Chapter 1
Fundamental Concepts Associated with Magnetic Reconnection

W.D. Gonzalez, E.N. Parker, F.S. Mozer, V.M. Vasyliūnas, P.L. Pritchett, H. Karimabadi, P.A. Cassak, J.D. Scudder, M. Yamada, R.M. Kulsrud, and D. Koga

Abstract The chapter starts with a discussion about the importance of the concept of magnetic field lines in space plasmas and magnetic reconnection, followed by presentations on: (a) the meaning and validity of empirical constructs related with magnetic reconnection research, such as: "moving" magnetic field lines, "frozen-in" condition and "diffusion region" of reconnection; and (b) experimental evidence of the diffusion region and related energetics. Next, aims to link external (MHD) with internal (non-MHD) regions of reconnection are discussed in association with

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W.D. Gonzalez (✉) • D. Koga
National Institute for Space Research (INPE), São José dos Campos, São Paulo 12227-010, Brazil
e-mail: walter.gonzalez@inpe.br

E.N. Parker
Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637, USA

F.S. Mozer
Space Sciences Laboratory, University of California, Berkeley, CA 94720, USA

V.M. Vasyliūnas
Max-Planck-Institut für Sonnensystemforschung, Göttingen 37077, Germany

P.L. Pritchett
Department of Physics and Astronomy, University of California, Los Angeles, CA 90095-1547, USA

H. Karimabadi
SciberQuest, Inc., Del Mar, CA 92014, USA

CureMetrix, Inc., Rancho Santa Fe, CA 92067, USA

P.A. Cassak
Department of Physics and Astronomy, West Virginia University, Morgantown, WV 26506, USA

J.D. Scudder
Department of Physics and Astronomy, University of Iowa, Iowa City, IA 52242, USA

M. Yamada • R.M. Kulsrud
Center for Magnetic Self-Organization, Princeton Plasma Physics Laboratory, Princeton University, Princeton, NJ 08544, USA

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the so-called “Axford conjecture”, followed by short presentations on: (a) global equilibria in reconnection; and (b) the role of the separatrices in global aspects of reconnection. In the last section, we present additional discussion about the concept of “diffusion region” and about the two fundamental questions associated with magnetic reconnection reviewed in this chapter.

Keywords Magnetic reconnection concepts • Magnetic field lines • Frozen-in condition • Magnetic diffusion • Generalized Ohm’s law • Global equilibria • Magnetic energy transfer • Magnetic reconnection onset • Magnetospheric reconnection • Magnetic reconnection separatrices

1.1 Introduction

Before discussing about magnetic reconnection and its applications in this Book, we review some fundamental concepts associated with magnetic reconnection in a somewhat different perspective from those presented in previous reviews, also trying to incorporate some recently developed ideas about them.

The main motivation for this introductory chapter is the presentation of some updated answers to the following fundamental and long-lasting questions associated with magnetic reconnection:

1. Near the X-line, magnetic field lines “get cut” and later “reconnect” and exit. What does this mean and how does it happen?
2. What defines the reconnection rate, internal processes in the diffusion region or external parameters associated with the overall reconnecting system, or both? What is the role/importance of the separatrices for the study of a combined reconnection rate?

Thus, with respect to Question 1, this Chapter starts in Sect. 1.2 with a review about magnetic field lines (E.N. Parker); followed in Sect. 1.3 by presentations on Empirical Constructs associated with “moving” magnetic field lines, “frozen-in” condition and “diffusion region” of reconnection (F.S. Mozer and P.L. Pritchett), and in Sects. 1.3A and 1.3B, on Experimental evidence of the diffusion region and related energetics (M. Yamada). Concerning Question 2, a discussion about “global aspects of magnetic reconnection and the Axford Conjecture” is given in Sect. 1.4 (V.M. Vasyliūnas); followed by discussions on Global Equilibria in reconnection in Sect. 1.4A (R.M. Kulsrud), and on the Role of Reconnection Separatrices in global aspects of magnetopause reconnection in Sect. 1.4B (W.D. Gonzalez and D. Koga). Finally, Sect. 1.5 presents additional discussion on the concept of “diffusion region” and on Questions 1 and 2, as formulated by some of the other authors.

Most of the Discussion presented in this chapter is done without mentioning much of the relevant references since, being the subject about diverse issues, the list of references would be too extensive.

1.2 Magnetic Field Lines (E.N. Parker)

Magnetic field lines present a graphic picture of the form and topology of the magnetic field, as well as playing a central role in the equilibrium of the field. In particular, it is the field line connections (topology) and the reconnections associated with resistive dissipation of the field, that are the subject of this Book. We consider a large-scale magnetic field embedded in a highly conducting fluid.

A field line is a curve that lies along the magnetic field $B_i(x_k)$ everywhere along its length. Thus the direction cosines of the curve are equal to the direction cosines of the field, and we have

$$\frac{dx_i}{ds} = \frac{B_i}{B}, \tag{1.1}$$

where B is the magnitude of the field and ds represents arc length along the field line. The field line through any point P is defined by the integration of Eq. (1.1) in both directions from P. A nearby point P' defines another field line, etc. and the set of all such points and their associated field lines form a manifold making up the continuous magnetic field $B_i(x_k)$. Neglecting the small resistivity of the fluid for the moment, the magnetic field is carried bodily with the fluid, so we think of the magnetic field lines as moving with the fluid. The connectivity of the fluid lines is preserved by the continuity of the flow velocity. The magnetic field lines play a basic role in the determination of the self-equilibrium of the magnetic stresses. The equilibrium is described by

$$\frac{\partial M_{ij}}{\partial x_j} = 0, \tag{1.2}$$

where

$$M_{ij} = -\delta_{ij}\frac{B^2}{8\pi} + \frac{B_i B_j}{4\pi} \tag{1.3}$$

represents the magnetic stress tensor. The magnetic field exerts an isotropic pressure $B^2/8\pi$ and a tension of twice that amount in the direction along the field lines. As is well known, the equilibrium equation for exact balance between pressure and tension reduces to the form

$$\nabla \times \mathbf{B} = \alpha \mathbf{B}. \tag{1.4}$$

The divergence of the equilibrium equation yields the remarkable result

$$B_j \frac{\partial \alpha}{\partial x_j} = 0, \tag{1.5}$$

stating that the torsion coefficient α is constant along each individual field line no matter what the field line topology. That is to say, the field lines form a family of real characteristics of the equilibrium equation, playing a fundamental role in the structure of the solutions to Eq. (1.4). Then there is the contradictory requirement that the torsion does not vary regardless of how variable may be the writhe of the field line through the region of field. The small set of continuous fields that satisfy this strenuous requirement is characterized by the solutions of the 2D vorticity equation, in which time is replaced by distance along the field. So almost all field line topologies fall outside this special category, providing what are called the *weak solutions* with their combination of current sheets and local domains of the vortex-like solutions. Note finally that each field line in an equilibrium field is subject to the *optical analogy*, that the path of a field line between any two points on a flux surface is identical with the optical ray path on the flux surface in an index of refraction proportional to the field magnitude $B(x_k)$. Thus the field line is described by Fermat's principle and the associated Euler equations (Parker 1991).

Interest lies in large-scale magnetospheric and astrophysical settings where the magnetic field is vigorously swirled by the active convection of the fluid. The evolution of the field is described on those large scales by the familiar MHD induction equation,

$$\frac{\partial B_i}{\partial t} + v_j \frac{\partial B_i}{\partial x_j} = B_j \frac{\partial v_i}{\partial x_j} - B_i \frac{\partial v_j}{\partial x_j} + \eta \nabla^2 B_i, \tag{1.6}$$

where η is the resistive diffusion coefficient, providing a simple example of the dissipation necessary for reconnection. In the absence of resistive diffusion the Cauchy integral for the magnetic field can be set up in terms of the Lagrangian coordinates $x_i(X_k, t)$ at time t of the element of fluid at X_i at $t = 0$, providing

$$\frac{B_i(x_k, t)}{\rho(x_k, t)} = \frac{B_j(X_k, 0)}{\rho(X_k, 0)} \frac{\partial x_i}{\partial X_j}. \tag{1.7}$$

The local tumbling and stretching of the magnetic field is expressed by the progressive tumbling and stretching $\partial x_i / \partial X_j$ of the Lagrangian element of fluid. In the presence of resistive dissipation the connectivity of the field lines is generally not conserved, becoming a function of time. For a brief glimpse of the field line reconnection phenomenon put the fluid at rest so that Eq. (1.6) reduces to the familiar diffusion equation for each of the Cartesian components of the magnetic field,

$$\frac{\partial B_i}{\partial t} = \eta \nabla^2 B_i. \tag{1.8}$$

It follows that the initial magnetic field $B_i(x_k, 0)$ in an infinite space diffuses into

$$B_i(x_k, t) = \frac{1}{(4\pi\eta t)^{3/2}} \int\int\int d^3x'_k B_i(x'_k, 0) \exp\left[-\frac{(x_k - x'_k)^2}{4\eta t}\right] \qquad (1.9)$$

in a time t. It is evident from the integration over space that the new field at time t represents a linear superposition of the diverse elements of field from a surrounding neighborhood of characteristic radius $(4\eta t)^{1/2}$. Thus the direction of the local field is perturbed in ways that depend on surrounding fields, thereby changing the path of the forward integration of Eq. (1.1). So the field line fails to connect with the same original field line ahead. And that is the nature of magnetic field line reconnection. It occurs in the presence of dissipation, with our illustrative example based on Ohmic diffusion. We can see that, with the ongoing reconnection, the individual field lines lose their original identity where they pass through a local region of diffusion.

In a field inhomogeneity with scale λ the characteristic reconnection time is comparable to the characteristic diffusion time λ^2/η. On astrophysical scales the diffusion time can be very long indeed, so very little reconnection occurs and can generally be ignored. On the other hand, in situations where the magnetic stresses and/or vigorous fluid motion create strong small-scale variation in the field, the reconnection goes rapidly and becomes a dynamical effect of interest in its own rite, providing such suprathermal phenomena as the aurora and solar flares and intense coronal heating. With these properties of magnetic field lines in mind, we turn to the rapid reconnection phenomenon itself in the active conditions presented by nature.

1.3 Empirical Constructs Associated with Magnetic Reconnection (F.S. Mozer and P.L. Pritchett)

Since the external/global regions associated with reconnection are usually fairly well described by the MHD approximation, in which the concepts "moving" magnetic field lines and "frozen-in" condition are commonly used, in this section we review these concepts together with that known as "diffusion region" of reconnection, considering them only as empirical constructs. Thus, the basic aim of this section is to caution about the validity of their applications.

What is an Empirical Construct?

An empirical construct is a model, concept, or image that exists in the mind that cannot be tested via experiment, so it doesn't exist in the physical world. While empirical constructs are extremely useful for visualizing physical problems, they can also be applied in domains where their solutions differ from those obtained from Maxwell's equations and Newton's laws of motion. This can lead to confusion and non-physical results. Examples of use and misuse of empirical constructs are the following:

- Moving magnetic field lines
- Frozen-in condition
- The diffusion region of reconnection

Moving Magnetic Field Lines

This is an extremely useful concept for visualizing the temporal evolution of a magnetic field geometry. However, it is also an extremely confusing concept when its application is not well justified. Under what conditions does the empirical construct of moving magnetic field lines produce the same answers as Maxwell's equations and Newton's laws of motion (Newcomb 1958; Longmire 1963)?

Consider the conditions under which field line motion in a plasma causes the magnetic field MAGNITUDE and DIRECTION to evolve in time in a manner consistent with Maxwell's equations and Newton's laws of motion.

Magnitude

In ideal MHD magnetic field lines are not created or destroyed. As the field strength changes, they simply move into or out of the region of interest. Thus, magnetic field lines are conserved.

For an ideal MHD, Ohm's law is $\mathbf{E} + \mathbf{v} \times \mathbf{B}/c = 0$. Thus, Faraday's law gives $\partial \mathbf{B}/\partial t = \nabla \times (\mathbf{v} \times \mathbf{B})$. Then, if we consider a curve C (bounding a surface S) which is moving with the plasma, in a time dt an element $d\mathbf{s}$ of C sweeps out an element of area $\mathbf{v}dt \times d\mathbf{s}$. The rate of change of magnetic flux through C is :

$$\frac{d}{dt}\int_S \mathbf{B} \cdot d\mathbf{S} = \int_S \frac{\partial B}{\partial t} \cdot d\mathbf{S} + \int_C \mathbf{B} \cdot \mathbf{v} \times d\mathbf{s}. \tag{1.10}$$

Thus, as C moves, the flux changes due to the change of $\mathbf{B}$ with time and due to the boundary C moving in space [last term of Eq. (1.10)]. Setting $\mathbf{B}\cdot\mathbf{v}\times d\mathbf{s} = -\mathbf{v}\times\mathbf{B}\cdot d\mathbf{s}$ and applying Stokes's theorem to the last term of Eq. (1.10), we have:

$$\frac{d}{dt}\int_S \mathbf{B} \cdot d\mathbf{S} = \int_S \left(\frac{\partial B}{\partial t} - \nabla \times (\mathbf{v} \times \mathbf{B})\right) \cdot d\mathbf{S},$$

which is equal to zero in the ideal MHD limit.

Therefore, if the magnetic field lines move with speed $\mathbf{v} = c\mathbf{E} \times \mathbf{B}/B^2$, the magnitude of the magnetic flux is conserved.

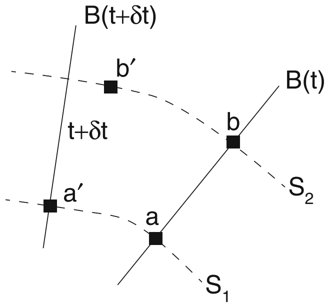

Fig. 1.1 Geometry of moving magnetic field lines (from Mozer 2005)

Velocity

Consider two surfaces, S_1 and S_2, as in Fig. 1.1, that are perpendicular to the magnetic field at times t and $t + \delta t$. At time, t, a magnetic field line intersects the two surfaces at points **a** and **b**. Thus, the vector $(\mathbf{b} - \mathbf{a})$ is parallel to $\mathbf{B}(t)$ and assumed to be $\varepsilon\mathbf{B}(t)$. At the later time, $t + \delta t$, the points **a** and **b** have moved at velocities $c\mathbf{E} \times \mathbf{B}/B^2(\mathbf{a})$ and $c\mathbf{E} \times \mathbf{B}/B^2(\mathbf{b})$ to points $\mathbf{a}'$ and $\mathbf{b}'$. What are the constraints on these motions that cause $(\mathbf{b}' - \mathbf{a}')$ to be parallel to $\mathbf{B}(\mathbf{a}, t + \delta t)$, i.e. $(\mathbf{b}' - \mathbf{a}') \times \mathbf{B}(\mathbf{a}, t + \delta t) = 0$?

From Mozer (2005) one obtains the following two equations:

$$(\mathbf{b}' - \mathbf{a}')/\varepsilon = \mathbf{B} + \mathbf{B} \cdot \nabla(c\mathbf{E} \times \mathbf{B}/B^2)\delta t$$

and

$$\mathbf{B}(\mathbf{a}, t + \delta t) = \mathbf{B} + (\delta\mathbf{B}/\delta t)\delta t + (c\mathbf{E} \times \mathbf{B}/B^2) \cdot \nabla)\mathbf{B}\delta t.$$

Finally, after simplifying to first order in δt, Mozer (2005) obtained the following equation:

$$\mathbf{B} \times (\nabla \times \mathbf{E}_{||}) = 0.$$

Thus, for example, if $\mathbf{E}_{||} = 0$, $c\mathbf{E} \times \mathbf{B}/B^2$ motion causes the field to evolve in a manner consistent with Maxwell's equations. But, if $\mathbf{B} \times (\nabla \times \mathbf{E}_{||}) \neq 0$, Maxwell's equations, together with the other plasma equations, must be solved to find $\mathbf{B}(t)$.

Figure 1.2 shows an example from a particle-in-cell simulation (Pritchett and Mozer 2009) of interacting magnetic fields at the magnetopause in which there are regions (especially those seen in red and blue) where $\mathbf{B} \times (\nabla \times \mathbf{E}_{||}) \neq 0$. For such regions the $c\mathbf{E} \times \mathbf{B}/B^2$ motion can not represent the correct evolution of $\mathbf{B}(t)$.

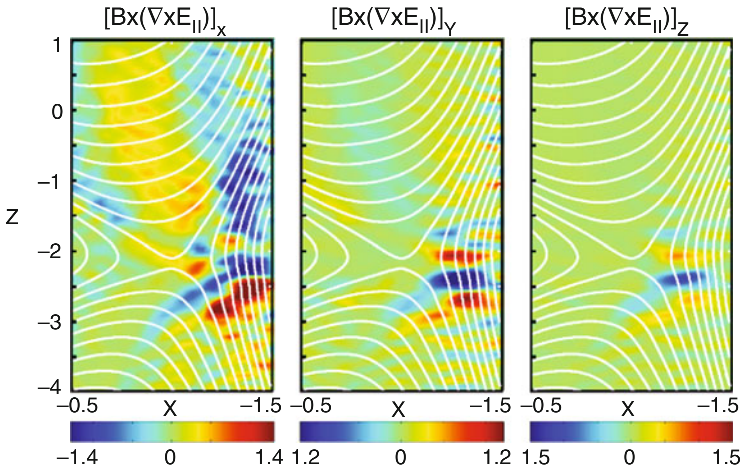

Fig. 1.2 Topology of fields and related quantities for asymmetric reconnection with a guide field (from Pritchett and Mozer 2009). Note that the color scales in all panels are saturated at half the maximum absolute value of the quantity of interest. This particle-in-cell (PIC) simulation was driven by an external E_Y field imposed at the magnetosheath boundary and the total systems size was $L_X \times L_Z = 25.6c/\omega_{pi} \times 25.6c/\omega_{pi}$

Frozen-In Condition

The frozen-in condition states that the plasma and the magnetic field move together at the $c\mathbf{E}\times\mathbf{B}/B^2$ velocity. Alfvén (1942) wrote "the matter of the liquid is fastened to the lines of force", but in 1976 he warned against use of "frozen-in" and "moving" magnetic field lines. Why did he change his mind? Because magnetic field lines cannot be said to move at the $c\mathbf{E} \times \mathbf{B}/B^2$ velocity during the most interesting situations in which the plasma is more complex than ideal MHD, such as at the reconnection-current sheets.

The Generalized Ohm's Law

A more general way of looking for regions where the frozen-in condition is violated is by analyzing the generalized Ohm's law. In two fluid theory, Newton's second law for a unit volume of plasma is:

$$\text{Ions: } n_i m_i (\partial \mathbf{U}_i/\partial t + \mathbf{U}_i \cdot \nabla \mathbf{U}_i) = n_i Ze(\mathbf{E} + \mathbf{U}_i \times \mathbf{B}/c) - \nabla \cdot \mathbf{P}_i + \mathbf{P}_{ie} \quad (1.11)$$

$$\text{Electrons: } n_e m_e (\partial \mathbf{U}_e/\partial t + \mathbf{U}_e \cdot \nabla \mathbf{U}_e) = -n_e e(\mathbf{E} + \mathbf{U}_e \times \mathbf{B}/c) - \nabla \cdot \mathbf{P}_e + \mathbf{P}_{ei} \quad (1.12)$$

where $\mathbf{P}_i$, $\mathbf{P}_e$ are the ion and electron pressure tensors, $\mathbf{P}_{ie}$ ($\mathbf{P}_{ei}$) is the momentum transferred from electrons (ions) to ions (electrons). Multiply Eq. (1.11) by e/m_i and Eq. (1.12) by e/m_e, then subtracting Eq. (1.12) from Eq. (1.11), neglecting quadratic terms, assuming electrical neutrality and ignoring m_e/m_i terms, for $Z = 1$, one gets the generalized Ohm's law:

$$\mathbf{E} + \mathbf{U}_i \times \mathbf{B}/c = \mathbf{j} \times \mathbf{B}/enc - \nabla \cdot \mathbf{P}_e/en + (m_e/ne^2)d\mathbf{j}/dt + (\mathbf{P}_{ie} - \mathbf{P}_{ei}). \quad (1.13)$$

Equivalently, because $(c/ne)\mathbf{j} = \mathbf{U}_i - \mathbf{U}_e$,

$$\mathbf{E} + \mathbf{U}_e \times \mathbf{B}/c = -\nabla \cdot \mathbf{P}_e/en + (m_e/ne^2)d\mathbf{j}/dt + (\mathbf{P}_{ie} - \mathbf{P}_{ei}). \quad (1.14)$$

In Eqs. (1.13) and (1.14) the last terms between parentheses at the right refer to the resistivity of the medium. Figure 1.3b presents a simulation of the components of $\mathbf{E} + \mathbf{U}_i \times \mathbf{B}/c$ and of $\mathbf{E} + \mathbf{U}_e \times \mathbf{B}/c$ for an asymmetric magnetopause (Mozer and Pritchett 2009), and shows locations where these components are different from zero, namely where the magnetic field lines are NOT frozen-in.

The Diffusion Region

The problem with this concept is that it is poorly-defined. If it was well-defined, it might be measurable and would not be an empirical construct. A common view is that the electron diffusion region is a box of size c/ω_{pe} (red rectangle in Fig. 1.3a) in which the electrons are not magnetized. This box is embedded in the ion diffusion region which is a box of size c/ω_{pi} (green rectangle in Fig. 1.3a) within which the ions are not magnetized. Figure 1.3b shows a computer simulation of the ELECTRON diffusion region, in which $\mathbf{E} + \mathbf{U}_e \times \mathbf{B}/c \neq 0$, and of the ION diffusion region, in which $\mathbf{E} + \mathbf{U}_i \times \mathbf{B}/c \neq 0$.

Comparison between Fig. 1.3a,b shows that a definition of the diffusion region as shown in Fig. 1.3a is not useful since, for example, the extension in the X and Z directions of the simulated electron and ion diffusion regions are not clearly different among them and do not resemble the model of Fig. 1.3a with the electron diffusion region clearly imbedded in the ion region.

Summary

One can't think of moving magnetic field lines that simply "get cut and reconnect" at the reconnection region because the concept of moving field lines do not apply there for being a non-MHD region. The concept of "diffusion region" usually adopted in reconnection models does not represent well the related observations and, therefore, needs to be better defined.

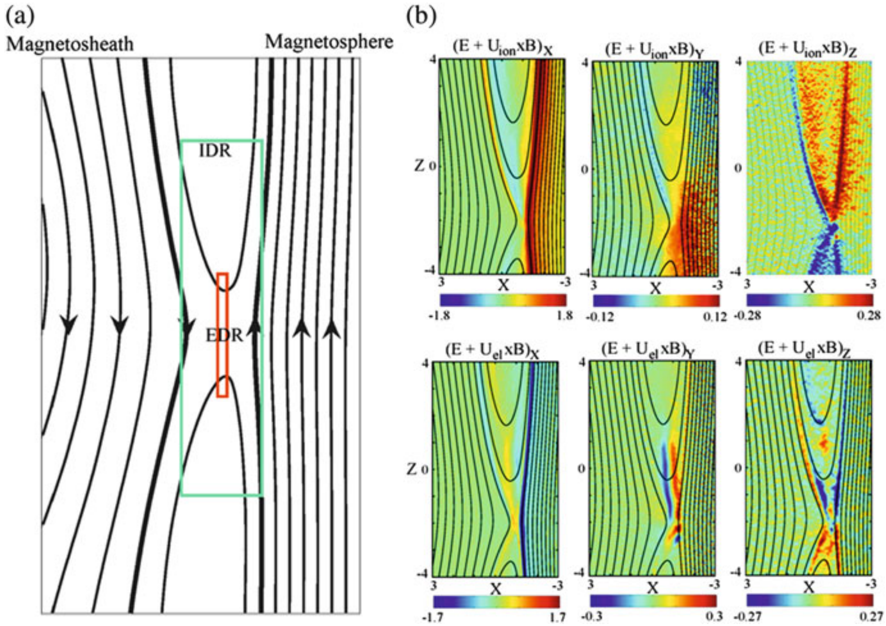

Fig. 1.3 (**a**) Illustration of ion (IDR) and electron (EDR) diffusion region. (**b**) Components of $\mathbf{E} + \mathbf{U}_i \times \mathbf{B}$ and $\mathbf{E} + \mathbf{U}_e \times \mathbf{B}$ (from Mozer and Pritchett 2009). The *red* and *blue* regions in each plot are the locations where the magnitude of the quantity of interest is greater than half of its peak value. This PIC simulation was driven by an external E_Y field imposed at the magnetosheath boundary and the total systems size was $L_X \times L_Z = 25.6c/\omega_{pi} \times 25.6c/\omega_{pi}$

1.3A Experimental Identification of Two-Scale Diffusion Region (M. Yamada)

In the MRX experiment (Yamada et al. 2010), we experimentally identified a two-scale diffusion layer in which an electron diffusion layer resides inside of the ion diffusion layer, the width of which is the ion skin depth (Ren et al. 2008). In this situation we define the ion diffusion layer as the regime of $\mathbf{E} + \mathbf{U}_i \times \mathbf{B}/c \neq 0$ and the electron diffusion layer as the regime of $\mathbf{E} + \mathbf{U}_e \times \mathbf{B}/c \neq 0$. Just outside of the electron diffusion layer, $\mathbf{E} + \mathbf{U}_e \times \mathbf{B}/c = 0$ holds, namely the out of plane reconnection $\mathbf{E}$ field is expressed by $\mathbf{U}_e \times \mathbf{B}/c$, where both $\mathbf{U}_e$ and $\mathbf{B}$ lie within the reconnection plane. It was concluded that Hall effects determine the reconnection rate. Furthermore, it was found that demagnetized electrons are accelerated along the outflow direction and within the reconnection plane, as shown in Fig. 1.4. The width of the electron outflow was shown to scale with the electron skin depth as $5 - 8c/\omega_{pe}$, which is ~3–5 times wider than predicted by 2D numerical simulations (Ji et al. 2008). While the electron outflow seems to slow down due to dissipation in the electron diffusion region, the total electron outflow flux remains independent of the width of the electron diffusion region. We note that even with presence of the

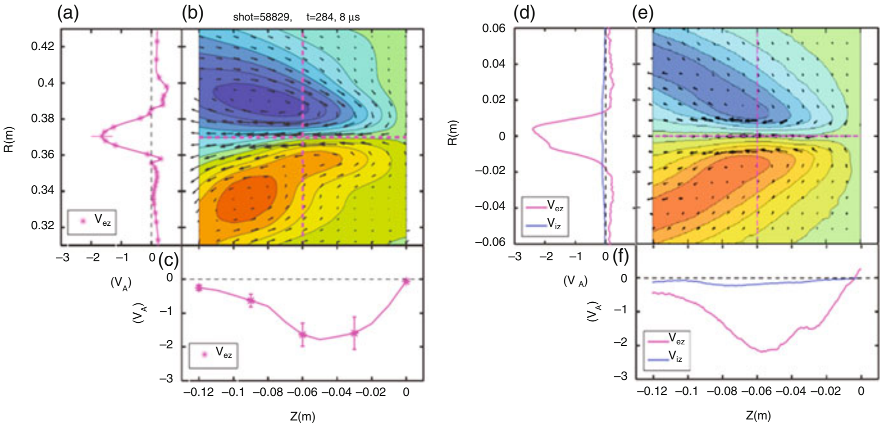

Fig. 1.4 Identification of electron diffusion layer. The *left three panels* (**a–c**) show measured out-of-plane field contours, flow vectors (*black arrows*), and flow velocities in the reconnection plane. Results from a corresponding 2D simulation at a reduced mass ratio are shown in the same format on the three panels (**d–f**) at the *right* using W. Daughton's 2D particle-in-cell code (from Ji et al. 2008; Dorfman et al. 2008)

narrow electron diffusion region, the reconnection rate is still primarily determined by the Hall electric field as was concluded by the GEM challenge (Birn et al. 2001). To our knowledge MRX results are one of the clearest observations of the electron diffusion region within a plasma. When either an externally imposed guide field or inflow asymmetry is applied, the configuration of the electron diffusion layer becomes deformed and changes to a more complex configuration.

1.3B The Energetics of the Two-Fluid Diffusion Layer (M. Yamada)

Our quantitative measurements in the MRX reconnection layer on the acceleration and heating of both electrons and ions demonstrate that half of the incoming magnetic energy is converted to particle energy at a remarkably fast rate (Yamada et al. 2014). In our study we have found that within a collisionless reconnection layer, the energy deposited into the ions is more than twice as large as that deposited into the electrons. Furthermore, a non-negligible amount of magnetic energy flows out the exhaust. It is important to note that when the energy deposition rate to electrons, $\mathbf{j}_e \cdot \mathbf{E}$, is decomposed into $\mathbf{j}_{e\perp} \cdot \mathbf{E}_\perp + \mathbf{j}_{e\parallel} \cdot \mathbf{E}_\parallel$, i.e. separating the inner product into that of the perpendicular and parallel components with respect to the local magnetic field lines, $\mathbf{j}_{e\perp} \cdot \mathbf{E}_\perp$ is measured to be significantly larger than $\mathbf{j}_{e\parallel} \cdot \mathbf{E}_\parallel$. Near the X-point where energy deposition is maximal, $\mathbf{j}_{e\perp} \cdot \mathbf{E}_\perp$ is larger than $\mathbf{j}_{e\parallel} \cdot \mathbf{E}_\parallel$ by more than an order of magnitude. We have observed that the conversion of magnetic energy occurs across a region significantly larger in area than the narrow electron diffusion region predicted by previous 2D simulations. A saddle shaped electrostatic potential profile is verified to exist within the reconnection plane both in the experiment and simulations and, as a result, ions are accelerated by the resulting electric field at the separatrices (Yoo et al. 2013). This acceleration and heating of ions happens in a wide region extending over an ion skin depth—the so-called ion diffusion region. These accelerated ions are then thermalized by re-magnetization in the downstream region. When the energy deposition rate to ions, $\mathbf{j}_i \cdot \mathbf{E}$, is decomposed into $\mathbf{j}_{i\perp} \cdot \mathbf{E}_{\perp} + \mathbf{j}_{i\parallel} \cdot \mathbf{E}_{\parallel}$, the perpendicular component, $\mathbf{j}_{i\perp} \cdot \mathbf{E}_{\perp}$, is again found to be dominant over $\mathbf{j}_{i\parallel} \cdot \mathbf{E}_{\parallel}$ in the regions where energy deposition to ions is maximal (Yamada et al. 2015, Chap. 4 of this book).

In Fig. 1.5a, c, it is clearly demonstrated that without guide field or asymmetry, the energy dissipation to electrons and ions occurs primarily due to $\mathbf{j}_{e\perp} \cdot \mathbf{E}_{\perp}$ and $\mathbf{j}_{i\perp} \cdot \mathbf{E}_{\perp}$ respectively, that is, the inner products of the perpendicular components of $\mathbf{j}$ and $\mathbf{E}$ with respect to $\mathbf{B}$. This demonstrates a different aspect of broad energy conversion from Mozer and Pritchett's (2011) results on asymmetric reconnection in

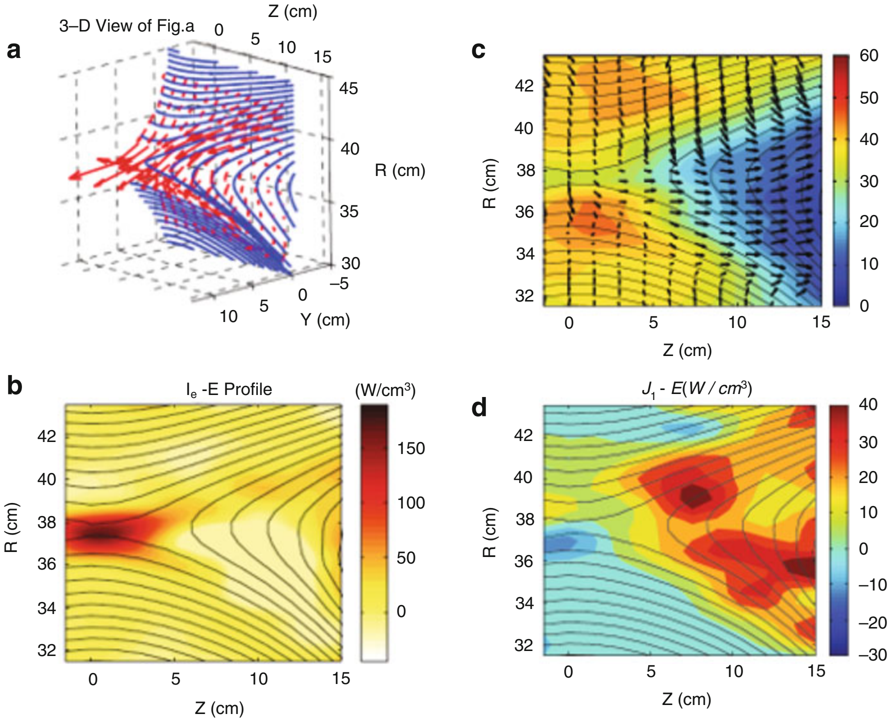

Fig. 1.5 Flow vectors of electron in 3-D views (**a**) and the energy deposition rate to electrons. High energy deposition is primarily due to $\mathbf{j}_{e\perp} \cdot \mathbf{E}_{\perp}$ which is concentrated in the electron diffusion region (**b**). Flow vectors of ion in the potential well (**c**). The energy deposition to ions occurs across the separatrices and in a much wider region than for electrons (**d**)

which $\mathbf{j}_{e\parallel} \cdot \mathbf{E}_{\parallel}$ was emphasized. Based on these results, it would be more appropriate to call these extended energy deposition regions, “energy conversion regions” rather than the “diffusion regions”.

1.4 Global Aspects of Magnetic Reconnection and the Axford Conjecture (V.M. Vasyliūnas)

1.4.1 Introduction

Magnetic reconnection can occur only if there are departures from ideal MHD. An obvious question is the extent to which the parameters specifying the non-MHD effects (electrical resistivity, inertial length, gyroradius, etc.) influence the configuration of the system. This question is often stated as: what determines the reconnection rate?. A more specific formulation, applied to a particular system (e.g., the Earth’s magnetosphere) is: what determines the amount of open magnetic flux and the rate of magnetic flux transport? These quantitative global parameters can be empirically estimated (from polar-cap area and from cross-polar-cap potential, respectively, among other methods) and have with some success been related to solar-wind parameters. The concept that such global parameters are determined primarily by large-scale MHD dynamics and boundary conditions, with non-MHD effects important mostly for determining properties of local small-scale structures such as boundary layers, was persistently and eloquently argued especially by W.I. Axford and is often called the “Axford conjecture”. Recent criticisms of the conjecture are based to a large extent on a misunderstanding of what it means. Unless the Axford conjecture is assumed to be valid at least to some degree of approximation, global MHD simulations of the magnetosphere (most of which do not even pretend to model non-MHD effects adequately) cannot be trusted to give reliable results on anything related to reconnection. Attempts to understand from first principles and derive theoretically the empirically established relations between the solar wind and the global properties of the open magnetosphere (or their proxies in geomagnetic/magnetospheric indices) require careful consideration of the Axford conjecture and related basic assumptions. Global MHD simulations of the magnetosphere, most of which do not even pretend to model non-MHD effects adequately, cannot be trusted to give reliable results on anything related to reconnection, unless the Axford conjecture is assumed to be valid at least to some degree of approximation.

1.4.2 Axford Conjecture

Perhaps the most succinct statement of what we now call the "Axford conjecture" is Axford's own summary of his opening talk at the Workshop on "Magnetic Reconnection in Space and Laboratory plasmas", held at Los Alamos National Laboratory in October 1983 (Axford 1984), Axford summarized his talk in the following way, which we now adopt as the "Axford conjecture":
"*Magnetic reconnection cannot occur unless there is a non-zero electrical resistivity (or some other departure from ideal MHD). However, the large-scale properties of the process are governed primarily by global dynamics and boundary conditions, not by the values of the resistivity or other non-MHD effects*"
(for other, more detailed statements, see Axford 1967, 1969). According to this conjecture, local properties of small-scale regions where the actual reconnection is occurring can depend strongly on resistivity or other non-MHD parameters, but the global configuration of the reconnecting system is largely independent of them. This is not an exact law but a useful approximation (somewhat like MHD itself). A simple analog frequently invoked by Axford is the role of viscosity in aerodynamics: the lift of a plane does not depend on the coefficient of viscosity, but if air were non-viscous then planes could not fly.

Recent criticisms of the Axford conjecture are based to a large extent on a misunderstanding of what it means. Sometimes the conjecture is interpreted as denying any role for the nonideal plasma "diffusion region"; this overlooks Axford's explicit acknowledgement that without nonideal effects there would be no reconnection. An even more extreme interpretation is that, because the solar-wind electric field is the boundary condition for dayside reconnection, the conjecture equates the solar-wind electric field to the magnetopause reconnection electric field; this holds only if any deflection of solar wind flow around the magnetosphere is negligible (a nonsensical assumption, never made by Axford).

1.4.3 Importance of Axford Conjecture

If it is assumed that the Axford conjecture does not hold to any significant degree of approximation, i.e., not only local but also global properties of reconnection are assumed governed primarily by non-MHD effects, then numerical global MHD simulations must be viewed as unreliable on issues involving reconnection (particularly on values of open magnetic flux, reconnection rates, and other quantitative parameters), because their non-MHD aspects are almost always unrealistic and are controlled only in part. Furthermore, it becomes difficult to demonstrate a rational basis for the construction and use of simple empirical coupling functions (driving functions), which relate magnetospheric indices to solar wind bulk parameters without reference to any non-MHD quantities.

When discussing the applicability or otherwise of the Axford conjecture, one should deal with specific defined quantitative physical parameters, not just vague general concepts (such as "reconnection rate") which may be ambiguous and depend on the non-unique definition of "magnetic reconnection". A specific example is discussed in the next section.

1.4.4 Quantitative Properties of an Open Magnetosphere

The simplest configuration of a magnetically open magnetosphere (Fig. 1.6) can be described by three basic quantities: Φ_M = total amount of open magnetic flux, $\mathscr{L}_X$ = length of the dayside reconnection X-line segment, projected along plasma flow streamlines back into the undisturbed solar wind (not the length at the X-line itself), and $\mathscr{L}_{MT}$ = distance between the dayside and the nightside locations of the outer (interplanetary/open) branch of the separatrix, extended into the undisturbed solar wind ("effective length" of the magnetotail). In terms of solar-wind parameters,

$$\Phi_M \simeq \mathscr{L}_X \mathscr{L}_{MT} B_s,$$

$$c\mathscr{E}_d \simeq \mathscr{L}_X V_{sw} B_s,$$

$$(d/dt)\Phi_M = c\mathscr{E}_d - c\mathscr{E}_n,$$

where B_s = reconnecting component of interplanetary magnetic field, and $\mathscr{E}_d$, $\mathscr{E}_n$ = line integrals of electric field along dayside and nightside reconnection segments of

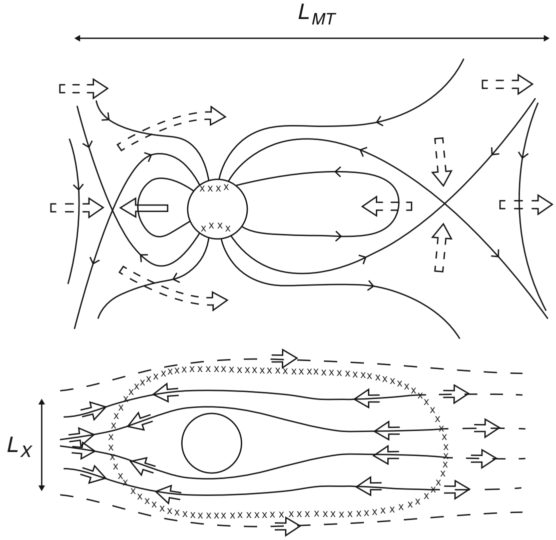

Fig. 1.6 Schematic topological view of magnetically open magnetosphere (from Vasyliūnas 2011). (*Upper*) noon-midnight meridian plane. (*Lower*) equatorial plane. Lines: plasma flow streamlines, x's: (projection of) magnetic X-line = interplanetary/open/closed field line boundary = polar cap boundary

X-line, respectively. In quasi-steady state: $\mathscr{E}_d \simeq \mathscr{E}_n$ = maximum line integral of electric field across polar cap (cross-polar-cap potential, transpolar potential).

The dayside reconnection rate can be specified by

$$c\mathscr{E}_d \simeq \mathscr{L}_X V_{sw} B_s \tag{1.15}$$

It is thus given by known solar wind parameters, plus two numbers to be determined: a length $\mathscr{L}_X$, and an angle that relates B_s to the interplanetary magnetic field B_{SW}. Equation (1.15) represents the electric field integral along a line segment which intersects all interplanetary magnetic field lines, transported by the solar wind, that are going to reconnect with geomagnetic field lines. The essence of the Axford conjecture is that these two numbers are global properties of the flow field, hence governed by the momentum equation and boundary conditions. The reconnection rate given by Eq. (1.15) can also be specified instead by the equivalent line integral along the X-line at the magnetopause and can (in principle!) be calculated from it, provided one knows in detail the extent and path of the reconnecting portion of the X-line and the variation of the electric field along it with local properties—all quantities governed (of course) by local non-MHD effects. (Much recent criticism of the Axford conjecture derives from confusing these two ways of defining the reconnection rate.)

The global calculation of dayside reconnection rate requires solving two coupled flow problems:

1. Magnetosheath (interplanetary field lines): How much solar-wind flow goes around the magnetosphere vs. how much enters the magnetosheath/magnetosphere interaction region?. $\mathscr{L}_X$ is the width in the solar wind of the bundle of streamlines connecting to the interaction region.
2. Magnetosheath/magnetosphere (open field lines): How much plasma entering from the magnetosheath can be accommodated in the diverted post-reconnection flow?. This provides the inner boundary condition necessary to calculate magnetosheath flow and inter alia determine $\mathscr{L}_X$.

The non-MHD-controlled reconnection at and in the immediate vicinity of the X-line (diffusion region) suffices to allow non-zero normal magnetic field and plasma entry elsewhere in the interaction region; the global rate of plasma entry, and hence the value of $\mathscr{L}_X$, should then be controlled primarily by large-scale dynamics of the post-reconnection flow (Axford conjecture in a nutshell!).

Empirical support for this concept may be provided by the observed phenomenon of cross-polar-cap potential saturation (see review by Shepherd 2007 and references therein): for sufficiently large values of the interplanetary electric field, the transpolar potential no longer increases but approaches a constant value. This means that, as the amount of "reconnectable" interplanetary magnetic flux transported by the solar wind increases, the fraction of the incoming flux that actually reconnects with the geomagnetic field (or, equivalently, the value of $\mathscr{L}_X$) decreases. The (increasingly large) remainder must then flow around the magnetosphere without reconnecting. A plausible explanation is that some property or process of post-reconnection flow acts to limit the amount of magnetic flux that can be transported; mechanisms involving collisional drag in the ionosphere or strong magnetic forces in the magnetosheath have been proposed.

1.4.5 Conclusions

1. Non-MHD terms in the generalized Ohm's law are essential for the occurrence of magnetic field line reconnection, but their direct effects are mainly local, confined to small regions. The primary global consequence is to remove certain constraints, allowing flow and field configurations that otherwise could not occur.
2. These newly allowed flows are subject to the same continuity and momentum balance conditions (Newton's and Maxwell's laws) as any others, hence (Axford conjecture) their large-scale properties should be governed to first approximation by global considerations (note that the Axford conjecture makes no predictions about local properties of non-MHD regions, a point often overlooked in recent criticism).
3. The dayside magnetopause reconnection rate is expected to be constrained primarily by removal of plasma and magnetic flux in (distant) post-reconnection flow. Magnetosheath (pre-reconnection) flow can always adjust itself to any required rate.
4. The observed cross-polar-cap potential saturation may be considered as evidence for the control process described in conclusion (3).

1.4A Global Equilibria (R.M. Kulsrud)

It was shown in the paper of Kulsrud (2011) that during reconnection the global evolution of the surrounding material is, other than its rate, independent of the nature of the processes occurring in the reconnection layer. This statement is valid if the reconnection is slow compared to dynamic times and if the reconnection layer and the separatrix dividing the unreconnected and reconnected regions are very thin. That is to say, one can lay out a series of global equilibria and in each case give the actual geometry and distribution of properties in the unreconnected and reconnected regions. The only dependence on the reconnection processes in the thin layers is the rate at which the global equilibrium progresses through this series.

This statement is based on the variational principle for magnetostatic equilibrium that states that for certain constraints the entire global equilibrium outside of the layers, including the geometry of the different regions, is given by minimizing the total potential energy (Kruskal and Kulsrud 1958; Uzdensky et al. 1996; Kulsrud 2011).

The equilibrium of course satisfies

$$\mathbf{j} \times \mathbf{B} = \nabla p \tag{1.16}$$

inside the two volumes and also the total pressure $P = p + B^2/8\pi$ is the same on each sides of the dividing region.

The constraints are as follows. Denote the unreconnected volume by A and the reconnected volume by B. Let the magnetic fluxes included by the magnetic surfaces in A be ψ_A and in B be ψ_B. Then the constraints which are held fixed under the variation are: the mass functions $M_A(\psi_A)$ and $M_B(\psi_B)$ representing the masses included in the corresponding flux surfaces, the toroidal flux functions $\phi_A(\psi_A)$ and $\phi_B(\psi_B)$ representing the toroidal flux included in the corresponding flux surfaces, and the entropy functions $S_A(\psi_A)$ and $S_B(\psi_B)$ representing the entropies ($S = p/\rho^\gamma$) on the corresponding flux surfaces. (These functions are of interest, because they are preserved during any MHD evolution.)

The variational principle states that of all possible choices of the pressure and magnetic fields that have magnetic surfaces and which satisfy the same constraints, the choice that gives the minimum potential energy

$$\int \left(\frac{p}{\gamma - 1} + \frac{B^2}{8\pi} \right) d^3x$$

where the integral is taken over both A and B, satisfies the magnetostatic equation Eq. (1.16). It also satisfies the continuity of P taken across all the layers. The converse is also true, that any equilibrium state must have a minimum energy under the constraints.

The consequence is that the global equilibrium is uniquely specified by giving the mass functions, toroidal flux functions and the entropy functions.

Now, consider that reconnection after a time dt has removed a flux $d\psi$ from the unreconnected region A, and added it to the reconnected region, B. Since the reconnection layer is very thin the loss of any toroidal flux $d\phi$ in passing from region A to B will be very small and similarly for the Mass dM.

The situation after the reconnection time dt will be that A will have less poloidal flux by an amount $d\psi$, but the functions ϕ, M and S, which are constraints of the motion in MHD, are unchanged over the remainder of the range. In region B the flux $d\psi$ will be added and the range of $d\psi_B$ will be extended by $d\psi$. Again the functions ϕ, M, and S will be unchanged over the original range. However in the extension of its range $d\psi$, the values of the toroidal function and of the mass function will be the same as they were in the last part of its range in A before the infinitesimal reconnection.

However, the entropy will change in the residual range by dissipation processes in the reconnection and separatrix layers. One could imagine that one would have to work out the entropy gain in the reconnection layer in order to complete the function in B. However, if the global region is surrounded by a rigid wall, the total energy must be unchanged. Thus, the value of S in the extended range of the energy is conserved, and the new resulting entropy in the residual flux region of B is determined.

Thus, since the new functions after the infinitesimal reconnection during dt are predetermined once $d\psi$ is known, the new global equilibrium including the changed geometry is completely determined by global physics alone. Only the amount of flux change in the time *dt* depends on the actual reconnection physics in the layer.

I have not mentioned the kinetic energy generated in the reconnection process. But under the assumption that reconnection is slow any velocities in region *B* will be quickly damped by parallel viscosity, which is very large, and the kinetic energy can be considered to be immediately converted to thermal energy and entropy.

Thus, after any reconnection time step all the constraints $(\phi(\psi), M(\psi), S(\psi))$ will be determined in both regions *A* and *B* by the amount of reconnected flux, $d\psi$. Therefore, since the global equilibrium is determined by these functions the new equilibrium is established independent of the physics in the narrow layers.

In conclusion, during any sufficiently slow reconnection the sequence of global equilibria will be independently determined by global considerations and not local ones. The role of the reconnection processes is merely to determine the rate at which the global equilibrium proceeds through this series.

1.4B Role of Reconnection Separatrices in Global Aspects of Magnetopause Reconnection (W.D. Gonzalez and D. Koga)

Figure 1.7 illustrates the B-fluxes and plasma flows at the inflow and outflow reconnection regions expected from classical reconnection models, as also claimed below in Sect. 1.5 concerning the needed curvature of the reconnecting B-field topology. The illustrated separatrices (discontinuities separating the non-reconnected from the reconnected B-fluxes) have been found to be rich in plasma and electric field-complex structures, including field-aligned flows, parallel electric fields, density non-uniformities, electron holes, etc (e.g., Lapenta et al., Chap. 8 of this volume). Thus, although from the kinetic point of view the separatrices have plasma and field structures similar to those proper of the diffusion region, from a global view of the overall reconnection region the separatrices can be considered to behave as an interlink between the central diffusion region (black rectangle) and the external large-scale reconnection region. From space and laboratory measurements at the moment we do not know the extension of the separatrices in the large scale reconnection domain, and of its participation in the influence of the external region plasma and field characteristics (boundary conditions) in the physics of the diffusion region, and vice versa. As discussed in Sect. 1.5.1 dealing with the diffusion region, one can also see from these considerations that it is not a simple matter to define spatial limits for the diffusion region since they can become confused with those of the separatrices. The structure of the separatrices should change from case to case according to the selected reconnection scenario for which the boundary conditions and external plasma and field properties can be different, as for example comparing the reconnection case at the dayside magnetopause of the Earth with that at the tail of the magnetosphere. In the former one has a typical asymmetric reconnection with different plasmas and fields entering from the magnetosheath and the magnetosphere to reconnect, the former being influenced by the changing solar wind. On the other hand, at the magnetospheric tail one finds usually a symmetric

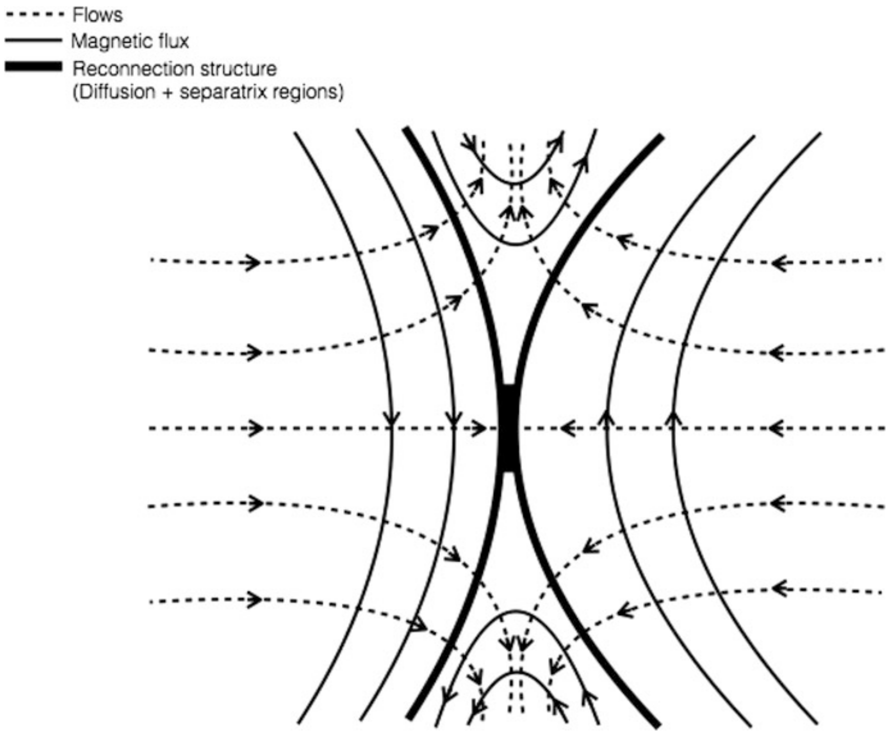

Fig. 1.7 Internal and external regions of the reconnection magnetic field topology and flows

reconnection scenario with plasmas and fields influenced, both, by the solar wind conditions and by the internal dynamics of the magnetosphere.

Figure 1.8 illustrates the expected geometry of the separatrices (dotted curves) between the reconnecting regions at the dayside magnetosphere, as seen on the noon-midnight meridional plane. The approaching solar wind speed, V_{sw}, after the Bow shock becomes decelerated down to the reconnection speed, V_o, close to the magnetopause. After reconnection the reconnected plasma is expected to exit the diffusion region with the local Alfvén speed V_A.

It is expected that the rate of reconnection should be governed both, by the physics of the diffusion region determining the amount of B-flux that this region allows to reconnect and by the properties of the external region, transmitted by the separatrices, determining the amount of reconnected flux that can be supported by the reconnecting system as a whole. Toward this latter understanding it should be necessary to look for the allowed total energy changes in the overall reconnecting system according to a sequence of appropriate states of minimum energy configuration (e.g., Kulsrud, this chapter). As shown in Fig. 1.8, the influence of two important boundary conditions in the overall reconnection process are expected to be considered. One of them refers to the region indicated by the circled number

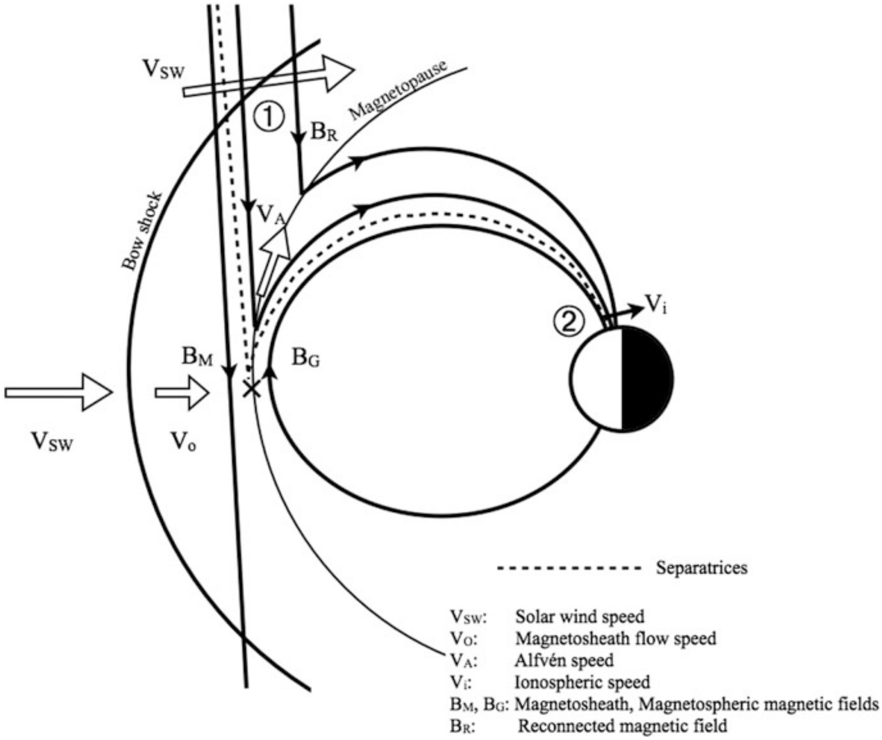

Fig. 1.8 Reconnection separatrices at the magnetosheath and magnetopause of the dayside magnetosphere (details are illustrated for the northern hemisphere assuming that a similar illustration holds for the southern hemisphere)

1, at the top, where the external separatrix finds a magnetosheath plasma with flow speed values that are close to the nominal solar wind speed V_{sw}. The other refers to the region indicated by the circled number 2, where the internal separatrix meets ionospheric plasmas, in which flow speeds associated with the reconnection process can become limited by internal plasma conditions of the ionosphere, such as conductivity, density levels and convection histories. The issue of how these two boundary conditions affect the separatrices and become transmitted down to the diffusion region is at present poorly known due the lack of simultaneous measurements at such separate regions, especially concerning the external separatrix (e.g., Lapenta et al., Chap. 8 of this volume).

With respect to the reconnection energetics associated with the region involving the external separatrix of Fig. 1.8, it is important to realize that the physics of energy transfer from the solar wind to the magnetosphere is expected to be of the dynamo type at high magnetopause latitudes ($\mathbf{E}\cdot\mathbf{J} < 0$), thus allowing transfer of mechanical energy from the solar wind to the magnetospheric tail, to be later transformed in energy supply for storms and substorms (e.g., Gonzalez and Mozer 1974; Gonzalez et al. 1994). On the other hand, the internal region of reconnection involving the diffusion region is of a load (dissipation) type ($\mathbf{E} \cdot \mathbf{J} > 0$), thus consuming energy from the solar wind rather than transmitting it to the magnetospheric tail. This issue needs to be clearly appreciated when developing the so called "coupling functions" (e.g., Borovsky 2013), since such functions may represent a dissipation region ($\mathbf{E} \cdot \mathbf{J} > 0$) rather than a dynamo region ($\mathbf{E} \cdot \mathbf{J} < 0$), the latter being the necessary type of process to consider in order to compute the energy budget for storms and substorms, as mentioned above.

One important parameter that also needs to be studied to understand the interaction between the diffusion region and the external region of reconnection is the electric field associated with each of these regions. At each of the separatrices, a large-scale electric field is set up by the solar wind and ionospheric flows, respectively, and by the reconnected magnetic field, whereas at the diffusion region, the reconnection electric field is expected to be set up mostly by internal processes (e.g., Scudder et al., Chap. 2 of this volume). We do not know yet how these electric fields get an equilibrium balance in order to compute an overall reconnection rate.

Another important factor to consider in order to find a self consistent solution for the large-scale reconnection problem at the magnetopause is the role of the Bow shock in determining regimes of magnetosheath plasma and magnetic field. For example, it is expected that the reconnection potential becomes saturated for sufficiently large values of the solar wind magnetic field via large-scale currents determined by the Bow shock (e.g., Lopez et al. 2010). On the other hand, during magnetospheric active times, the internal magnetospheric plasma and the plasma sheath are expected to influence the magnetospheric plasma entering in reconnection at the magnetopause (e.g., Borovsky and Denton 2006). With the advent of powerful computers and advanced 3D reconnection models, we may be able to start getting self consistent solutions for the magnetosphere-magnetosheath-Bow shock interaction during magnetopause reconnection, which could be compared with relevant observations to be obtained from the MMS and from other dedicated magnetospheric satellite missions.

1.5 Discussion

1.5.1 What is the "Diffusion Region"?

P.A. Cassak

As discussed in Sect. 1.3, it is challenging to rigorously define the diffusion region, also known as the dissipation region (since the effect allowing magnetic field lines to reconnect need not be of the form of a classical diffusion). The standard way of thinking about the diffusion region is quite operational—outside the diffusion region, the plasma obeys the frozen-in condition, and inside it does not. However, this operational definition is not precise!

To see why, consider the simplest system we can think of, namely two-dimensional resistive magnetohydrodynamics (MHD) with a uniform resistivity. Suppose we have a magnetic field with a Harris sheet profile,

$$B_X \sim \tanh(Z),$$

which has B_X reversing signs at $Z = 0$. From Ampère's law, this magnetic field has an associated current density profile

$$J_Y \sim \operatorname{sech}^2(Z).$$

Since $\operatorname{sech}(Z)$ is non-zero for all finite Z, the current density J_Y is non-zero for all Z out to infinity. In resistive-MHD with a uniform resistivity, this implies that the resistive electric field $E_Y = \eta J_Y$ is non-zero everywhere out to infinity, and this is true even if the Harris sheet is not undergoing reconnection! Thus, the frozen-in condition is formally broken for all Z, implying that the diffusion region extends over all space. This would be a useless definition of the diffusion region!. Consequently, the idealized picture of having a diffusion region with a sharp boundary outside of which is frozen-in simply does not work, even for the simplest system we could possibly study.

This only means that there is no rigorous definition of the diffusion region, but this does not mean it is not a useful construct. By and large, far from a reconnection site, the departure from the frozen-in condition is relatively small, while near the reconnection site the departure is significant. Therefore, in practice, researchers make an arbitrary choice about where to define the edge of the diffusion region based on when the departure from the frozen-in condition is significant for the application in question. But it is merely a convention, and nature draws no such lines!

Especially with the recent launch of the Magnetospheric Multiscale (MMS) mission, it is important and timely to develop a convention to define the diffusion region, and that this convention should be compared with observations. One very reasonable choice is the location where the convective and non-ideal electric fields are of the same size. Then, inside that location, non-ideal effects are larger and outside the location non-ideal effects are smaller.

Unfortunately, even this simple and logical convention is not without its complications. For example, the scalar part of the gradient of the electron pressure tensor can be non-zero, which leads to the electric field differing from the convective electric field. However, a scalar pressure does not break the frozen-in condition. This has been reported to be an issue at the electron diffusion region in collisionless plasmas. There have been a number of quantities proposed for defining the diffusion region, as will be seen in subsequent sections and chapters of this book.

I think that the key to the issue—whether in 2D or 3D and whether in a fluid or kinetic system—is *dissipation*, which by definition is the irreversible transformation of ordered energy into heat. This is associated with an increase in the entropy of the plasma. Consequently, I believe a true measure of the diffusion region is where the frozen-in condition is broken *and* entropy is increasing. It would be rather straight-forward to develop a model for this within the confines of resistive-MHD, but in a kinetic system where the entropy is related to a velocity space integral of the structure of the distribution function, it is less obvious how to proceed. The interesting question of how to define the diffusion region will undoubtedly continue!

J.D. Scudder

The diffusion region may have different shapes in different geometries: guide, parallel, symmetric, anti-symmetric and 2D vs 3D. It is almost certainly a place in collisionless reconnection where the thermal electrons become demagnetized. (This is not an if and only if statement however, as we demonstrate in Chap. 2.) We have also documented 5–6 different observable ways to find this condition by "asking" the electrons themselves, i.e. their agyrotropy (Scudder and Daughton 2008). This region needs to be a flux slippage region where $\nabla \times (\mathbf{E} + \mathbf{V} \times \mathbf{B}/c)$ is different from zero. However, since this condition is related to the time scale of disruption of Guiding Center ordering, its size and locale can be inferred by other observable signatures of demagnetization. In 3D this layer is most likely not time independent, spawning ancillary (a) flux ropes and (b) secondary reconnection sites. We will show examples of this in 3D in Chap. 2. The merger of diffusion region concepts such as Vasyliūnas's demagnetization idea with the global conditions (a) squashing and (b) field aligned potential drops have already been demonstrated (Scudder et al. 2015).

H. Karimabadi

The idea of a central diffusion region is most meaningful in simple 2D steady state models in which the reconnection rate can be related to the aspect ratio of the diffusion region. However, this simplification can still be a reasonable idealization in scenarios where there is a well-defined and dominant inflow-outflow region. Unfortunately even in such idealized cases, there is no first principle theory that provides an estimate for the dimensions of the diffusion region. For example, in a collisionless plasma, the width of the electron diffusion region is about one electron skin depth but there is no theory currently that provides an estimate for the length of the diffusion region. An interesting idea that yields an estimate for the aspect ratio of the diffusion region is based on linear theory mode. Since tearing mode is the eigenfunction of a current sheet, one may suppose that a sufficient condition for reconnection is for the tearing to be unstable. The wavenumber for the most unstable tearing mode is given by $k\delta = 2\pi\delta/D \sim 0.5$ or $\delta/D \sim 0.08$ where δ and D are the width and length of the diffusion region. This is in reasonable agreement with the rate of ~ 0.1 which is often observed in various reconnection regimes. Although suggestive, this explanation is not a proof and is not widely adopted. External boundary conditions and system size can also play significant roles in the rate. For example, if the system is driven, the rate will clearly be affected. Similarly, depending on whether the system has periodic or conducting boundary conditions, the rate would be affected. So, in general, the reconnection rate is determined through a combination of internal and external conditions.

W.D. Gonzalez

Since the initial reconnection papers, considering only the resistive term in the generalized Ohm's law and inserting it in Faraday's equation to follow the time evolution of B, it was clear that the only non ideal term in the equation was of the DIFFUSION type. Thus, from then on people has been calling "diffusion region" to the central/non-ideal reconnection region.

However, from later research dealing mostly with collisionless plasmas we know that there are extra terms in the generalized Ohm's law that need to also be inserted in Faraday's equation creating terms that are not any more of the diffusion type. Thus, trying to keep the same name (diffusion) for the collisionless cases seems to introduce semantic complications with an implicit need of looking for a better name that could represent more appropriately the central region of reconnection for such regimes.

On the other hand, I believe that it will be a difficult task to find a common name for the central region that could represent well all reconnection cases, even in 2D, in which the location, extension and dynamics of the reconnection site can vary depending on the dominant local physics as well as on the different boundary conditions applicable to each case.

In spit of these considerations, calling the central reconnection region a diffusion region, besides having an historical importance, has been helping reasonably well to organize reconnection research and for the time being it may still continue doing it so until, with more advanced observations and models (especially in 3D), we may move towards finding more appropriate nomenclatures, maybe not any more trying to represent just with a single name the whole central region of reconnection, but naming more specific subregions, such as ion Hall region, electron nongyrotropy region(s), and so on.

1.5.2 Comments on Question 1

P.A. Cassak

What does it mean for magnetic field lines to "get cut" and "reconnect"? The overarching answer, I would say, is that there must be some dissipative (irreversible) effect that is important right at the location where field lines get cut and reconnect. In a (theoretical) "ideal" system, there is no reconnection because there are no dissipative effects, and electrons are free to move essentially infinitely fast to short out any electric fields in the system. In a resistive system, which is relatively easy to understand compared to collisionless systems, resistivity provides the necessary irreversible dissipation to cut the field lines. Much like driving a current through a wire, collisions between electrons and ions prevent the electrons from moving essentially infinitely fast to short out electric fields, so an electric field can exist. From Faraday's law, this electric field allows the field lines to change, and they can undergo the process that appears to observers from afar as magnetic field lines cutting and reconnecting.

In collisionless systems, the same basic picture still holds, in that some dissipative effect allows an electric field to arise. What effect allows this seems to depend on the system parameters. There is pretty broad agreement that for the symmetric case without a guide field, the off-diagonal elements of the electron pressure tensor, effectively an electron viscosity, provide the irreversible dissipation. However, the case with a guide field or with asymmetries has not been studied as much, and there is still much to be learned.

R.M. Kulsrud

The line breaking process is rather simple when viewed from a particle point of view. In a no guide 2D case there is a region near the X-point where the magnetic field is very weak. This region extends out to a distance x where the nominal gyroradius is equal to x. This region is called the betatron radius since the electrons execute betatron orbits rather than gyro-orbits there. In this region they are free to move into the Y direction on betatron orbits. The secret of line breaking is that there is a finite electric field in the Y direction. In any case the rate of line breaking is given by this electric field by Faraday's law. On the other hand such a field will drive a very large current stopping the reconnection and this current is limited by the average speed of the electrons in this betatron region. In normal reconnection this current is limited by collisions (resistivity) which gives the Sweet-Parker reconnection rate. But in the collisionless case the average velocity is the acceleration by the E field during the time τ for the electrons to cross the betatron region, and if τ is shorter than the collision time then one can have a larger E field for the same current (Yamada et al. 2010). This point is difficult to understand from the MHD picture because this process is equivalent to an off diagonal term in the electron pressure term, as also spelled out in the review paper by Yamada et al. (2010).

J.D. Scudder

The "cutting" and "reconnection" short hands are after the effect descriptions, not explanations of how this happens. Maxwell's equations are about the 4-vector potential and that description is smooth in space and time. In the short scaled "diffusion" region it is not longer possible to prove that there is a well defined evolutionary equations for "field lines". If one remains in the dialect of describing the behavior of magnetic field lines this lapse of an equation of motion for them requires a discontinuity in their causal description, that clever popularizers have dubbed cutting and reconnection. From this vantage point the question “how do they get cut and reconnect” is not a question that theory at that level will ever clarify. If one agrees to go to the 4 vector potentials of Maxwell one does obtain an evolutionary description in space and time that is smooth. While $\mathbf{B}(x, y, z, t)$ as curl of $\mathbf{A}(x, y, z, t)$ at any given time has a definite field line topology, that topology is not predictive of the topology of $\mathbf{B}(x, y, z, t+dt)$. The MHD regimes do not require the 4-vector potential to predict the rearrangement of field lines; at some level the ubiquitous simplifications that MHD can afford, does not serve the student well to predict what can happen when the foundations of MHD are supplanted in strong gradient current channels. It is widely subscribed that the non-ideal corrections to the generalized Ohm’s law that preclude field and/or flux preservation under the evolution equations is generally dominated by the agyrotropic electron pressure tensor, with possible corrections from inertial terms. More generally this regime is indicated as sites where the curl of the non-ideal electric field $\mathbf{R}_e = \mathbf{E} + \mathbf{V}_e \times \mathbf{B}/c$ is not equal to zero. An agyrotropic electron pressure tensor generally fulfills this type of violation and microphysically corresponds to the disruption of the magnetization of the bulk of the plasma electrons. Colloquially this implies that the approximations of guiding center theory for electrons are disrupted in these narrow current channels. The most commonly cited approximation involved in guiding center theory is the gyroradius over scale of variation is small. The early work by Vasyliūnas (1975) and the most recent full PIC codes of the process agree that this and other underpinnings of guiding center theory for electrons are disrupted in the electron diffusion region.

W.D. Gonzalez

With respect to the initial reconnection models (Sweet 1958; Parker 1957), if one starts with opposite PLANAR reconnecting magnetic fields (pointing, say, in the Y and $-Y$ directions, approaching $X = 0$ from X and $-X$, with the current sheet in the Z direction), for an incompressible plasma and a stationary situation we have:

$$\nabla \times (\mathbf{V} \times \mathbf{B}) = \eta \Delta \mathbf{B}, \text{ or}$$

$$(\mathbf{B} \cdot \nabla)\mathbf{V} - (\mathbf{V} \cdot \nabla)\mathbf{B} = \eta \Delta \mathbf{B},$$

(with η being the resistive diffusion coefficient at the current sheet). Thus, the X-component of this equation gives:

$$B_Y \partial V_X/\partial Y + B_X \partial V_X/\partial X - V_X \partial B_X/\partial X - V_Y \partial B_X/\partial Y = \eta \Delta B_X.$$

If there is no B_X in the convecting region (planar fields), all the terms in the left hand side of the equation are zero EXCEPT the first, if $B_Y \partial V_X/\partial Y \neq 0$. If so, there must also be a nonzero B_X in the current sheet. However, if $\partial V_X/\partial Y \neq 0$ one can not continue having a planar **B** field since V_X should change with Y and, assuming a frozen-in condition outside the current sheet, B would become curved. Therefore, in order to have reconnection, reconnecting fields need to have a curved topology near the current sheet, for which $B_X \neq 0$. In reality, of course, the reconnecting fields can present external curvatures, defined by the boundary conditions in each case, as assumed in several models after those by Sweet and Parker (e.g. Petschek 1964; Sonnerup 1970). If one also assumes time-dependence, instabilities in the current sheet, such as the tearing mode (Furth et al. 1963) can provide $B_X \neq 0$, which can facilitate the occurrence of reconnection (Karimabadi et al. 2013).

H. Karimabadi

Reconnection does require formation of a finite normal (to the current sheet) field component (B_X) but a finite B_X does not necessarily imply reconnection. In a simple 2D laminar picture, reconnection requires formation of an X-point which by definition has a finite B_X. If one starts with a current sheet with no imposed perturbation, then the only way it can reconnect is through the tearing mode. The tearing mode has certain wavelength so one can think of a tearing perturbation growing in the sheet. As the size of the perturbation grows due to the growth of tearing, it starts to pinch off the current sheet and create X-lines and trigger reconnection at those points. In some simulations, people impose a GEM-like perturbation which effectively forces the X-point to be at the center of the sheet (Birn et al. 2001) and only a single X-line is formed initially. The generation of finite B_X originates at the X-point. However, in 3D the situation becomes much more complex.

2D steady state MHD models of reconnection present different reconnection solutions as a function of resistivity model. As such they assume B_X. Otherwise there won't be any reconnection. Steady state models by definition don't address generation mechanisms since that involves a time evolving solution requiring dB/dt. The connection to tearing is controversial. If one sees islands forming, then it is clear that tearing is operational, but one can also have reconnection without formation of islands as shown in many simulations. In such cases it is harder to prove tearing as the cause of B_X/reconnection. A good way to think of it is as follows: a current sheet is susceptible to reconnection. This means that any fluctuations in B_X would grow in time and the system would organize itself into an inflow-outflow configuration. This can happen in two ways: (a) since tearing is an eigenfunction of a current sheet, any current sheet that is unstable to tearing would form a finite B_X; (b) one imposes a perturbation in a current sheet that is stable to tearing. This can nonlinearly cause reconnection to occur. It is not clear in such cases where the underlying mechanism becomes nonlinear tearing however. In short, the connection of tearing to reconnection remains controversial.

What causes the field lines to have an open geometry, rather than say something like Sweet-Parker is not understood. Tearing does give the right aspect ratio as required for open field lines but this explanation remains not universally accepted.

Linear tearing has an island chain and if one doesn't impose an X-line perturbation initially, one would form bunch of tearing islands which would coalesce. But if one imposes an X-line perturbation as done in (Birn et al. 2001), then there is only one active X-line (i.e., avoids forming tearing island chains) and one bypasses linear tearing. So the open question that remains in such a case is whether tearing is still playing a role in giving rise to the open geometry.

R.M. Kulsrud

Sweet and Parker implicitly assume incompressibility and replace this with $\nabla \cdot \mathbf{V} = 0$ where $\mathbf{V}$ is the in-plane velocity. This is correct if the transverse field or the ambient pressure is large. If the transverse field is zero, one still has flux freezing out side of the layer, but in the layer the transverse field can slip relative to the velocity, but only by an amount inversely proportionally to the square root of the magnetic Reynolds number. To this extent the global helicity is conserved. (of course it is zero without a transverse field).

M. Yamada

In the classical Sweet-Parker model, there is no flux conservation. All flux is dissipated in the current sheet. B_X is limited to the very narrow region of the current sheet ($d \ll L$). So in this model, we do not discuss the role of B_X in the sheet (it is a black box). As it was analyzed by Priest and Forbes (2000), incoming magnetic energy ($\nabla \cdot (\frac{c}{4\pi}\mathbf{E} \times \mathbf{B})$) is converted to plasma energy, divided usually to internal energy (Enthalpy) and Flow energy $(1/2)mV^2$. Thus there is no outflow of magnetic energy. Only Petschek's model and the two-fluid model can predict magnetic energy outflow.

1.5.3 Comments on Question 2

P.A. Cassak

About how the external MHD region and the internal diffusion region depend on each other and in which circumstances one drives the other, this is a challenging question and it is not clear that we know the answer for naturally occurring systems. One can gain some perspective from simulations. The simplest case is 2D systems, for which much is known. For given system parameters, there is a characteristic rate at which the system would want to reconnect the magnetic flux, quantified by the reconnection electric field. The external system can have its own electric field which need not to be the same. If they are the same, the system will reconnect at the common rate and will continue to do so steadily for as long as there is more magnetic flux to reconnect.

If, however, the external electric field is larger than the characteristic rate the reconnection would reconnect at and the external electric field is held fixed, then flux is introduced faster than it can reconnect, so it piles up near the diffusion region. This increases the magnetic field strength near the reconnection site, which leads to faster reconnection, so the natural rate of the reconnection would increase. When the reconnection is fast enough to have the same electric field as the external one, a steady state is reached at the external electric field. However, if the external electric field is not fixed, one could imagine that the piled up magnetic field would produce a back pressure on the external field, slowing it down and decreasing the external electric field.

One could make a similar statement if the external electric field is weaker than the reconnection electric field—either the reconnection electric field will decrease when the upstream magnetic field weakens until they are the same, or the external field will increase to supply more flux. The end result is that they should end up at the same electric field. In simulations, the external field is often imposed so the system typically ends up at the imposed external field, but in a real (2D) system, it is not obvious which should dominate. Many believe it is the external field, but I do not think this has been studied sufficiently well.

This is all for 2D, but the situation totally changes for 3D. In 3D, the system has another option—the external flow can simply go around the reconnection site instead of changing the magnetic field at reconnection site, as has been seen in simulations and may take place, for example, at the dayside magnetopause. In such a case, it is not clear whether or how the two are related, and this remains an open question.

J.D. Scudder

This situation is common in boundary layer physics. The diffusion region is a boundary layer that affords a connection between external regions that are increasingly more ideal insofar as MHD approximations are concerned. This problem between LOCAL MHD boundary conditions on the inflow and exhaust is only compounded by the contextual system of external boundary conditions for each reconnection situation. At present this interrelationship should include a list of mechanisms that are capable of (a) changing the time independent assumption of the local MHD boundary conditions usually assumed, or (b) changing the spatial uniformity of the local MHD boundary conditions, such as having undulations in properties that are significant across the 10–100 ion gyroradii scales currently assumed to be planar in 2D. Clearly the physics of these layers becomes more complicated with Kelvin-Helmholtz waves traveling along the current channel for example. To explore these effects requires global modeling of the reconnection current channel together with the external region. This type of modeling is just coming of age.

R.M. Kulsrud

The separatrices are important as the bulk of the mass on the reconnected line crosses the separatrices and has to be accelerated from rest to the outflow velocity. The separatrices are the dividing boundaries between unreconnected and reconnected regions. Roughly speaking the freshly reconnected plasma has to flow along them. Of course they are also moving into the outflow regions and what was freshly reconnected plasma gradually becomes part of the downstream reconnected region. Further, since the field is weaker in the downstream region there is a discontinuity in it and the separatrices are also current regions (Kulsrud 2011).

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