intense mass loading happens locally other than the cusp.

All the above models for the transient magnetosheath plasma injections predict very similar mid- and low-altitude signatures, such as the energy-time and energy-pitch angle dispersions of ions, the bipolar magnetic deviations and the ionospheric convection burst. They form so-called "reconnection signatures," but this does not mean that the injection is caused by the reconnection mechanism (this is further discussed in Yamauchi and Lundin [2001]).

3. Equi-|B| view

In Table 1, many mechanisms require local weak |B| without caring about its direction. The physical problem then is how to sustain the local minimum of magnetic pressure, e.g., by wave pressure, thermal pressure, dynamic pressure or high density. Apparently the view by equi-|B| is more useful than the traditional magnetic field line view in the current discussion. Then the obvious question is how the x-line configuration is illustrated by this new equi-|B| view. The neutral sheet in the reconnection terminology simply means a minimum |B| plane, and the x-point means the location of the minimum magnetic pressure sustained by the thermal pressure. In this view, the x-configuration is not a pre-requisite but could even be the result of the reconnection (in the sense that plasma flows across the separatorix). The x-type configuration may simply be an unstable situation that nature likes to avoid, and that might cause the sporadic positive feedback to convert the energy, but in this case the triggering mechanism must be related to the local minimum |B| rather than the x-type configuration.

4. Causality relation

Newton's Law is normally written as:

$$d\mathbf{p}/dt = \mathbf{F}$$

meaning that force $\boldsymbol{F}$ causes the change of momentum $\boldsymbol{p}$, but cannot be written in the opposite way;

$$\mathbf{F} = d\mathbf{p}/dt$$

Instead we write:

$$\mathbf{F} = - d\mathbf{p}/dt$$

meaning that change of the momentum causes the inertia force. Thus the left hand side (LHS) and the right hand side (RHS) of Newton's Law are not completely equivalent although we use the mathematical equal sign "=", which allows the exchange of LHS and RHS. A part of this aspect has long been discussed under the concept of "time arrow" (I do not go into the detail of time arrow here).

The "=" sign is thus not adequate to keep track of the causality relation which implicitly contains the time arrow. Here I propose to introduce a new sign "/=" instead of "=" when the equation defines the physical causality (or time arrow) in such a way that RHS of "/=" represents the cause terms (physical conditions) and LHS of "/=" represents the effect terms (resultant state). LHS and RHS of the "/=" sign are thus not interchangeable. With this new sign, the causality of the Newton's Law is expressed by:

$$d\mathbf{p}/dt \mathrel{/=} \mathbf{F}$$

Obvious restrictions related to this new sign are:

1. One may not freely exchange or move terms between RHS and LHS of the "/=" sign.

2. Therefore, one may not freely add/subtract the cause terms on the LHS of the "/=" sign, and one may not freely add/subtract the effect terms on the RHS of the "/=" sign.

3. Therefore, elimination of terms must be done in such a way that the entire effect terms (entire LHS of "/=") are substituted into the cause terms (parts of RHS of "/=").

4. The "/=" sign can be replaced to a symmetric equal sign "=" if and only if the physical feed-back that closes the equation (i.e., physical process that causes RHS from LHS of "/=") is faster than the time-scale that we consider.

These restrictions are somewhat similar to those in computer language. In fact the "=" sign in computational algebra is no longer symmetric. Furthermore, the forward-time method in the computer simulation is normally more stable than centered-time method, i.e., forward time and reverse time are different, suggesting that this algebric system keeps the time arrow.

The other basic laws of physics with the causality relation (or time arrow) are Energy conservation (time arrow of the conserved energy makes the Entropy Law), Faraday's Law, and Ampere's Law.

$$dU \mathrel{/=} dQ' + dW'$$

$$\nabla \times \mathbf{E} \mathrel{/=} - \partial \mathbf{B}/\partial t$$

$$\nabla \times \mathbf{H} \mathrel{/=} \mathbf{j} + \partial \mathbf{D}/\partial t$$

where dQ' is the total heat given to the fluid and dW' is the total work actually given to the fluid.

The direct consequence is that the Pointing Theorem must be a causality relation:

$$\nabla \cdot (\mathbf{E} \times \mathbf{H}) \mathrel{/=} -\partial/\partial t(\mathbf{H} \cdot \mathbf{B}/2 + \mathbf{E} \cdot \mathbf{D}/2) - \mathbf{j} \cdot \mathbf{E}$$

From both fluid consideration and Boltsman equation, we equally obtain the basic equations of MHD from the above laws as:

$$dn/dt = n \nabla \cdot \mathbf{v}$$
$$n\, d\mathbf{v}/dt \mathrel{/=} -\nabla P + \mathbf{j} \times \mathbf{B}$$

where the continuity equation (conservation of mass) is not the causality equation but a simple equation with symmetric "=" sign. To complete the MHD equations we need the equation of state (simplified energy equation) and the simplified Ohm's Law, and:

$$\mathbf{E} + \mathbf{u}\times\mathbf{B} = \text{small}$$

where the RHS is a complicated function of $\boldsymbol{j}$, $\partial\boldsymbol{j}/\partial t$, etc.

Here I did not include the causality relation because this condition is a result (quasi-equalibrium) of a fast feedback of the electron motion.

This type of causality study must be completed in the future as a textbook effort, and here I consider only the causality relation of the frozen-in condition. This is formulated from the induction equation:

$$\begin{aligned}\text{small} &= \nabla\times(\mathbf{E} + \mathbf{u}\times\mathbf{B})\\ &/= -\partial\mathbf{B}/\partial t + \nabla\times(\mathbf{u}\times\mathbf{B})\\ &= -d\mathbf{B}/dt + (\mathbf{B}\cdot\nabla)\mathbf{u}\end{aligned}$$

in an analogy to the vorticity equation of the ideal neutral fluid:

$$\partial\boldsymbol{\Omega}/\partial t \;/= \nabla\times(\mathbf{u}\times\boldsymbol{\Omega}) + \text{small}$$

Where $\boldsymbol{\Omega}$ is vorticity.

The causality is opposite between these two equations. While the conservation of the vorticity flux is the direct consequence of viscous-free assumption, conservation of the magnetic flux causes an electric field which adjusts itself very quickly to fulfill the ideal Ohm's Law. In other words, the toroidal electric field in the induction equation is the result, not the cause, of the conservation of magnetic flux. Furthermore, the above set of MHD does not include the parallel electric field except in Ohm's Law, which is a simple relation but not the causality relation in the MHD time-scale. Therefore it is meaningless to discuss the causality between $\boldsymbol{E}_{//}$ and $\boldsymbol{j}_{//}$ in MHD (where electron dynamics is infinitely fast).

The momentum equation simply states that the blocking of the SW at the magnetopause is by pressure gradient force or electromagnetic force, and in this sense weak-|B| condition mentioned in section 2 can be declared as the cause terms. If one rewrites the electric current $\boldsymbol{j}$ in the momentum equation by $\nabla\times\boldsymbol{B}$, one loses the original causality of Ampere's Law. Therefore we should be careful in stating "magnetic tension force causes" because that statement omits a fast causality feedback that allows us to use Ampere's Law as a simple equation rather than a causality equation.

5. Nightside phenomena

One of the qualitative differences between the dayside phenomena mentioned above and the magnetotail phenomena is the release of huge stored energy. If any dayside mechanism can be applied to such energy release, one must explain why such a difference appears. The idea of using the reconnection mechanism is that both have the same triggering mechanism inherent to the x-type configuration. Then, the same logic can be applied to the other mechanisms. For example, since the morphological reconnection (and the x line) can be caused by magnetosheath plasma injection in the dayside (see Figs 1 and 2), a sudden plasma injection from the tail lobe to the plasma sheet can also cause the morphological reconnection and the x-line in the same way. Even the opposite flow (from plasma sheet to the lobe) might cause the morphological reconnection if we apply the counter pressure pulse. Why not the plasma flow before the near-Earth x-point formation? This view is immediate consequence of the equi-|B| line.

The other suggestion from the dayside study to the nightside is that the triggering mechanism of the substorm and/or plasmoid might not be unique although all the plasmoid looks similar. Even if they were a direct consequence of morphological reconnection, several different triggering mechanisms can be responsible.

6. Conclusions

I have listed and discussed various possible mechanisms of solar-wind injection to the magnetosphere, a phenomena which can be classified as reconnection in the sense that plasma flows across the separatorix. To understand the physical difference of these mechanisms in a systematic way, I introduced a new view using the equi-strength (equi-|B|) line of the magnetic field. It is nonsense to use only the magnetic field line (i.e., field direction only) to illustrate the configuration because vector information can only be completed with direction and strength.

To differentiate the physics of various mechanisms, I also introduced a way to keep track of the causality chain which is rooted in the very basic laws of physics by, e.g., Newton, Faraday, Ampere and Thermodynamics. Although one does not have to worry about the causality chain in solving the closed set of ideal MHD, plasma injection takes place due to the violation of MHD, and hence we need to go back to the original causality chain.

The variety of the dayside mechanisms of plasma flow across the separatorix indicates that bulk flow from the tail lobe to the plasma sheet might have several different mechanisms. It is very possible that x-line and the plasmoid can be generated as the result of such flow. Even if the reconnection could be the cause of the plasmoid, its triggering mechanism does not have to be unique.

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Magnetic Reconnection in the Magnetotail

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Abstract:

Magnetic reconnection is defined as physical processes in which magnetic field energy is converted into particle kinetic and thermal energies in association with a change in the magnetic field topology. In past spacecraft observations, fast tailward flows with negative Bz are attributed to occurrence of magnetic reconnection in the magnetotail. These fast tailward flows are expected to form plasmoids in the distant tail and plasmoids are observed in the distant tail beyond 100 R_E. Plasmoids are also observed as Traveling Compression Regions (TCRs) in the magnetic field in the tail lobes.

It is indeed difficult to identify any change in the magnetic field topology with a single point observation. However it is known in spacecraft observations that Bz becomes strongly negative in the mid-tail equatorial plane in association with fast tailward flows during substorms. This signature is believed to be strong evidence of magnetic reconnection, and it is believed to exclude other explanations. Observations of plasmoids strongly support this belief. These interpretations are based on our knowledge on magnetic reconnection at the MHD level. Various simulation studies for magnetic reconnection have been carried out in an MHD code. Several distinguished characteristics of plasmas and fields are found in the MHD simulation studies, and these should be examined with *in situ* observations. 1) Fast outward flows show a pure convection motion in the equatorial plane. 2) Fast outward flows tend to be field-aligned flows off the equatorial plane. 3) Near the separatrix layer, slow-mode shock forms and ions are accelerated and heated. 4) Electrons are accelerated near the X-type neutral line.

1. Geotail Observations and Simulations

The spacecraft Geotail was launched in 1992. Geotail surveyed mostly the distant tail in 1992-1994. Geotail changed its apogee near 50 R_E in 1994 and near 30 R_E in 1995. Geotail has surveyed the mid-tail at radial distances of 20-30 R_E over seven years, and has added significantly to our knowledge of magnetic reconnection not only at the MHD level but also at the kinetic level.

Various new characteristics of magnetic reconnection at the kinetic level are revealed with recent simulation studies in a hybrid code and a full-particle code. In the magnetic reconnection site, the ideal MHD condition breaks down, and the scale length there becomes smaller than ion inertial length and electron inertial length. Ion inertial length, typically 600 km in the plasma sheet, is approximately 40 times longer than electron inertial length. Ions are easily unmagnetized, even when electrons are still coupled with the field. Ion diffusion region forms and ion-electron decoupling takes place here. In the inflow region, electrons can be transported with the magnetic field lines very close to the electron diffusion region, well inside ion diffusion region, whereas ions easily escape from the magnetic field lines and do not approach the electron diffusion region. This relative motion produces currents, namely, the Hall current system. Furthermore, the relative motion of electrons and ions would form the electric field, whose direction is expected to be toward the neutral sheet in the inflow region. This electric field Ez, which is another good indicator of magnetic reconnection, would produce a dawnward convection motion for incoming magnetized plasmas in both the northern and southern tail lobes.

In the MHD simulations, speed of outflows is considered to become the tail lobe Alfven velocity (typically 3000 km/s in the mid-tail). In the full-particle simulations, electron outflow velocity exceeds the Alfven velocity and is higher than ion outflow velocity in the immediate vicinity of the electron diffusion region. This ion-electron decoupling would produce the electric field Ex. These high-speed electron outflows are decelerated and then the electron outflow velocity becomes comparable to the ion outflow velocity. This deceleration process would produce a large Bz field. It is important to note that only a weak Bz field forms in the outflow region at the MHD level. Hence, the large Bz field is another good indicator of magnetic reconnection in the kinetic level.

2. In Situ Observations of Magnetic Reconnection

It is not evident to find a position where magnetic reconnection really takes place with a single spacecraft observation. In order to find the magnetic reconnection site, we can utilize a so-called velocity filter effect. For a plasmoid in the distant tail, high-energy electrons are first observed, and observed energies of electrons decrease. And then high-energy ions are observed, and finally a plasmoid itself, which contains low-energy plasmas with a bipolar Bz signature, is observed. This velocity filter effect indicates that magnetic reconnection for substorm onsets starts rather abruptly in a spatially limited region. In the case when high-energy flowing electrons and high-energy flowing ions are observed simultaneously, the observations are thought to be carried out in the immediate vicinity of the magnetic reconnection site. Indeed, Geotail have found several events in which electrons are strongly accelerated and heated and coexist with high-energy ions. Observed characteristics in plasmas and fields are consistent with several expectations in the simulation studies, and they provide new insight for magnetic reconnection.

Plasma and field characteristics in the immediate vicinity of the magnetic reconnection site are studied with the data obtained in the period 1400-1410 UT on January 26, 1996 with Geotail. The position of Geotail is (-28.9, 5.7, -2.5 R_E) in the GSM coordinates. Ion and electron velocity distribution functions reveal ion and electron behaviors at the kinetic level (Fig. 1).

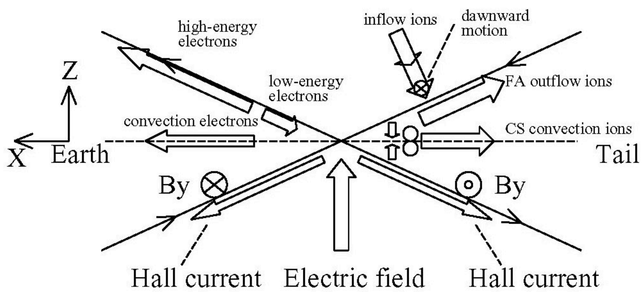

Fig.1. Summary of Geotail observations near the magnetic reconnection site. The upper right panel shows ion behavior, whereas the upper left shows electron behaviors. The lower panel shows the Hall currents, associated-By deflections, and the Ez electric field.

The near equatorial plane is defined as the region where Bx is almost zero and Bz is near -10 nT. The ion distribution consists of two hot ion components with a peak at Vperp = 2500 km/s (tailward). This indicates the bulk tailward velocity of 2500 km/s. The ions are counterstreaming parallel to the magnetic field (almost perpendicular to the equatorial plane) with speed of 800-1200 km/s. High-speed counterstreaming ions are particles that just come from the north and south tail lobes and are making a meandering motion in the magnetic reconnection site. Electrons have a rather flat-top distribution, indicating strong acceleration and heating. The center of the distribution is shifted tailward and this shift corresponds to an electron convection velocity of approximately 4000 km/s (tailward), which is higher than the estimated Alfven velocity. These characteristics are consistent with the results in the simulations.

The off-equatorial plane is defined as the region where Bx is less than 10 nT and Bz is near -5 nT. Ions have a field-aligned component and a convection component. The field-aligned component shows fast tailward flows almost along the field line and its velocity can exceed 2800 km/s (the upper limit of the instrument). The convection component consists of warm ions, and the convection velocity is in the wide range of 500-1500 km/s toward the equatorial plane. The Bx magnitude is regarded as the distance from the equatorial plane. Just off the equatorial plane, the field-aligned flow velocity is high, the convection velocity is high, and the convection component has higher temperature. Far from the equatorial plane, the field-aligned flow velocity is still high, the convection velocity is lower, and the convection component has lower temperature. These characteristics indicate ongoing acceleration and heating processes for ions. The electron distribution is an almost flat-top distribution with an excess of higher-energy electrons in the field direction. This excess means tailward escaping of high-energy electrons. The electrons are more energetic off the equatorial plane than those in the equatorial plane.

The ion-electron decoupling is the most evident in the plasma sheet/tail lobe boundary. Ions have two components: a field-aligned component and a convection component. The field-aligned component has a high tailward velocity. The electron distribution is elongated along the field line, and the excess of the high-energy electrons is more evident. Hence, ions and electrons make field-aligned high-speed outflows. A prominent feature in the electron distribution is a low-energy (3-keV) electron beam in the direction opposite to that of the ion outflows. The inflowing electrons are observed in the four quadrants of the 2D magnetic reconnection plane. These low-energy electrons can become current carriers. Indeed, the current density is calculated to be 6-13 nA m^{-2} and the currents flow out the magnetic reconnection region.

In the original idea of the Hall current system, outward currents are almost perpendicular to the field lines in the inflow region, and there are inward currents in the outflow region in order to keep the current continuity. The observed currents are almost parallel to the magnetic field. In the simulations, outward currents are confined into the plasma sheet/tail lobe boundary, and counterstreaming features are reproduced in electron distributions. Since electrons are fairly mobile in the field direction, it is likely that field-aligned currents are much more evident in the inflow region. However, it is not evident how current-carrying electrons have energies of a few keV. The electrons seem to be accelerated with parallel electric fields. As indicated in the simulations, Ez toward the equatorial plane forms in the inflow region and tailward/earthward Ex forms in the outflow region. The potential structure results in outer field-aligned electric field in the separatrix layer. This field-aligned electric field probably accelerates electrons up to a few keV.

The effect of the Hall current system should be observed as the By deflection in the magnetic field. The four-current loop of the Hall current system would result in a quadrupole structure in the By field in the vicinity of the magnetic reconnection site. Indeed, the consistent By deflection is easily found in the observations. Thus, the existence of the Hall current system is firmly established with the direct detection of the currents and the detection of the magnetic field deflection as its effect.

The Ez field is observed as ion flows in the inflow region. Far from the separatrix layer, incoming ions are cold and show a convection motion toward the equatorial plane. Near the separatix layer, incoming ions become hot and show persistently a dawnward motion. This can be interpreted as the ExB drift of incoming ions which are partially magnetized. Hence, this observation provides good evidence on the electric field Ez produced by the ion-electron decoupling.

Furthermore, Geotail has provided various characteristics of magnetic reconnection in the MHD level. Analyses of flow directions and fields associated with substorm onsets have shown that strong coupling between fast tailward (earthward) flows and negative (positive) Bz is persistent and that magnetic reconnection frequently takes place in the premidnight region at radial distances of 20-30 Re in association with substorm onsets. Plasma flows toward the equatorial plane are enhanced in the mid-tail tail lobes in association with substorm onsets. This indicates that tail lobe plasmas become inflows for magnetic reconnection. Plasmoids can be observed in the magnetotail beyond a radial distance of 20 R_E and evolution of plasmoids is observed during their tailward flowing in the magnetotail from 20 R_E to 200 R_E. Even in the prolonged southward IMF Bz period, the energy is stored in the tail lobes and it is released in the substorm expansion phase.

3. Conclusions

All crucial aspects of magnetic reconnection are confirmed in the observations at the kinetic level as well as at the MHD level. Magnetic reconnection is an indisputable physical process for plasma transport, plasma acceleration and heating, and changes in the magnetic field topology in the magnetotail. In the present day, our observations have revealed ion dynamics and ion-electron decoupling process. The future direction in the study of magnetic reconnection is to resolve electron dynamics, in order to expand our understanding of magnetic reconnection.

Magnetic Reconnection as a Cause of Substorm: Models versus Observations.

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1. Introduction

Magnetic reconnection has been invoked as the cause of substorm for several decades. However the physical origin of magnetic reconnection has not been identified and there is no explanation for the mechanism acting in the diffusion region. In another hand, models of magnetic reconnection or current instabilities use a quasi-static approach which seems far away of the real conditions of the plasma sheet. In this situation, it is often difficult to interpret the observations relatively to the existing models.

In this paper, we attempt to provide some input and questions inspired by observation analysis experience in order to develop magnetic reconnection definition and models.

2. Magnetic Interconnection (MI) and Magnetic Reconnection (MR)

In a general sense, magnetic reconnection means that a large scale magnetic field is reconfiguring, leading to flux and connectivity redistribution. In most cases, such a large scale process is considered as associated with a X-type topology as illustrated in Fig. 1.

Two distinct phenomena have to be distinguished: (i) when the magnetic reconfiguration is due to a plasma process occurring at the X-line location, also responsible for particle acceleration and energy electro-mechanical conversion, we will talk about Magnetic Reconnection (MR); (ii) if the magnetic reconfiguration is due to another process and when the X-line does not drive any acceleration process, we will talk about Magnetic Interconnection (MI).

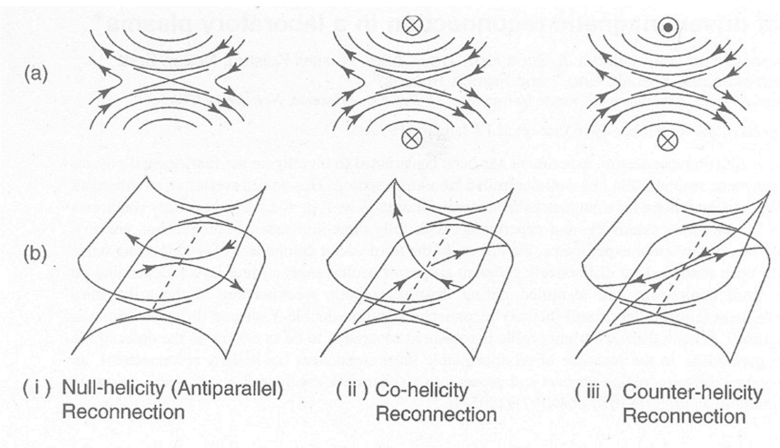

Fig. 1. Two-dimensional (a) and three-dimensional (b) views of magnetic reconnection. (Yamada et al., 1997).

This is the case for example in a large scale current sheet including two stationnary excess current inhomogenities in absence of any electric field.

3. Magnetic Reconnection and plasma beta parameter

Fig. 2 illustrates the Standard Magnetic Reconnection Model (SMR). A X-line configuration takes place at a diffusion region where the frozen-in condition is violated. In this region where exists an out-of-plane electric field (required for MR), particles are accelerated and magnetic energy is converted into particle kinetic and thermal energy. Particle flow distribution and magnetic flux circulation follow the electric drift pattern.

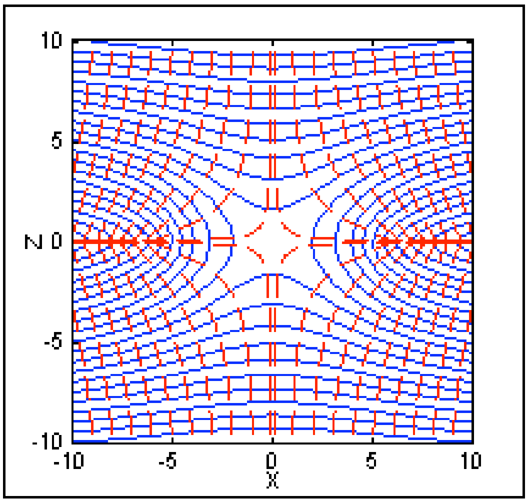

Fig. 2: schematic magnetic topology (blue solid lines) and flow distribution (dashed red lines) in the SMR model.

In this model, it is implicitly considered that the medium is organized, dominated by the magnetic field. However, the observations show that the situation is quite different in the night side plasma sheet. The plasma beta parameter is low in the lobes indicating that the magnetic field is there dominating. But in the central plasma sheet, both electron and ion beta parameters are generally significantly greater than 1. In this case, it is not clear that the SMR picture could provide an appropriate representation of what can physically happen in the medium. If high beta flows or plasma pressure inhomogeneities are present, we may expect that they produce their own electro-magnetic field which could be locally dominant. We may imagine that there is a coupling between high beta plasma inhomogeneities located inside the plasma sheet and the low beta surrounding lobes (i.e. the large scale magnetic field configuration), but this remains to be demonstrated and formalized. Moreover, GEOTAIL data suggest that the magnetic topology associated with the high beta plasma flow observed in the deep tail during substorm are organized by the plasma itself, the lobes simply serving as a guide (Rouquette et al., 2000, Jacquey et al., in preparation).

4. Model topology and observed topology

Magnetic reconnection is interpreted as a MHD process and is generally described in quasi-static models. It is assumed that the frozen-in condition is respected everywhere (ideal MHD) except in a localized region, the diffusion region, where magnetic reconnection and particle acceleration occur. The process responsible for the break down of the frozen-in condition is presently unknown. Most attempts of both simulation and theoretical analysis are based on the use of the non-ideal MHD i.e. using the resistive, Hall or electron inertial terms of the generalized Ohm law. In these quasi-static models, the magnetic field is regular and its topology is defined at any times. The observed plasma sheet show a different picture, especially during active periods. In situ magnetic field measurements often display large amplitude turbulence or waves. These short time and length scale disturbances can be of the order of or smaller than the gyroperiod and the Larmor radius of the ions. This situation is still more likely in a region where the B-field is expected to be null or very weak as expected in the diffusion region. This suggests that the MHD, in the ideal paradigm or in the non-ideal one as well, is not appropriate for describing the magnetic reconnection in a realistic way. At most, MHD could describe the averaged re-arrangement of the magnetic topology and the plasma flow distribution. The key question is to know if such an averaged representation remains a physical representation. In other words, (i) does the turbulence play a crucial role involving specific kinetic mechanisms responsible for electro-mechanical energy conversion or (ii) does the turbulence have minor effect on the MR process which still can be described in average by quasi-static MHD models.

5. Magnetic reconnection and large scale cross-tail current redistribution

The large scale dynamics of the near-Earth (<25 Re) plasma sheet during substorm expansion is mainly characterized by energetic particle injections (e.g. Moore et al., 1981, Huang et al., 1992) and plasma sheet thinnings (Aubry et al., 1972, Sauvaud et al., 1987) observed within a few minutes after the onset. Both processes can be interpreted as due to a large scale electric field induced by a fast cross-tail current reduction occurring between the geosynchronous and the ISEE (~20 Re) orbits (Sauvaud and Winckler, 1980, Sauvaud et al., 1984).

The lobe magnetic field measurements performed by the ISEE, IMP-8 or INTERBALL-1 have provided the opportunity to identify and to model the large scale current redistribution occurring during substorm expansion. For numerous cases, it has been shown that a cross-tail reduction is initiated in the near-Earth plasma sheet (7~15 Re) at substorm onset. The current reduction is partial (current decrease is less than 30%), is first localized and then propagates tailward and azimutaly (Lui, 1978, Jacquey et al., 1991, 1993, Ohtani et al., 1992) and also earthward (Ohtani, 1998). The spatio-temporal distribution of the electrojet/field aligned current system allowing the diversion of the reduced cross-tail current has been observed in a consistent way (Jacquey, 2000). These observations closely correspond to the current wedge model (Akasofu, 1972, McPherron et al., 1973).

The observation of plasmoids and TCR (Travelling Compression Region) is often considered as a proof of the occurrence of magnetic reconnection. However, close examination of lobe magnetic field observations show that tailward propagating cross-tail current reduction and plasmoid develop concurrently (Sauvaud et al., 1996, Jacquey, 2000).

The Magnetic Reconnection models generally do not predict the large scale redistribution of the cross-tail current. This one is nevertheless a crucial and powerful input for interpreting the observations of the large scale plasma sheet dynamics, the large scale pressure changes and the magnetic reconfiguration. As the satellites are rarely inside the instability region, it is important to extend the models in order to predict its medium and large scale effects which are more likely observable.

6. Current Disruption (CD) and Magnetic Reconnection (MR): concurrent processes?

As reported in the previous section, the large scale magnetotail reconfiguration result from cross-tail current reduction locally initiated earthward and then expanding tailward. Such current distribution can be successfully modelled by a simple reverse ($J_Y < 0$) current slab of which the length increases with time. In an electro-magnetic (i.e. in vacuum) picture, the superimposition of the field produced by this current slab on the undisturbed magnetotail field leads to the formation of an X-type configuration, as illustrated in Fig. 3. This picture does not take into account the response of the plasma but it may represent the general trend of the magnetic field reconfiguration.

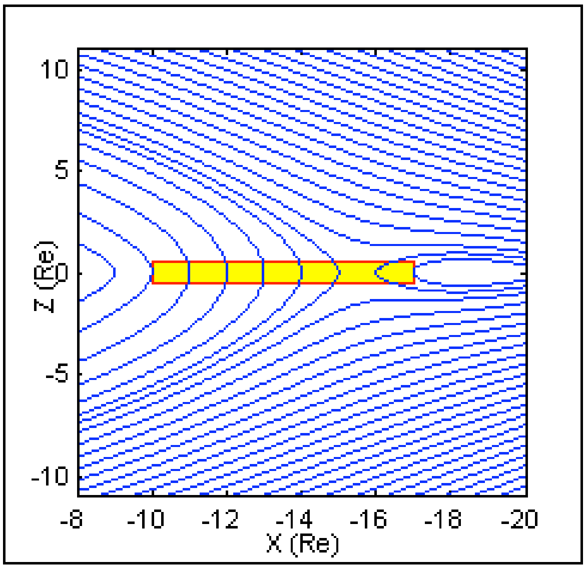

Fig. 3: superimposition of a reverse current slab (yellow rectangle) on a tail-like topology.

As the cross-tail current reductions start close to the Earth where the effect of the Earth dipole is still important (i.e. significant positive Bz in the equatorial plane), the magnetic reconnection does not seem to be an appropriate candidate for their initiation. The cross-tail reduction front has been observed by the AMPTE-CCE satellite and is seen as a highly turbulent region. This one propagates tailward as a transition region between stretched configuration (in the tailward side) and a dipolarized configuration (in the earthward side). The in situ observations have been interpreted as the signatures of the development of a current instability (e.g., Lui et al., 1992, Lui, 2002).

A key question is to know if the tailward cross-tail current disruptions leads to the formation of a X-type magnetic topology at their propagation front, as suggested by the electromagnetic picture. In this case, CD should drive at least magnetic inter-connection. More likely, as the cross-tail current reduction induces a strong electric field, such a X-type configuration should be a strong acceleration region and could be interpreted as an active reconnection site. To summarize, it looks likely that CD drives MR. In such scenario, MR is not the cause of the destabilization of the current but could significantly participate to particle heating and flow generation and to electro-mechanical energy conversion in the course of the tailward propagation of the CD. Such a situation, if it occurs in reality, should make difficult to distinguish between the current instability or the reconnection process as the cause of substorm. This question could be solved by a multi-scale observatory (e.g. the HERACLES project, Louarn et al., 2002): closely separated ($10^2 – 10^3$ km) spacecraft in tetraedron configuration and capable of very high time resolution associated with more separated (1 – 5 Re) satellites around the tetraedron. This kind of spacecraft configuartion should allow to derive and model the topology reconfiguration, the propagation effects and differential timing at small scale and characterize the mechanisms acting at microscopic scale as well.

7. Conclusion

At present, it is not demonstrated that magnetic reconnection occurs in the night side plasma sheet. Moreover, it still less clear if magnetic reconnection is to be considered as a driving process or as a large scale effect of another process, such as the cross-tail current disruption.

Magnetic reconnection is generally described with the help of quasi-static MHD models. In contrats, in situ measurements show that the plasma sheet is strongly turbulent during substorm. Such conditions suggest that the MHD may not be applicable. Moreover, the turbulence is likely able to play a crucial role in the energy conversion process. These aspects need to be characterized with the help of multi-scale observatory and should eventually included in the models to be developed.

Magnetic reconnection models implicitely assume that the medium is dominated by the magnetic field. The in situ observation show that it is not the case (in general) inside the plasma sheet where both ion and electron pressures significantly exceed the magnetic pressure. The applicability of magnetic reconnection models in regard to the plasma beta parameter should be investigated.

The models of substorm instability, magnetic reconnection or others, need to be expanded in order to predict the medium and large scale effects, the current redistribution and the instability propagation in particular.

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Current Disruption and Magnetic Reconnection

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Abstract:

Dynamic processes in the magnetosphere are often associated with thin current sheets. Two different concepts have been invoked to describe the process responsible for the dynamics of thin current sheets with intense current densities. One description of this process is current disruption, utilizing the "Ej approach" which considers the electric field and current density as primary quantities. The other description is magnetic reconnection, utilizing the "Bu approach" which treats the magnetic field and plasma bulk flow as primary quantities. The similarities and differences between current disruption and magnetic reconnection are discussed, with the conclusion that they can be clearly distinguished by careful examination on the characteristics exhibited in a given energetic phenomenon.

1. Introduction

Current sheets are ubiquitous and well recognized to exhibit dynamic activity in particle acceleration, intense wave generation, and plasma turbulence. Intense current densities in current sheets can lead to the phenomenon known as current disruption. The issue to be addressed here is whether or not current disruption can be considered as a manifestation of magnetic reconnection.

These two terms, namely, current disruption and magnetic reconnection, arise from two different approaches in treating space plasma problems. The "Ej approach" considers electric field and current density as primary quantities while the "Bu approach" considers magnetic field and plasma flow as primary quantities (see, e.g., *Lui*, 2000 for more discussion of these two approaches). Current disruption is used in the former approach while magnetic reconnection in the latter.

In considering their similarities and differences, we first summarize some relevant observations of current disruption and dipolarization in the Earth's magnetotail, introduce a new definition of magnetic reconnection to extend the previously limited definition, and compare features expected for current disruption and magnetic reconnection. We conclude based on this examination that these two terms are not equivalent. Each has its distinct characteristics that can be used to clearly distinguish it from the other.

2. Observed Characteristics of Current Disruption

Current disruption is associated with thin current sheets and is probably caused by current-driven plasma instabilities (Fig. 1). Characteristics of current disruption (CD) have been obtained mostly from CCE observations in the near-Earth magnetotail (< 9 R_E geocentric distance) [*Takahashi et al.*, 1987; *Lui et al.*, 1988, 1992; *Ohtani et al.*, 1998].

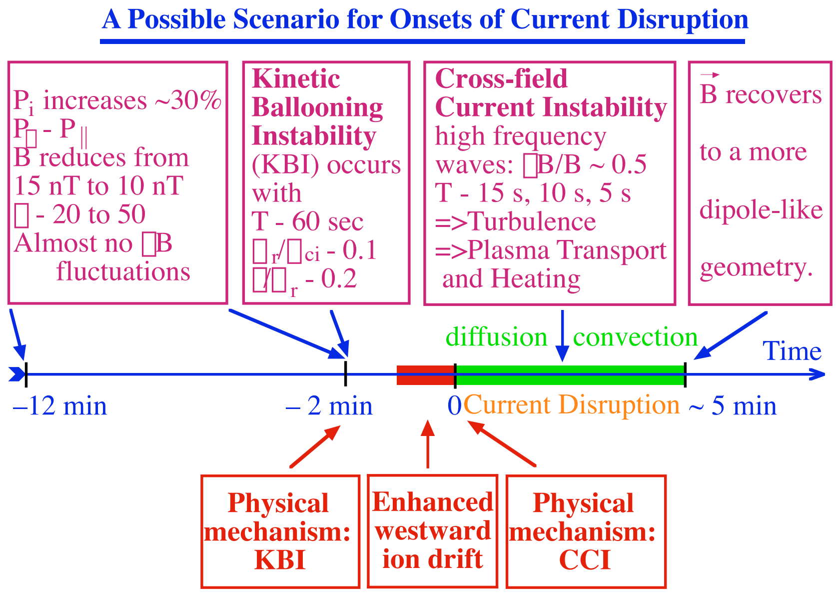

Fig. 1. A possible scenario that leads to current disruption.

Well before CD onset, plasma pressure and plasma beta increase steadily in the near-Earth magnetotail [*Lui et al.*, 1992]. The magnetic field component normal to the current sheet B_n decreases gradually, suggesting the buildup of a strong cross-tail current nearby. The B_n component, however, remains substantially positive (>5 nT) typically even to the time of CD onset. About 1-2 min before CD onset, the plasma beta can reach to a value of ~70 and low frequency wave with a period of ~60s occurs with a growth rate of ~0.2 of the wave frequency [*Lui and Najmi*, 1997; *Cheng and Lui*, 1998]. Enhanced westward ion drift is observed just prior to CD onset, suggesting that the current sheet is thinned to the extent that the thermal ions become unmagnetized. A possible mechanism for these developments is the kinetic ballooning instability (KBI) [*Cheng and Lui*, 1998].

During CD, a band of high frequency waves with periods shorter than the ion gyroperiod appears, causing large magnetic fluctuations. Simultaneously, particle fluxes are enhanced. Detailed analysis of particle anisotropy indicates that ions are heated perpendicular to the magnetic field while electrons are heated parallel to the magnetic field [*Lui*, 1996], which are known to be characteristics of the modified two-stream instability [*McBride et al.*, 1972]. These disturbances are very localized [*Lopez and Lui*, 1990; *Ohtani et al.*, 1992, 1998]. A possible mechanism of these activities is the cross-field current instability (CCI) [*Lui et al.*, 1991, 1993].

The high frequency waves associated with CCI are probably the direct cause of disrupting or reducing the local current density, giving rise to turbulence and much plasma transport and heating. These characteristics may be used to define the CD phenomenon. After a few minutes of large magnetic fluctuations, magnetic field settles down to a value indicative of a more dipolar field configuration. The dipolarization is found to propagate tailward

[*Jacquey et al.*, 1991, 1993; *Ohtani et al.*, 1992], possibly in a discontinuous fashion. From a detailed study of dipolarization events in Geotail data, *Lui et al.* [1999] concluded that dipolarization is a phenomenon violating the ideal MHD condition (i.e., violating $E + v \times B = 0$).

3. Definition of Magnetic Reconnection

For comparing current disruption with magnetic reconnection, it is important to define what magnetic reconnection (MR) is. Unfortunately, no universally agreed definition of MR exists. *Dungey* [1961] invoked MR to explain auroral electron acceleration and magnetospheric convection. Auroral electron acceleration is now known to take place at about 1 R_E altitude above auroral arcs and not at the neutral sheet in the magnetotail as suggested by *Dungey*. However, magnetospheric convection may well be driven by MR, which was envisioned by *Dungey* to be in a two-dimensional steady state. There is ample evidence now that many energetic space plasma phenomena are spatially localized and transient. Therefore, the MR concept needs to be extended to a three-dimensional geometry and be recognizable in transient phenomena.

A generalized definition of MR describes it in terms of the connectivity between plasma elements and individual magnetic field lines [*Schindler et al.*, 1988]. It emphasizes localized non-ideality, i.e., a localized break down of magnetic connectivity. This MR definition is too liberal. The physical processes for a localized breakdown in connectivity could be numerous, implying that MR includes all non-ideal MHD processes that are not originally intended for. For example, the presence of a magnetic-field-aligned electric field above an auroral arc breaks the non-ideal MHD condition. However, no magnetic field line in this situation could be visualized to be "cut" and "joined" with another magnetic field line, even though it would be included under this generalized definition.

To preserve the original spirit of MR envisioned by *Dungey*, we use five examples in the magnetosphere as a guide in formulating a new definition for MR. The first is the structure of a magnetic flux rope. It has close similarity to a plasmoid, except that it has a strong magnetic field along its axis. This structure could be formed by MR with the inclusion of a magnetic field component normal to the plane where a two-dimensional picture of MR is realized. This implies that a general definition of MR should include the possibility of a non-zero guide field for the case of a magnetic flux rope, extending the concept to three dimensions. The second example is the non-ideal MHD condition posed by a magnetic-field-aligned electric field above an auroral arc. As discussed previously, this situation should not be considered as MR. The third example is dayside entry of magnetosheath plasma by impulsive penetration. The new definition should differentiate this process from MR independent of whether MR really exists or not. The fourth example is the inner magnetosphere where the dynamics is governed by individual particle drifts rather than by the fluid equations of MHD. The new definition should exclude such breakdown of non-ideal MHD condition as MR. The fifth example is simple stochastic (classical, nonclassical or anomalous) diffusion which should be regarded as distinct from MR, though MR might be related to diffusive processes as well.

With the above consideration in mind, we define MR as a plasma phenomenon with the following characteristics: (a) magnetic field energy is released to kinetic particle energy through plasma bulk flow crossing a boundary separating regions with topologically different magnetic field lines if projected on the plane of MR, (b) the out-of-the-plane magnetic field should be no stronger than the magnetic field in the plasma inflow region without the out-of-the-plane component, (c) there is a non-zero electric field along the intersection line of separatrix surfaces (which is the X-line in a 2D magnetic reconnection geometry), and (d) the region exhibiting the non-ideal MHD condition ($E + v \times B \neq 0$) with plasma dynamics significantly different from the MHD expectation should be localized to a scale comparable to the ion inertial length in the direction of the plasma inflow velocity.

The above definition allows the superposition of an out-of-the-plane magnetic field on the standard MR configuration. Criterion (b) is introduced so that MR does not encompass automatically all current-driven processes because an electric current based on the Ampere's law is associated with a non-zero curl B and thus can be cast into a MR configuration when the background field is removed. Criterion (c) is needed to distinguish between MR and interconnection of magnetic field lines in two different plasma regimes [*Lemaire*, 1977; *Lemaire and Roth*, 1978]. Criterion (d) is used to ensure that MR would exclude configuration in which broad regions with non-ideal MHD condition, such as the inner magnetosphere where the dynamics is governed by individual particle drifts and MR bears no meaning in this situation.

This new definition clearly allows MR to occur with an out-of-the-plane magnetic field, thus including situations of dayside and nightside MR that produces magnetic flux ropes. It excludes the magnetic-field-aligned electric field above an auroral arc as MR because the out-of-the-plane magnetic field required to visualize it as MR would be orders of magnitude stronger than the magnetic field without the out-of-the-plane component in the plasma inflow region. It distinguishes impulsive penetration as MR because the projected magnetic field configuration and plasma flow pattern differ from that of the classical two-dimensional MR picture. The particle-drift-dominated inner magnetosphere is not a MR region because the non-ideal MHD region is not localized. Stochastic diffusion which does not involve plasma bulk flow across a configuration resembling the two-dimensional MR picture is not MR. On the other hand, diffusion is always included locally in MR whenever ideal MHD condition is violated in the center of the MR region.

4. Comparison Between Current Disruption and Magnetic Reconnection

We tabulate the similarities and differences between CD and MR in Table 1. Both phenomena involve breakdown of the ideal MHD condition and lead to plasma acceleration from conversion of magnetic field energy to particle energy. There are several major differences, however. Recent numerical simulations of MR indicate that the violation of the ideal MHD condition in the dissipation region is achieved with the electron inertial term or the off-diagonal terms in the electron pressure tensor [e.g., *Shay et al.*, 1998], implying that no large magnetic fluctuations are expected for the dissipation region. On the other hand, one major characteristic of CD is the large magnetic fluctuations. A magnetic neutral line is essential for MR but not for CD. Plasma flow pattern is ordered by magnetic field in MR but not in CD. Local current is reduced and breaks up into filaments in CD but not so in MR. The plasma instabilities invoked for their onsets are different. For MR, the tearing instability (TI) is the main mechanism [*Coppi et al.*, 1966] while KBI and CCI are the main ones for CD. Therefore, these instabilities do have distinguishable characteristics.

5. Summary

Current disruption is a phenomenon produced by current-driven plasma instabilities in thin current sheets. It is similar to magnetic reconnection in releasing stored magnetic field energy to accelerate particles by non-ideal MHD processes. It differs from magnetic reconnection in that the plasma flow pattern associated with current disruption is not ordered by the magnetic field configuration, change in magnetic field topology is not essential (although it may occur), large magnetic fluctuations are its essential characteristics, and the local current is reduced and breaks up into current filaments. Therefore, current disruption is not a form of magnetic reconnection.

Acknowledgments

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Table 1. Comparison between Current Disruption and Magnetic Reconnection

	Magnetic Reconnection	Current Disruption
Breakdown of ideal MHD condition	yes	yes
Magnetic field is the primary energy source	yes	yes
Plasma acceleration	yes	yes
Plasma flow across separatrix essential	yes	no
A magnetic neutral line essential	yes	no
Plasma flow ordered by magnetic field	yes	no
Large magnetic fluctuations essential	no	yes
Reduction and filamentation of local current	no	yes
Potential mechanisms for its onset: ω : wave frequency; k : wavenumber; Ω_i : ion gyrofrequency; L_z : current sheet thickness scale	TI: $\omega << \Omega_i$; $k_x L_z \sim 1$	KBI: $\omega << \Omega_i$; $k_y L_z \sim 1$ CCI: $\omega \sim (0.1 \text{ to } 10)\, \Omega_i$; $k_y L_z \sim 1$ to 10

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Multiple Magnetic Reconnection Events Observed by Cluster II

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1. Introduction

Magnetic reconnection (MR) is a fundamental process in magnetized plasmas by which magnetic field topology changes and connections of plasma particles with the magnetic field are re-arranged. MR occurs in the thin current sheet separating two plasmas with magnetic fields of opposite (or significantly different) directions when the frozen-in condition in the ideal MHD is violated and motions of ions and electrons are decoupled from the magnetic field. MR generates an open field line region or flux ropes. In the process, magnetic field energy converts to plasma kinetic and thermal energy; and energy, momentum and mass may transport across the interface.

When MR takes place in the dayside magnetospheric boundary, the closed geomagnetic field becomes connected to the interplanetary magnetic field. Creation of open magnetic flux has two major consequences. First, solar wind plasma has easy access to the magnetosphere and the ionosphere along the open magnetic field lines. Second, the open magnetic flux is convected from the dayside magnetopause to the magnetotail[1]. When MR occurs in the magnetotail, it releases the magnetic energy stored in the tail lobes. Much of this energy is deposit into the inner magnetosphere, polar ionosphere and atmosphere through coupling processes, generating magnetic storms and substorms. On the other hand, there are a number of energetic phenomena in solar wind-magnetosphere interaction which do not involve MR. There are often situations, too, in which magnetic field conditions are favorable to MR, but it does not appear as expected. Therefore, it is of vital importance to understand the processes that lead to MR and to properly describe its multiple-scale properties and its impact on the global magnetospheric system.

MR can be sorted by driving energy as free reconnection or forced reconnection . It can also be classified by the mechanism violating the frozen-in condition as resistive reconnection or collisionless reconnection . We inter that it is the collisionless MR that occurs in the magnetospheric system. High-speed plasma flows, energization of particles and other MR signatures were observed long ago by in-situ measurements. Evidences of collisionless MR have been detected by Geotail and Wind spacecraft[2-4]. More reliable measurements of MR have recently been performed by four-spacecraft Cluster II mission. In the following we briefly discuss the properties of two MR events observed by Cluster II in the magnetospheric system.

2. A Multiple Flux Rope Event in Dayside High-Latitude Magnetopause

On January 26, 2001, Cluster II moved from the magnetosphere into the magnetosheath across the mantel, northern cusp and the high-latitude magnetopause. From 11:10 to 11:35 UT when four spacecraft were just outside the duskside magnetopause [5], Cluster II observed a multiple energetic ion burst event. At 11:10 UT C3 was located at $X \approx 2.3\ R_E$, $Y \approx 5.8\ R_E$, and $Z \approx 8.8\ R_E$ (GSE). The

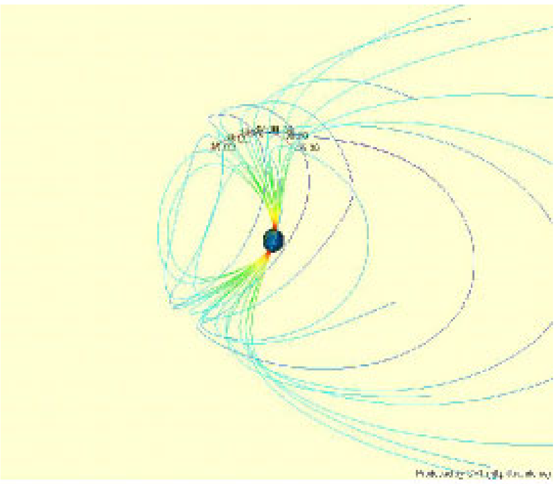

Fig 1 Orbit on Jan 26, 2001

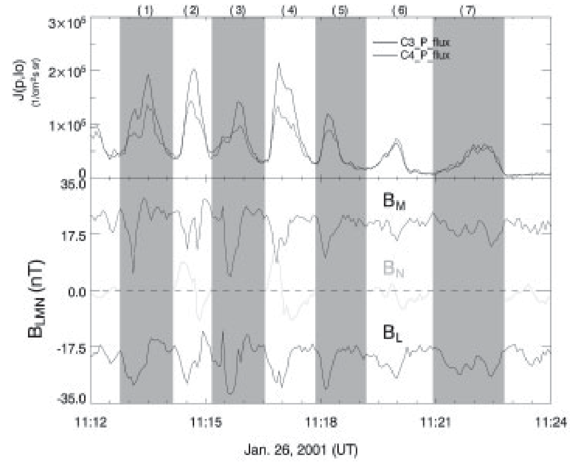

Fig. 3 J(p) vs B_{LMN}

distances between four spacecraft are ~600 km. Fig. 1 shows the Cluster orbit from 06:00 to 18:00 UT looking from local time of 15 PM. The field lines of the T-96 geomagnetic field model[6] are also shown as a reference. Fig. 2 plots multiple flux bursts of energetic protons, He and CNO ions. Ion fluxes of these three species all increase up to one order of magnitude from their background level, while energetic electrons remained at low value. It is of interest to notice that the ratios of *J*(CNO)/*J*(p)~10% and *J*(He)/*J*(p)~20%. This indicates that these ions are originated from the magnetosphere. The duration of the repeated bursts ranged from about 30 s to one min. Fig. 3 displays the magnetic field data in the magnetopause normal coordinate system compared with the flux of energetic protons *J*(*p*), where B_L, B_M and B_N represent the field component in the maximum, intermediate and minimum variation direction, respectively. The last event has been identified to be an flux transfer event[7] which is in fact composed of two events associated with an oscillation of the magnetopause. One sees that each energetic ion burst is coincident with a bi-polar B_N and a band B_L and B_M signatures. Fig. 4 presents an azimuthal and polar angle plot for the moving direction of energetic ions in the spacecraft coordinate system. For the FTE energetic ions mostly move duskward in the equatorial plane, while in other events ions were basically moving

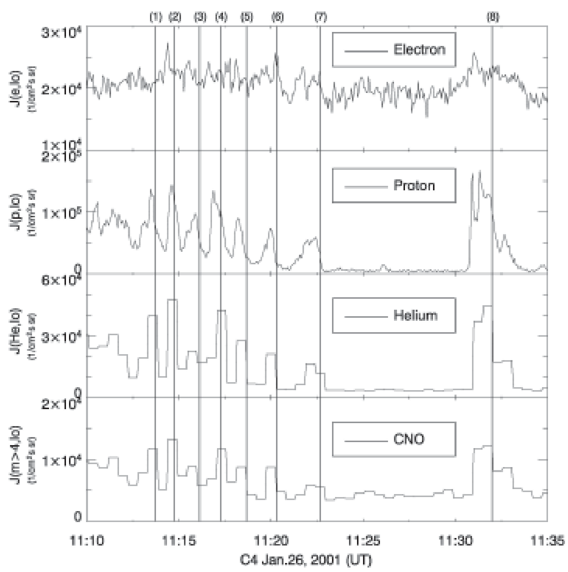

Fig 2 Energetic particle fluxes

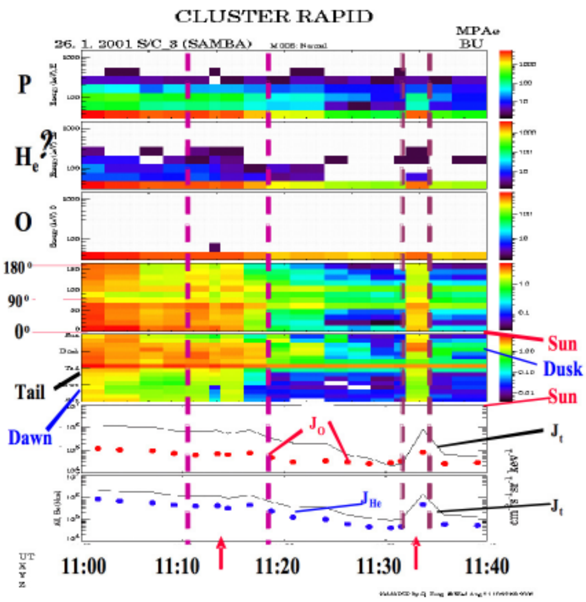

Fig.4 Angle-Angle plot of ion fluxes

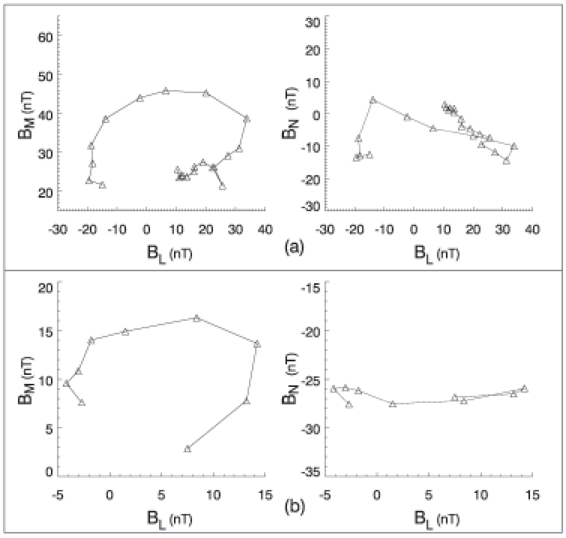

Fig.5. Hodograms of (B_L, B_M) and (B_L, B_N)

duskward/tailward and southward. We have applied the minimum variation analysis (MVA) [8] to the magnetic field data. Table 1

Table 1 MVA Results of Multiple Flux Rope Events in GSE

Event	F	q	Nx	Ny	Nz	λ_2/λ_3	λ_3/λ_1
~11:10	126º	44º	-0.41	0.56	0.72	3.0	0.08
~11:14	125º	63º	-0.51	0.73	0.46	7.7	0.18
~11:15	57º	83º	-0.91	0.38	0.11	2.1	0.03
~11:17	132º	70º	-0.63	0.70	0.35	6.7	0.03
~11:18	125º	88º	-0.58	0.81	0.03	50.7	0.01
~11:20	119º	68º	-0.45	0.81	0.37	4.7	0.08
~11:22	120º	52º	-0.40	0.69	0.61	8.3	0.02
Event	F	q	Mx	My	Mz	λ_2/λ_3	λ_3/λ_1
~11:31	123º	92º	-0.55	0.84	- 0.03	19.2	0.01

lists the results. The ratios λ_2/λ_3 and λ_3/λ_1 indicate that the MVA is valid[8]. To determine whether the ion burst-related magnetic structures are flux ropes we have drawn the relevant hodograms. Figs. 5a and 5b illustrate plots of (B_L, B_M) and (B_L, B_N) for the first part of FTE and the event at ~ 11:18 UT, respectively. It can be inferred that

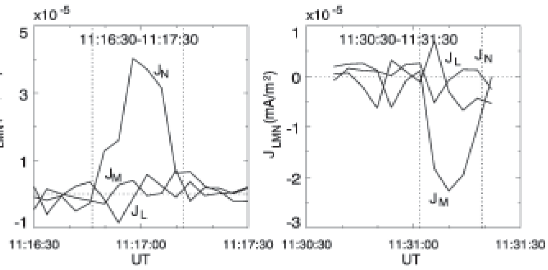

Fig.6 Current density

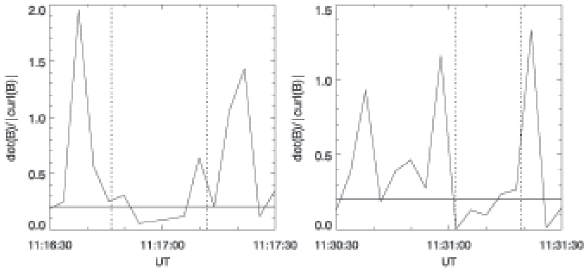

Fig.7 Uncertainty of current evaluation

in these two events Cluster II encountered with a flux rope with a strong core field along the M (the axis) direction and a flux rope with a strong core field along the N (the axis) direction, respectively. Most other events are similar to the 11:18 UT event. Note that the axies of all these flux ropes are roughly in the direction anti-parallel to the ambient magnetic field. It can thus be concluded that during these events energetic ions were essentially moving out of the magnetosphere along the open flux ropes. Furthermore, we have evaluated the current density J inside the tetrahedron of 4 spacecraft. Fig. 6 shows the three components of J for the event occurring at 11:16-11:17 UT and the first part FTE. One sees inside the flux ropes there is strong current flowing along the axis. Fig. 7 shows the uncertainty of the current evaluation (|$\Delta \boldsymbol{J}$

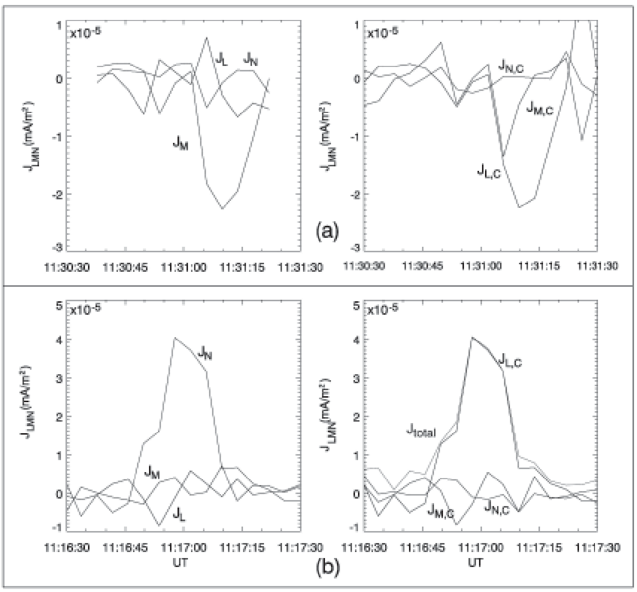

Fig.8 MVA of the calculated currents

|/ |$\boldsymbol{J}$ |= $|\nabla\cdot\boldsymbol{B}|/|\nabla\times\boldsymbol{B}|$[9]) which is less than 0.2 near the centers of the ropes. We have also made a further MVA of the calculated currents. Fig. 8 plots the event of 11:16-11:17 UT and the first part FTE. One finds that the maximum component of J is along the maximum variation direction of J which is also the direction of the flux rope axis! Other events possess the same feature. Finally we caaried out an FFT analysis and the deHoffmann-Teller analysis (HTA) for these events. The repeated period of the multiple flux ropes (not including the FTE) was found

Table 2 HTA Results of Multiple Flux Rope Events in GSE

Event	F	q	Vx (km)	Vy (km)	Vz (km)
~11:10	154°	59°	-218.8	105.9	145.0
~11:14	159°	59°	-203.0	77.9	132.2
~11:15	155°	62°	-241.3	113.8	141.2
~11:17	154°	57°	-220.2	105.6	156.5
~11:18	152°	59°	-212.6	111.1	143.1
~11:22	147°	64°	-273.8	174.6	160.1
~11:31	155°	67°	-278.9	131.2	130.6

to be ~72 s. The HTA results are given in Table 2. Apparently all flux ropes, including FTE, were convected toward the spacecraft along a similar direction.

The following conclusions can be obtained from the data: (1) Each energetic ion burst was related to a flux rope of which the characteristic diameter is roughly ~ 1 R_E (the diameter of FTE is ~ 2 R_E[7]), while the repeated period is ~ 72 s. (2) Each flux rope has a strong guide field along the axis and manifests a current tube. The axes of flux ropes are basically coincident with the axes of current tubes along which strong currents are flowing. The maximum current dansity J can reach as high as ~10^{-8}A/m^{-2}. (3) These flux ropes were produced by MR somewhere away and convected to the spacecraft along a same direction. (4) Energetic protons, He and CNO ions were moving basically along the axes of flux ropes out of the magneto-sphere toward the magnetosheath.

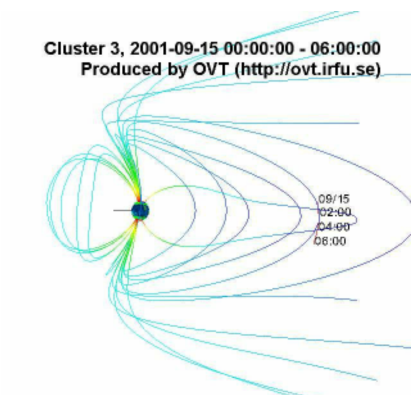

Fig.9 Position of Cluster 3 on September 15, 2001, 00:00 to 06:00.

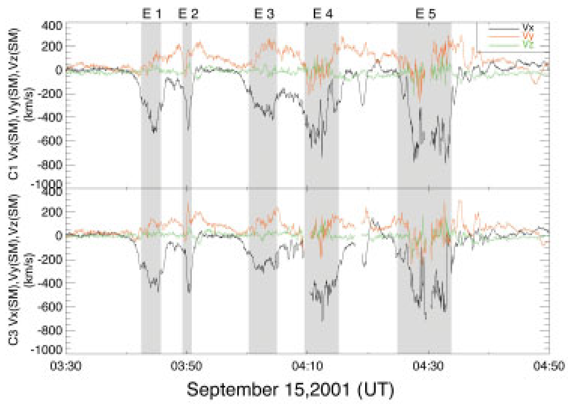

Fig.10 Five high-speed tailward ion flow events.

3. Multiple Collisionless MR Events in the Magnetotail

On September 15, 2001 when Cluster II moved across the plasma sheet at the apogee four spacecraft observed five multiple MR events. Fig. 9 shows the spacecraft location and orbit. Five high-speed tailward ion flows were detected which are plotted in Fig. 10. Fig. 11 presents magnetic field measure-ments obtained from four spacecraft. From the observed X- and Z-components it is inferred that during all five events MR took place earthward of the spacecraft. In events 1, 2 and 4 four spacecraft were all situated north of the equator. On the other hand, in events 3 and 5, C1, C2 and C4 were north of the equator, while C3 was south of the equator. The tetrahedron configuration of Cluster II is schematically shown in Fig. 12 for these two events. It is of importance to note that when measurement was made south of the equator where B_x <0, B_y became positive, a signature of the quadrupole out-of-plane Hall B-field pattern near the

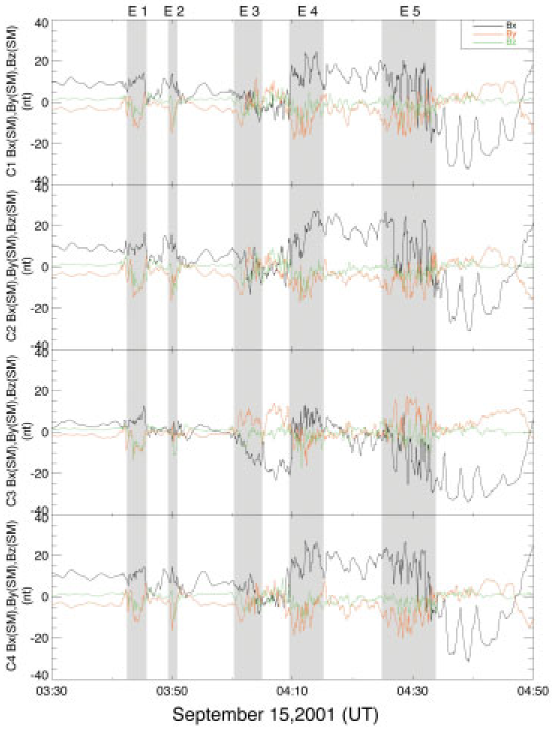

Fig.11 Magnetic field measurements obtained from four spacecraft.

diffusion region in collisionless MR. Energetic electron fluxes of four spacecraft and tailward flows of hot ions show that electron energizaton apparently appeared earlier than the bulk ion flow and magnetic field variations. The energization of 50 keV and 96 keV electrons happens simultaneously, indicating that the diffusion region was not far from the spacecraft. The observations thus provide evidence that collisionless MR occurs in the magnetotail.

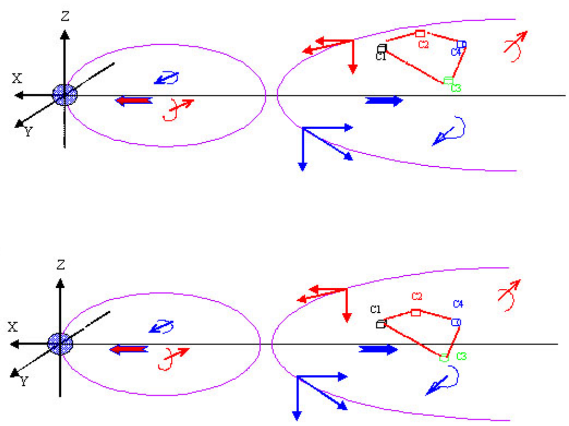

Fig.12 The tetrahedron configuration of Cluster II.during events 1, 2 and 4 (top) and events 3 and 5 (bottom).

In summary, MR is now no longer an essentially theoretical and simulation subject. The MR processes in the magnetospheric system themselves offer excellent opportunities to observe and thereby understand MR. More detailed features of MR will be revealed in the near future by combined efforts of theortical, simulation and in situ multiple spacecraft measurements.

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