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2013 Plasma Phys. Control. Fusion 55 124001

(http://iopscience.iop.org/0741-3335/55/12/124001)

OPEN ACCESS
IOP Publishing
Plasma Physics and Controlled Fusion
Plasma Phys. Control. Fusion **55** (2013) 124001 (6pp)
doi:10.1088/0741-3335/55/12/124001

Influence of asymmetries and guide fields on the magnetic reconnection diffusion region in collisionless space plasmas

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Received 4 July 2013, in final form 5 August 2013
Published 28 November 2013
Online at stacks.iop.org/PPCF/55/124001

Abstract
Collisionless magnetic reconnection is considered to be one of the most important plasma phenomena because it governs the transport of energy, momentum and plasma in a wide variety of situations. In particular, understanding the central diffusion region is crucial to gaining a full understanding of the physics of reconnection. Although most diffusion region studies have historically focussed on simple reconnection geometries (antiparallel fields and symmetric reconnecting plasmas), in recent years significant progress has been made in understanding the impact of plasma asymmetries, guide fields and flow shear on collisionless diffusion region physics. Here we present a review of this recent progress, which is based both on supercomputer simulations and increasingly detailed multi-point satellite measurements of collisionless magnetic reconnection in space plasmas.

(Some figures may appear in colour only in the online journal)

1. Introduction

Magnetic reconnection is fundamental to many plasma systems, since it enables the explosive release of stored magnetic energy, creating jets, energetic particles, and heating of the plasma [1]. Although reconnection has large-scale consequences, it is ultimately controlled by the small central diffusion region where the plasma decouples from the magnetic field and reconnection actually occurs [2–5]. Antiparallel, symmetric reconnection has received much attention, since this is the simplest case to investigate theoretically, and is also of practical interest because it describes conditions in the Earth's magnetotail that drive magnetic storms and substorms. In the diffusion region, the protons decouple from the magnetic field on a larger scale than the electrons, and under symmetric conditions, it is now well established that this leads to the formation of a two-scale diffusion region, a characteristic feature of which is the quadrupole Hall magnetic field (e.g. [6] and references therein).

Here, however, we briefly review recent advances in collisionless reconnection and our understanding of the diffusion region when the reconnecting plasmas are not symmetric and the reconnecting magnetic fields are not antiparallel. Recently there has been increased interest in understanding more complex configurations, in part motivated by a desire to better understand the nature of collisionless reconnection at the Earth's magnetopause where high density, low field strength magnetosheath plasma reconnects with

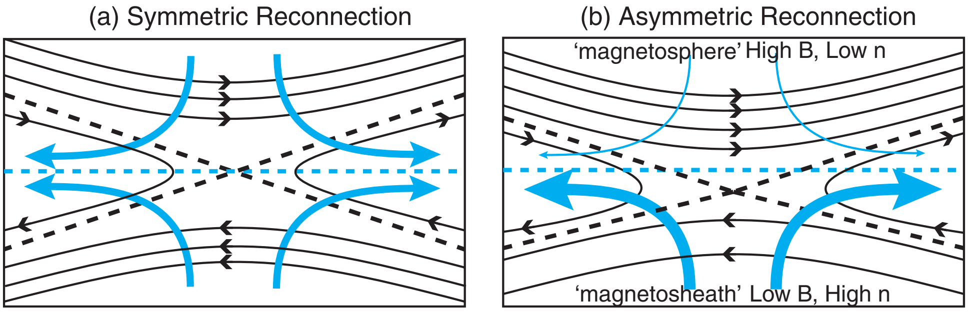

Figure 1. Cartoon showing the geometry of (*a*) symmetric and (*b*) asymmetric reconnection. Magnetic field lines are shown in black and plasma flow lines are shown in blue.

low density, high field strength magnetospheric plasma. We may consider three complicating effects: (1) asymmetric reconnecting plasmas (where the magnetic field strength, plasma density and temperature are not the same on either side of the reconnecting current sheet), (2) guide field (where the magnetic fields on either side of the current sheet are not antiparallel) and (3) flow shear.

2. Theory

2.1. Asymmetric reconnecting plasmas

If the reconnecting plasmas are asymmetric, then a key feature of the diffusion region is that the X-line and stagnation point (where the flow velocity is zero) are not collocated [7]. In fact the stagnation point is displaced to the low mass flux side, i.e. the side with smaller ρ/B ($\propto \rho v$), or larger Alfvén speed, and the X-line is displaced to the high β side as shown in figure 1. This is closely linked to the more general structure of the macroscopic reconnection boundary layers under asymmetric boundary conditions: at the magnetopause, the rotational discontinuity which changes the field is on the magnetosheath (weak field) side, and the slow expansion fan which changes the density is on the magnetospheric (low mass flux) side [8]. Asymmetric boundary conditions also affect the outflow density ρ_{out}, the outflow speed v_{out} and the reconnection rate E. Scaling arguments based on a Sweet-Parker type analysis of incompressible plasma [7] show that

$$\rho_{\text{out}} \sim (\rho_1 B_2 + \rho_2 B_1)/(B_1 + B_2), \tag{1}$$

$$v_{\text{out}}^2 \sim [(B_1 B_2)/(4\pi)][(B_1 + B_2)/(\rho_1 B_2 + \rho_2 B_1)], \tag{2}$$

$$E \sim [(B_1 B_2)/(B_1 + B_2)](v_{\text{out}}/c)(2\delta/L), \tag{3}$$

where '1' and '2' refer to the conditions on the two sides of the current sheet, δ and L are the height and width of the diffusion region and $\sim$ means 'scales like'. When extended to compressible systems, the outflow speed is the same, but the reconnection rate is modified by a compression factor r [9]. These scaling relationships are expected to be generally valid because they do not make use of any particular dissipation mechanism and have been verified using resistive MHD [7, 10, 11], two-fluid simulation [12], and particle in cell (PIC) simulation [13].

Figure 2 shows results from a PIC simulation of asymmetric reconnection [13]. The X-line is located at (x, y) $\sim$(150, 27) c/ω_{pi} and the jets transfer plasma into islands whose growth bulges down into the weak field (high β) side. The current density is strongest along the separatrix bounding the low β side. In the out-of-plane magnetic field, there is a bipolar, rather than quadrupolar, signature. Effectively, the two quadrants associated with the Hall field on the low β side have disappeared, because the out-of-plane Hall field is generated by in-plane Hall currents $\boldsymbol{J}_H$, which are higher on the high β side because of the higher plasma density [14]. E_y, the electric field normal to the original current sheet is unipolar (existing only on the low β side) rather than bipolar as would be expected for symmetric reconnection. This is the signature of the Hall electric field $= \boldsymbol{J} \times \boldsymbol{B}/ne$, which is evident only on the low β side since B/n and the out-of-plane current are larger there [15]. Vertical cuts through the simulation along $x = 150c/\omega_{\text{pi}}$ (which passes between the two exhaust outflow jets) show that the flow does not stagnate (i.e. $v_{i,y} \neq 0$) where $B_x = 0$ (marked by the vertical dotted line); this separation is consistent with the original analytic model.

Under asymmetric conditions, the diffusion region in reality is expected to be very structured, with different identifying features in different physical locations and additional kinetic structure that may obscure or alter the separation of the X-line and stagnation point [16, 17]. Furthermore, very recent work indicates that the models used to describe the electron behaviour may be important in controlling overall evolution; for example reconnection develops more quickly in a fully kinetic model [18, 19]. Also, inconsistencies in the behaviour of resistive magnetohydrodynamic (MHD) simulations compared to PIC simulations have been attributed to the fact that they do not allow mixing of the plasma from the two sides of the current sheet on newly connected field lines [20], indicating that care must be taken when developing and choosing simulation models to compare with experimental data. Finally we note that although up to this point, the vast majority of simulations are 2.5D, large 'petascale' 3D simulations are now becoming possible, revealing considerable structure, turbulence, and flux rope formation, as well as complex interactions and dynamics [21, 22].

2.2. Guide field

If the magnetic fields on opposite sides of the current sheet are not antiparallel, then the magnetic field is typically

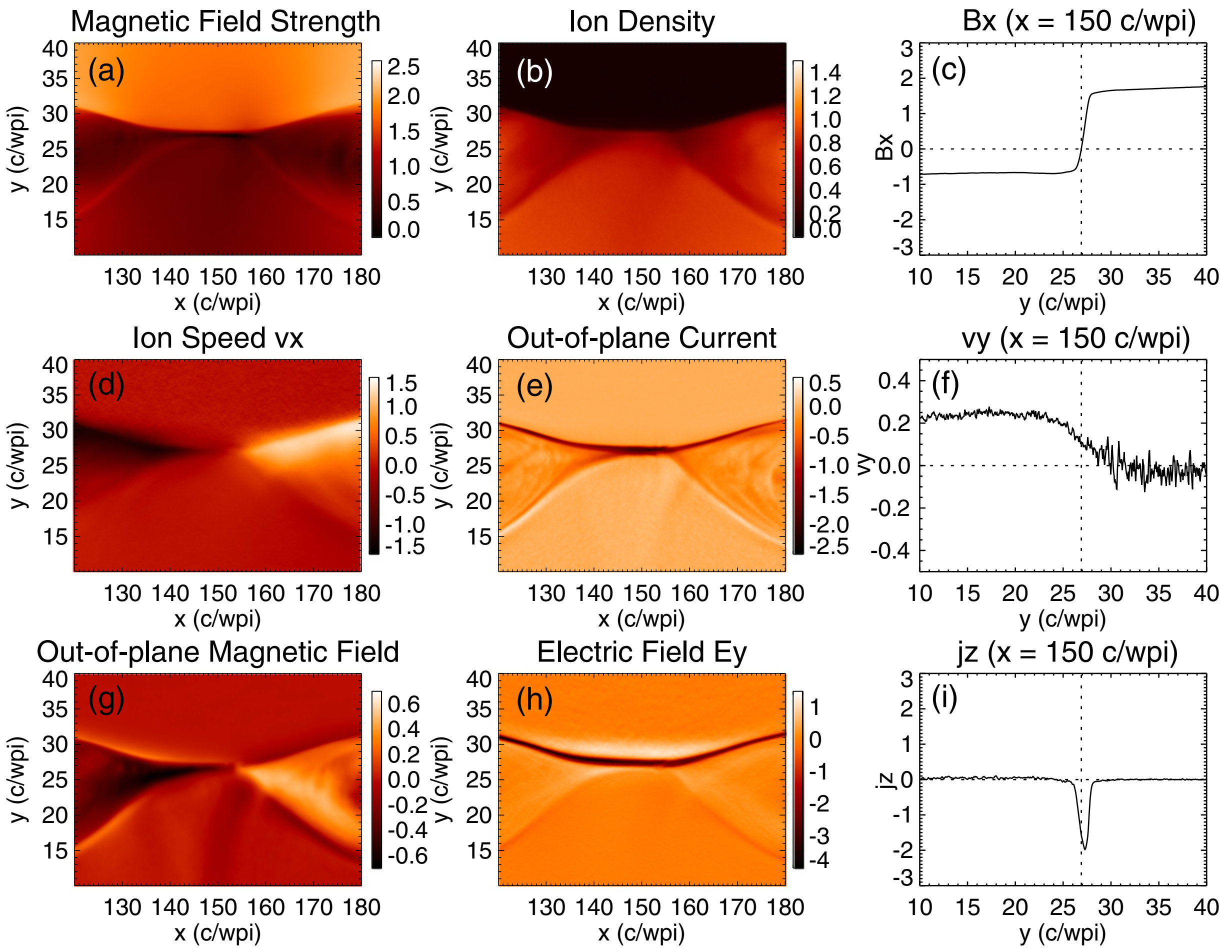

Figure 2. Simulation of asymmetric reconnection. This data corresponds to run BN2a from Malakit *et al* [13]. The low β region (initial conditions: $\boldsymbol{B} = (2.0, 0.0, 0.0)$, $n = 0.1$) is above the current sheet and the high β region (initial conditions: $\boldsymbol{B} = (-1.0, 0.0, 0.0)$, $n = 1.0$) is below the current sheet. Only part of the simulation domain centred on the X-line is shown, and the data are time-averaged from $t = 240$ to $241\ \Omega_{ci}$ ($\Delta t = 0.01$), after reconnection has been established.

decomposed into a reconnecting component perpendicular to the X-line and a guide field component (B_G) along the X-line. If the reconnection is otherwise symmetric, then the Hall magnetic field becomes distorted because of the deflection of the electron outflow jet by the $\boldsymbol{J}_H \times \boldsymbol{B}_G$ force associated with the guide field (see [23] and references therein). The combined effect of asymmetries and a guide field has been studied in detail by [15, 24, 25], who found that the bipolar Hall magnetic field structure is also distorted. A more general issue concerns the orientation of the X-line, which is easily defined only for symmetric, antiparallel conditions. Most recently, it has been proposed and demonstrated with simulations that the X-line orientation maximizes the strength of the reconnecting magnetic field components and in fact results in a larger reconnection rate [26].

In fact, the combination of a guide field and asymmetries can prevent reconnection from occurring. If an asymmetric configuration is in equilibrium, then the difference in magnetic pressure across the current sheet is balanced by a corresponding change in plasma pressure. If there is a guide field, then a diamagnetic drift will occur, along the outflow (see figure 3(*a*)). If the current sheet reconnects, the X-line moves left at the electron drift speed (although new simulations also show that in fact the X-line drift may also reverse during the course of reconnection [18]). However the ions are also drifting (in the direction opposite to the electrons) and so the net velocity between the ions and X-line is given by the sum of the ion and electron drifts [27]. If this drift effect is larger than the expected reconnection jet speed, then the reconnection is suppressed. Essentially, this occurs because the reconnection plasma flows around the nascent X-line cannot be established before it has moved a significant distance away from the initial site. This condition can be expressed as: $\Delta\beta > (2L/d_i) \times \tan(\theta/2)$ where $\Delta\beta$ is the change in plasma β, L is the thickness of the current sheet at the X-line (related to the plasma pressure gradient), d_i is the ion inertial length, and θ is the magnetic shear [28]. It is expected that $L \sim d_i$, but the effect does not switch on at one exact particular value of the drift speed and so this relationship is shown in figure 3(*b*) for three different values of L. In the regions well above the curves, reconnection is allowed, whereas well below the curves, reconnection cannot occur. Systems in the vicinity of the dividing lines should be treated with care. Note that this condition is considered necessary but not sufficient for reconnection: other conditions may prevent its occurrence.

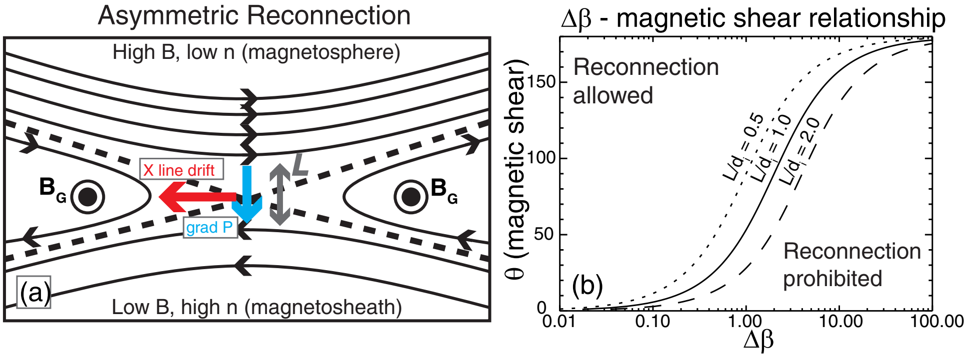

Figure 3. (*a*) Cartoon showing drift of the X-line under asymmetric boundary conditions with a guide field (shown pointing out of the page. (*b*) Relationship between $\Delta\beta$ and the magnetic shear θ.

2.3. Velocity shear

Velocity shear can also play a significant role controlling where and when reconnection may occur [29], and in altering the structure of the diffusion region (see e.g. [30] and references therein). Initial simulations using resistive MHD confirmed that if the flow shear was super-Alfvénic, then reconnection would not occur [31]. More recent scaling studies show that the flow shear slows down the reconnection, with the outflow speed and reconnection rate falling as the flow shear increases, and that the reconnection layer can become Kelvin-Helmholtz unstable if the flow shear is strong enough [30]. Ultimately, the interplay of flow shear, guide field and asymmetry controls the drift of the X-line in the current sheet. For example, the effect of any shear flow in causing the X-line to drift may be offset by the guide field causing drift in the opposite direction [32]. The ultimate configuration is thus sensitive to the exact strength of each forcing.

3. Observations

Although satellite observations have progressed to the extent that regions of space plasma, such as the Earth's magnetopause, can now be considered 'laboratories' for collisionless reconnection research, observing the diffusion region itself is difficult because this region is small and the satellite must be in the right place at the right time. Often satellites cut through the magnetopause observing one exhaust, and so the distance to the X-line is unknown. Furthermore, once one becomes interested in conditions that are not symmetric and antiparallel, there is an enormous variety of behaviour, and so each individual candidate event must be studied in detail to understand its signatures. In particular, it is difficult to find events where only one complicating aspect is present. As such, progress thus far has been based on the detailed analysis of case studies, and in fact a number of important theoretical predictions still remain to be tested.

To illustrate the nature of space data, figure 4 shows 3 min of data from the THEMIS P2 satellite, as it made an inbound crossing of the magnetopause from the high density magnetosheath to the low density magnetosphere. During this crossing, first presented by [33], a plasma jet was observed

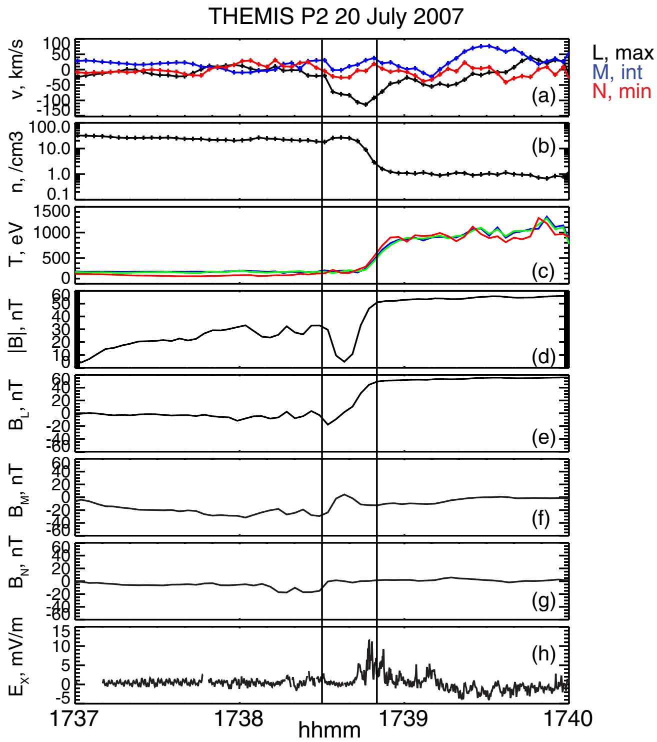

Figure 4. Observation of asymmetric reconnection during a crossing of the Earth's magnetopause: (*a*) ion velocity; (*b*) ion density; (*c*) ion temperature; (*d*)–(*g*) magnetic field strength and components; (*i*) electric field normal to the current sheet. This event was first discovered and analysed by [15, 33]. $\boldsymbol{B}$ and $\boldsymbol{v}$ are shown in boundary normal coordinates where $\boldsymbol{L}$ contains the reconnecting magnetic field, $\boldsymbol{M}$ contains the out-of-plane magnetic field and $\boldsymbol{N}$ is normal to the magnetopause, pointing into the low β region.

in the $-\boldsymbol{L}$ direction, indicating the presence of reconnection. The two vertical lines bracket the reversal in B_L, which largely occurs before the drop in density, which is consistent with the separation of the X-line and stagnation point, and the associated separation of the rotational discontinuity and slow expansion fan. The deviation in the out-of-plane magnetic field B_M occurs over a broad region on the high β magnetosheath side. However, it should be noted that in this event there is a guide field in the $-\boldsymbol{M}$ direction, and so the Hall field deviation in fact reduces B_M ($B_M \sim 0$), in good agreement with simulations of asymmetric reconnection in the presence of a guide field [15]. The normal electric field, $E_{x,\mathrm{GSM}}$ ($x_{\mathrm{GSM}} \sim -\boldsymbol{N}$) is confined to a thin boundary, on the low β magnetosphere side, pointing towards the high β magnetosheath.

Other case studies have also confirmed basic predictions of reconnection under asymmetric boundary conditions. In an earlier observation of asymmetric reconnection in the magnetotail, it was possible to measure both the density asymmetry and the jet density, which was subsequently found to be in excellent agreement with the predicted values [7, 34]. In a second event observed on the dayside magnetopause [35] there was no guide field and the magnetic field was symmetric, but the density was asymmetric and there was a flow shear. It was concluded that the satellites passed $\sim 50c/\omega_{\mathrm{pi}}$ away from the X-line and good agreement was found with the predictions of PIC simulation [36]. In a third event, a guide field was present with a clear asymmetry in the density and the reconnecting magnetic field [37]. Here, four spacecraft Cluster data was used to show that the thickness of the layer was a few c/ω_{pi} but it was not possible to establish the distance to the X-line. Interestingly, a bipolar out-of-plane magnetic field was observed; the reason for this requires further investigation. Finally, magnetic reconnection also forms secondary islands, and these have been observed, a few c/ω_{pi} in size, under asymmetric boundary conditions [38], as well as in simulations [22].

3.1. Guide field

The effect of the guide field on otherwise symmetric reconnection has been studied using data from the magnetotail current sheet, showing that the guide field does indeed distort the ion diffusion region structure in a manner consistent with theory [23]. The diffusion region in the presence of a guide field and asymmetric boundary conditions has also been examined via case study, as described above. More generally, experimental verification of X-line orientation predictions remains difficult because of the need to establish both the boundary conditions and the X-line orientation with a limited number of in situ satellite measurements.

Regarding the beta-shear condition, the first test of this used solar wind reconnection events to show that it was indeed satisfied [39]. However, this investigation only considered reconnecting events, and so only demonstrated that the condition is necessary, but not necessarily sufficient. In a follow up study of the Earth's subsolar magnetopause, the condition was found to divide the observations of reconnecting and non-reconnecting current sheets [40]. The fact that no non-reconnecting events were observed in the 'reconnection-allowed' regime is thought to imply that the magnetopause is usually sufficiently thin to allow reconnection to occur. An interesting implication of the beta-shear relationship is that it leads to different occurrence rates of reconnection at the inner versus the outer planets, because the solar wind plasma β changes with distance from the Sun. At Saturn $\Delta\beta$ is larger and under typical conditions, magnetic reconnection at Saturn's magnetopause is most likely restricted to a small region where the fields are antiparallel [41]. In contrast, $\Delta\beta$ at Mercury is relatively low and so in principle, reconnection can easily occur for even very small magnetic shear [42].

4. Discussion

In this paper we have very briefly reviewed developments in our understanding of the collisionless reconnection diffusion region when the geometry is not anti-parallel and the reconnecting plasmas are not symmetric. Significant progress in theory has been made, with the result that there are several specific predictions that can be tested with in situ satellite observations. However, it is challenging to make observations of the diffusion region, particularly when investigating structure that can strongly depend on the boundary conditions, and so whilst progress has been made, it still remains to demonstrate experimentally: the separation of the X-line and stagnation point; the dependence of this separation on different boundary conditions; the predicted scaling of reconnection rate and outflow density, velocity; and to directly observe the drift of the X-line as a result of beta-shear. Progress towards addressing these goals will be stimulated by the upcoming NASA Magnetospheric Multi-Scale (MMS) mission [43].

Acknowledgments

JPE is supported by an STFC Advanced Fellowship. In using THEMIS data we acknowledge NASA contract NAS5-02099 and PI V. Angelopoulos.

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