DOI 10.1007/978-1-4899-7413-6_12
Reprinted from *Space Science Reviews* Journal, DOI 10.1007/s11214-012-9957-2

In-Situ Observations of Reconnection in Space

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Received: 3 October 2012 / Accepted: 4 December 2012 / Published online: 2 February 2013

Abstract This paper gives an overview of the insights into the magnetic reconnection process obtained by in-situ measurements across current sheets found in planetary magnetospheres and the solar wind. Emphasis is placed on results that might be of interest to the study of reconnection in regions where no in-situ observations are available. These results include the role of symmetric versus asymmetric boundary conditions, the identification of the onset conditions, the reconnection rates, and the spatial and temporal scales. Special attention is paid to observations in the so-called diffusion region surrounding the reconnection sites, where ions and eventually also electrons become demagnetized and reconnection is initiated.

Keywords Magnetic reconnection · Current sheets · Diffusion region · Magnetosphere · Solar wind

1 Introduction

This paper describes the insights on magnetic reconnection that have been obtained from in-situ observations in planetary magnetospheres and in the solar wind, and their comparison with theory and simulations. Emphasis is placed on results general enough to possibly be of interest to the study of reconnection in regions where no in-situ observation are available.

The reconnection scenario can be split into two regimes: the small region surrounding the reconnection site, commonly referred to as the diffusion (or dissipation) region, where non-MHD effects dominate and allow reconnection to occur, and the large-scale reconnection layer away from the diffusion region, for which a fluid description is appropriate, but where kinetic effects can also be important.

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We discuss the two regimes in reverse order. Section 2 deals with the large-scale aspects that have emerged from observations obtained in the reconnection layer downstream from the actual reconnection site. Section 3 then focusses on observations of the microphysics in and near the diffusion region. Section 4 summarizes the results and lists some open questions.

2 Large-Scale Aspects

To set the scene, Fig. 1 shows a 2D cut through Earth's magnetosphere. Reconnection is shown to occur at two sites, the subsolar magnetopause and the magnetotail current sheet. At the subsolar magnetopause, a southward directed interplanetary magnetic field (IMF) can connect with the northward directed magnetospheric magnetic field. Once reconnected, field lines are pulled over the polar caps, enter the magnetotail, and are reconnected once more across the tail current sheet, setting up a global circulation of plasma and magnetic field (Dungey 1961). Early observations demonstrating that magnetospheric activity responds to the southward turnings of the IMF (Fairfield and Cahill 1966), as well as measurements of the convection over the polar caps (Heppner 1972), provided strong support for the reconnection concept, long before any in-situ observations at the magnetopause or the magnetotail current sheets were available. In addition to the magnetopause and magnetotail, reconnection has also been observed to occur across current sheets in the solar wind, and in the magnetosheath, the region downstream of the bow shock.

2.1 Plasma Conditions

Boundary conditions and configurations at these various reconnection sites differ greatly. The magnetopause is usually characterized by highly asymmetric conditions on the two sides of the current layer, the density being lower and the magnetic field strength higher on the Earthward side. The magnetic shear across the magnetopause varies, reflecting the variable orientation of the interplanetary magnetic field carried by the solar wind. Thus the reconnection configuration at the magnetopause is generally characterized by substantial guide fields. In Earth's magnetotail, reconnection occurs across the current sheet that separates the oppositely directed magnetic fields in the northern and southern tail lobes. As a result, the boundary conditions are nearly symmetric and there is essentially no guide field,

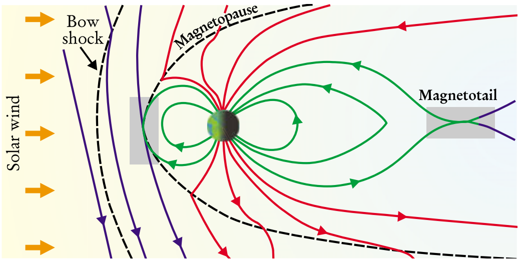

Fig. 1 2D cut through Earth's magnetosphere and upstream solar wind, showing reconnection at the subsolar magnetopause and in the magnetotail. Bow shock and magnetopause are indicated by *curved dashed lines*, with the magnetosheath in between. Interplanetary field lines are in *dark blue*, closed magnetospheric field lines in *green*, and reconnected field *lines in red* (From Day 2001)

at least not in the near-Earth magnetotail. Solar wind and magnetosheath current sheets, finally, are characterized by nearly symmetric plasma conditions, but the magnetic shear is variable.

Not only the boundary conditions at the various reconnection sites differ, but so do the key plasma parameters. The plasma β, the ratio between plasma pressure, Nk_BT, and magnetic field pressures, $B^2/2\mu_0$, is of order 1 in the solar wind, in the range 1–10 in the magnetosheath outside the magnetopause, but only of order 0.01 in the magnetotail lobes surrounding the magnetotail current sheet. The Alfvén speed, which sets the scale for the reconnection outflow velocities, is near 50 km s^{-1} in the solar wind, a few hundred km s^{-1} at the magnetopause, and 1000–2000 km s^{-1} in the tail lobes. The ion inertial length, λ_i, which is the characteristic length scale, is about 100 km in the solar wind, 50 km in the magnetosheath outside the magnetopause, and 1000 km around the magnetotail current sheet.

2.2 Reconnection Signatures

2.2.1 Normal Magnetic Field and Flow; Reconnection Electric Field

As reconnection implies the presence of a significant component of the magnetic field normal to the current layer, B_n, and a proportional inflow velocity, v_n, it would seem that the most direct way to prove the occurrence of reconnection would be to measure B_n and/or v_n. However, those quantities usually are small compared to the tangential components, and their determination is dependent on precise knowledge of the current sheet orientation, which makes their reliable determination difficult. Similarly, the reconnection electric field tangential to the current layer, E_t, is not only small, but has to be determined in the frame comoving with the current sheet. To get a rough estimate of B_n, one usually relies on minimum variance analysis of the magnetic field (Sonnerup and Cahill 1967), where B_n is identified with the minimum eigenvalue, but this technique has a number of pitfalls that must be considered before the resulting B_n's can be trusted (e.g., Sonnerup and Scheible 1998).

2.2.2 Accelerated Plasma Flows: The Walén Relation

Given the difficulties with the determination of B_n, v_n, and E_t, the clearest evidence for reconnection are detections of the accelerated plasma flows. As plasma flows across a current layer with $B_n \neq 0$, the components of the plasma velocity, $\boldsymbol{v}$, tangential to that layer change in response to the $\boldsymbol{j} \times \boldsymbol{B}_n$ force. For an ideal rotational discontinuity (RD), the change in the velocity is (Hudson 1971):

$$\Delta \boldsymbol{v} = \pm \Delta \boldsymbol{v}_{\mathrm{A}}, \tag{1}$$

where the symbol Δ refers to changes relative to some reference state (upstream of the magnetopause for example), and $\boldsymbol{v}_{\mathrm{A}}$ is the local Alfvén velocity, corrected for the effect of pressure anisotropy,

$$\boldsymbol{v}_{\mathrm{A}} = \boldsymbol{B}\sqrt{(1-\alpha)/\mu_0\rho}, \tag{2}$$

with $\alpha = (p_\parallel - p_\perp)\mu_0/B^2$. The positive (negative) sign on the r.h.s. of Eq. (1) applies if the normal components of the magnetic field and plasma velocity, B_n and v_n, have the same (opposite) signs. Equation (1) is the Walén relation expressed in the spacecraft frame. A more convenient frame is often the Hoffmann-Teller frame, as first demonstrated by Sonnerup et al. (1987). In the Hoffmann-Teller frame, the flow velocity, $\boldsymbol{v}'$, is aligned with the magnetic field, and the Walén-relation reduces to $\boldsymbol{v}' = \pm \boldsymbol{v}_{\mathrm{A}}$.

In spite of the fact that the flow acceleration $\Delta \boldsymbol{v}$ is due to the $\boldsymbol{j} \times \boldsymbol{B}_n$ force, the Walén relation does not contain B_n. This is because for an RD, as for any planar Alfvén wave, $\boldsymbol{v}_n$ is proportional to B_n. Thus the smaller B_n, the smaller the inflow velocity, and thus the less mass to accelerate. This independence means that a successful Walén test does not say anything about the reconnection rate, which in turn is proportional to B_n.

2.2.3 Kinetic Effects

Strong evidence for reconnection has also been obtained from the kinetic effects, which manifest themselves in the ion and electron velocity distribution functions (Cowley 1982, 1995). Among those are a D-shape of the 2D distributions of the transmitted ions, and interpenetrating ion beams, an example of which is shown in Fig. 9.

2.3 Earth's Magnetopause

In ideal MHD, the magnetopause is an impenetrable boundary forever separating the solar wind from the magnetosphere. Among the many possible plasma transfer mechanisms, it is primarily magnetic reconnection that allows solar wind plasma to penetrate the magnetopause and enter Earth's magnetosphere (Sibeck et al. 1999).

2.3.1 Structure, Flows, and Kinetic Effects

The left part of Fig. 2 shows the magnetopause reconnection configuration assuming antiparallel magnetic fields on the two sides of the current layer, i.e., 180° magnetic shear. Reconnection occurs in a small 'diffusion' region near the X that is considered a black box in all of Sect. 2. Outside the diffusion region, the MP current layer is akin to a rotational discontinuity. Plasma flowing across the RD gets accelerated by the $\boldsymbol{j} \times \boldsymbol{B}_n$ force, which can be visualized as the slingshot effect from the sharply bent magnetic field lines. The outflow forms a boundary layer on the Earthward side of the RD, with a plasma density dropping rapidly with increasing distance from the RD. Because of the large vertical extent of the RD, most of the plasma in the boundary layer entered way downstream from the X, never encountering the diffusion region at the X itself.

The right part of Fig. 2 shows the first in-situ observation of the predicted plasma jetting (Paschmann et al. 1979), made possible when high time-resolution 3D plasma measurements became available. The figure shows time-series of key plasma parameters for an outbound orbit by the ISEE spacecraft that included a complete magnetopause crossing, followed by partial re-crossings caused by magnetopause motion reversals. The magnetic shear across the magnetopause was 100° for this case. As expected for a crossing near the subsolar point, flow speeds were near-zero in the adjacent magnetosheath, but increased to almost 500 $\mathrm{km\,s^{-1}}$ upon crossing of the current layer, in agreement with the predictions from the Walén-relation.

More accelerated flows were subsequently detected both on the dayside and flank magnetopause (e.g., Sonnerup et al. 1981; Gosling et al. 1986). By now, the detection of the accelerated outflows and their comparison with the predictions from the Walén-relation have become the prime in-situ evidence for reconnection, as shown by the many references to Walén-relation tests in the review by Paschmann (2008). Further support for the magnetopause reconnection configuration illustrated in Fig. 2 has been provided by simultaneous observations by two spacecraft of the oppositely directed plasma outflows away from the X-line (Phan et al. 2000).

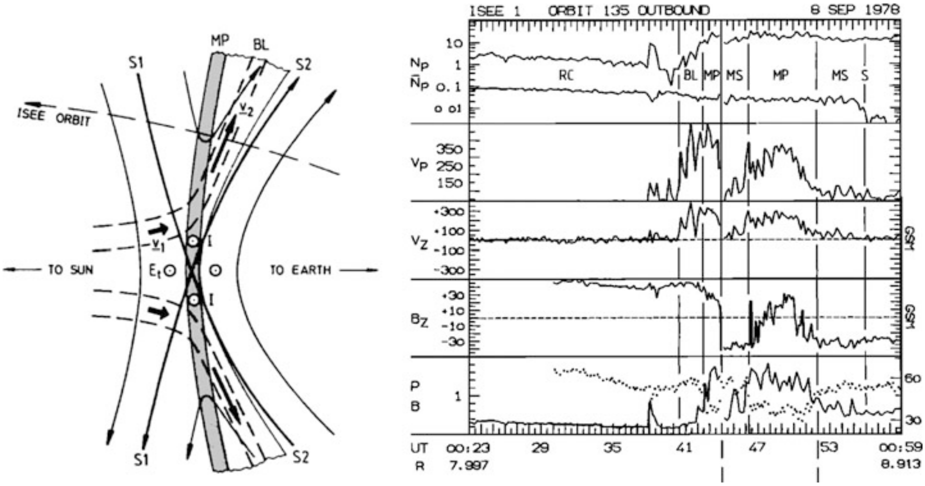

Fig. 2 *Left*: The magnetopause reconnection configuration for assumed antiparallel magnetic fields. The magnetopause (MP) is shown as a *grey-shaded* current layer, with a boundary layer (BL) on the Earthward side. Reconnection occurs at the X-line at the center, and the field lines emanating from the X form the separatrices, labeled S1 and S2. The *dashed lines* are stream lines, and the *solid arrows* indicate the plasma inflow and outflow velocities. E_t is the reconnection electric field, which is aligned with the current I. The magnetic field normal component is directed inward (outward) north (south) of the X-line. *Right*: First observation of plasma jetting at Earth's magnetopause. The figure shows the measurements along the spacecraft trajectory shown on the left. From top to bottom, it shows the plasma density (in cm^{-3}), the magnitude and z-component of the flow velocity (both in $km\,s^{-1}$), followed by the z-component of the magnetic field (in nT), and the pressures of the magnetic field (*dotted line*) and plasma (*solid line*), both in nPa. The magnetopause is recognized by the magnetic field rotation from positive B_z in the magnetosphere to negative B_z in the magnetosheath (From Paschmann et al. 1979)

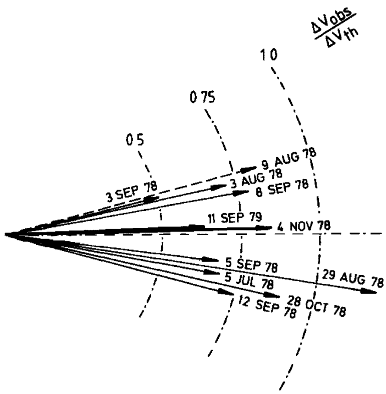

Fig. 3 Comparison of the measured changes in flow velocity, $\Delta \boldsymbol{V}_{obs}$, with those predicted by the Walén-relation, $\Delta \boldsymbol{V}_{th}$, for 11 high-speed flows observed at the dayside magnetopause. The velocities have been normalized to a common scale and orientation, such that the predicted velocity change is of unit length and oriented horizontally (Figure from Sonnerup et al. 1981)

It should be noted that the accelerated flows do not always match the Walén-relation perfectly. While the observed flow direction agrees with the prediction usually quite well, the flow magnitude is often less than the predicted value. This is illustrated in Fig. 3, which shows that the measured velocity directions are close to the prediction, but that their magnitude can be as low as only 50 % of the prediction (Sonnerup et al. 1981). These discrepancies are likely due to deviations of the real situation from the locally 1D, time-stationary conditions assumed in the Walén-relation, or to obstructions in the flow.

In addition to the plasma flow jets, a number of kinetic effects are observed at the magnetopause, among them a D-shape of the 2D distributions of the transmitted ions (e.g., Fuselier et al. 1991) that is caused by a cut-off at the Hoffmann-Teller velocity, interpenetrating ion beams (Gosling et al. 1990), and edge effects from velocity dispersion (Gosling et al. 1990; Vaivads et al. 2010).

2.3.2 Component Versus Anti-parallel Reconnection

The variable magnetic shear across the magnetopause allowed to resolve a long-standing controversy, namely whether or not reconnection requires anti-parallel magnetic fields, i.e, shear-angles of 180°. Observations near the reconnection X-line for shear angles of ∼90° conclusively show that magnetopause reconnection can occur in the presence of strong guide fields (e.g., Retinò et al. 2005; Pu et al. 2007; Trenchi et al. 2008). Reconnection in the presence of significant guide fields is often referred to as component reconnection.

2.3.3 X-Line Location

The special geometry of the Earth's magnetic field, together with the variability of the IMF direction and the draping of the field lines over the magnetopause surface, imply that the magnetic shear angle depends on time and location, with values ranging from 0° to 180° along the magnetopause surface at any given time. Although of mainly geophysical interest, the question is therefore, where the reconnection X-lines will occur. In general it is located in the subsolar region for southerly directed IMF, while for northward orientations it can occur along the polar magnetopause, tailward of the polar cusps. For east-west directed IMF, there is a tendency for reconnection to occur along a tilted X-line across the dayside magnetopause, where the magnetic shear maximizes (Trattner et al. 2012).

2.3.4 Spatial and Temporal Scales

Another controversy that magnetospheric observations have resolved is whether reconnection is intrinsically transient or whether it can be quasi-stationary. In-situ and remote-sensing observations of magnetopause reconnection have provided evidence for both modes.

Quasi-stationary Versus Transient Reconnection That reconnection can be quasi-stationary is well-known from observations of its ionospheric signatures (e.g., Heppner 1972; Rich and Hairston 1994; Greenwald et al. 1995). In-situ measurements at the magnetopause lead to the same conclusion. Gosling et al. (1982) had observed reconnection jets at each of several crossing occurring within a 5-hour interval, which suggests quasi-stationary reconnection. More recently, fortuitous circumstances left the Cluster spacecraft close to the magnetopause for long times, with the measurements indicating the presence of reconnection jets at all crossing instances, for up to several hours (Phan et al. 2004; Retinò et al. 2005). Figure 4 shows excellent agreement between the measured flow velocities and those predicted by the Walén-relation for the many magnetopause crossings occurring within a half-hour interval. Remote-sensing optical observations of bright auroral features caused by ion beams from a magnetopause reconnection site that lasted for almost four hours have provided additional evidence (Frey et al. 2003).

On the other hand, magnetopause reconnection frequently is transient, causing what is commonly referred to as flux-transfer-events (FTEs). FTEs are recognized as bipolar pulses of the normal component of the magnetic field. Russell and Elphic (1979) envisioned FTEs as a pair of elbow-shaped flux tubes, having diameters of order one Earth

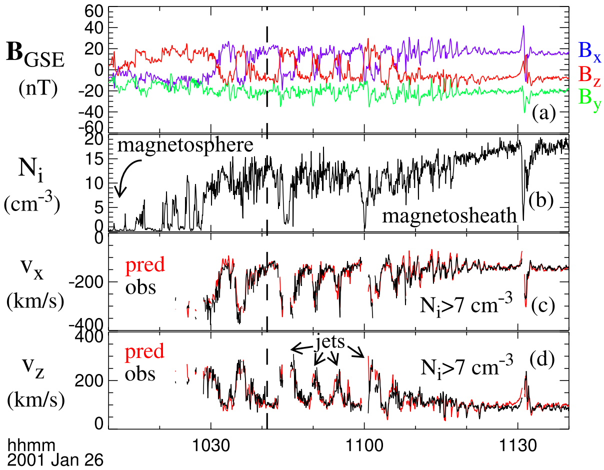

Fig. 4 Multiple magnetopause crossings by the Cluster 1 spacecraft: (**a**) magnetic field components in GSE; (**b**) ion number density; (**c**–**d**) *x* and *z* components of the predicted (*red*) and observed (*black*) ion bulk velocity, showing excellent agreement. The magnetopause crossings are recognized by the magnetic field rotation (Adapted from Phan et al. 2004)

radius (R_E), interconnecting the interplanetary with the terrestrial magnetic field, and moving away from the reconnection site, as shown in Fig. 5(a). In the models of Scholer (1988a) and Southwood et al. (1988), FTEs are caused by transient single X-line reconnection, leading to a pair of bulges moving away from the reconnection site at essentially the Alfvén speed (Fig. 5(b)). Ionospheric signatures of FTEs tend to support this picture of pulsed, but longitudinally extended reconnection (e.g., Lockwood et al. 1990b; Fear et al. 2012). Alternatively, elongated structures could be formed by multiple X-line reconnection (Lee and Fu 1985), produced by the tearing mode in the magnetopause current layer, leading to magnetic flux ropes connected to the Earth on one end and to the solar wind on the other, as illustrated in Fig. 5(c).

In either case the resulting structures are flux ropes with twisted (helical) fields (Song and Lysak 1989; Scholer 1995). The twisted magnetic fields will exert tension which will enhance the core magnetic field to preserve pressure balance (Paschmann et al. 1982). As

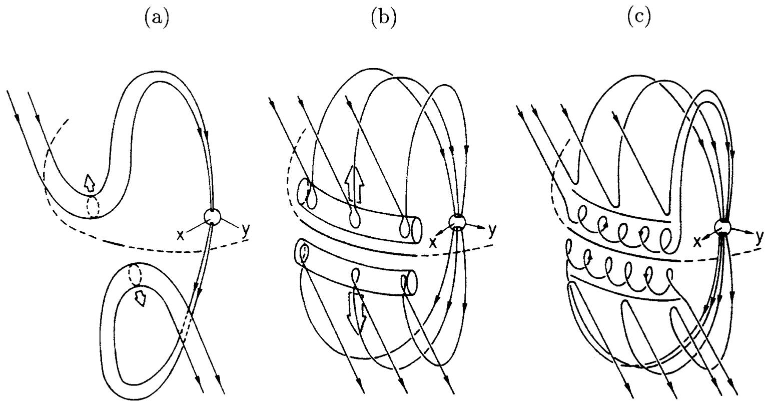

Fig. 5 Three FTE models. (**a**) Localized reconnection creating a pair of elbow-shaped flux tubes, as proposed by Russell and Elphic (1979); (**b**) Single X-line bursty reconnection, leading to a pair of bulges with a substantial longitudinal extent (Scholer 1988a; Southwood et al. 1988); (**c**) Multiple X-line reconnection (Lee and Fu 1985). From Scholer (2003), after Lockwood et al. (1990a)

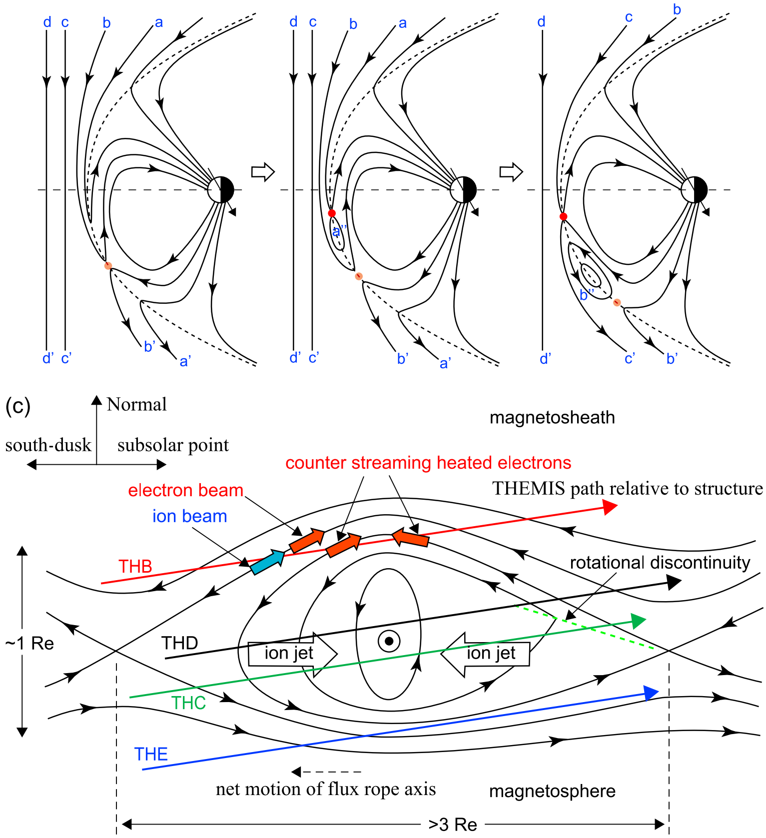

Fig. 6 *Top*: 2D views of the field line evolution in global MHD simulations showing the formation of a flux rope by reconnection at two sequentially activated X-lines marked in *red*; *bottom*: structure of the flux rope inferred from ion and electron beams observed along the trajectories of four THEMIS spacecraft (Adapted from Hasegawa et al. 2010)

argued by Sonnerup (1987) and Scholer (1988b), enhanced core fields can also be produced by a sweeping up of magnetopause flux by the reconnected field lines. As far as simulations are concerned, core-field enhancements are evident in the 3D MHD simulations by Ma et al. (1994). Global 3D simulations have also been able to model so-called crater FTEs, which possess a strong core field embedded in weak fields (Sibeck et al. 2008).

Large- Versus Small-Scale Reconnection at the magnetopause can be large-scale, extending essentially over the entire dayside magnetopause, as demonstrated by the simultaneous detection of reconnection signatures at widely spaced locations, both in-situ (Phan et al. 2006b; Dunlop et al. 2011a, 2011b) and by remote-sensing (e.g., Pinnock et al. 2003).

Whether magnetopause reconnection can be localized ('patchy'), as envisioned by Nishida (1989), and also evident in the 'elbow' model of FTEs (Fig. 5(a)) has not been fully resolved. Only a few ionospheric observations have been reported that suggest that FTEs can indeed be small-scale (e.g., Oksavik et al. 2004). It should be pointed out though that transient magnetotail reconnection can be localized, as discussed in Sect. 2.4.2.

Flux Ropes The recent multi-point measurements from the Cluster and THEMIS missions have revealed in considerable detail the structure of flux ropes. Figure 6 shows a magnetopause case, reported by Hasegawa et al. (2010), where a 2D flux-rope is formed by reconnection at two sequentially activated closely-spaced X-lines, as suggested by global MHD simulations (Raeder 2006). Hasegawa et al. also show maps of the transverse magnetic field within the flux rope, as obtained from Grad-Shafranov reconstruction, a technique that had been applied to FTEs already earlier (Sonnerup et al. 2004). Another flux rope, again flanked by two active X lines producing colliding plasma jets near the center, but with properties suggestive of 3D effects and suprathermal electron energization, has been reported by Øieroset et al. (2011). In a comprehensive study of almost 4000 FTEs observed by the THEMIS spacecraft (Zhang et al. 2012a), 41 flux ropes that were flanked by two X-lines could be identified, suggesting that multiple X-lines are rare or shortlived.

2.4 Earth's Magnetotail

As already mentioned in Sect. 2.1, reconnection in the magnetotail is characterized by nearly symmetric plasma conditions and a magnetic shear that is near 180° in the near-Earth magnetotail, but can deviate from 180° in the distant magnetotail. There are two preferred locations for magnetotail reconnection. First, there is the large-scale, nearly continuous reconnection in the distant tail, which on average must balance subsolar reconnection, because otherwise magnetic flux would be added to the magnetotail forever. The distant X-line lies typically around 140 R_E (Nishida et al. 1997), but can also be as close as 60 R_E (Øieroset et al. 2000). Second, there is near-Earth reconnection that is transient and associated with magnetospheric substorms (e.g., Angelopoulos et al. 1994, 2008; Nagai et al. 1998). The near-Earth X-lines form at distances between 10 and 30 R_E (Nishida and Nagayama 1973). There is a dependence on solar wind energy input, with the position near 15 R_E at high input, but beyond 20 R_E at low input (Nagai 2006). An example of the substorm-related bursty high-speed reconnection flows, observed during the passage of an X-line at a distance of 22 R_E, is shown in Fig. 7 (Angelopoulos et al. 2008).

2.4.1 Structure and Flows

For symmetric conditions, the outflow region is expected to be bounded by slow shocks and such shocks have indeed been reported (Feldman et al. 1985; Saito et al. 1998; Eriksson et al. 2004).

Initially, near-Earth magnetotail reconnection involves field lines embedded within the hot plasma sheet surrounding the current sheet, where the Alfvén-speed is typically several hundred km s^{-1}. If reconnection proceeds long enough, it will eventually reconnect the much more tenuous lobe flux tubes where the Alfvén-speed is typically 1000–2000 km s^{-1}. It is this fast reconnection phase that is generally believed to be the phase associated with magnetospheric substorm (e.g., Baker et al. 2002).

2.4.2 Spatial and Temporal Scales

In contrast to dayside magnetopause reconnection which at times can be quasi-steady and extended in space, reconnection in the near-Earth magnetotail is generally highly intermittent (Baumjohann et al. 1990; Angelopoulos et al. 1992) and patchy, producing narrow flow burst channels. The spatial scale of these flow channels is a few R_E, corresponding to a few tens of ion inertial lengths (Angelopoulos et al. 1997; Nakamura et al. 2004). Braking of

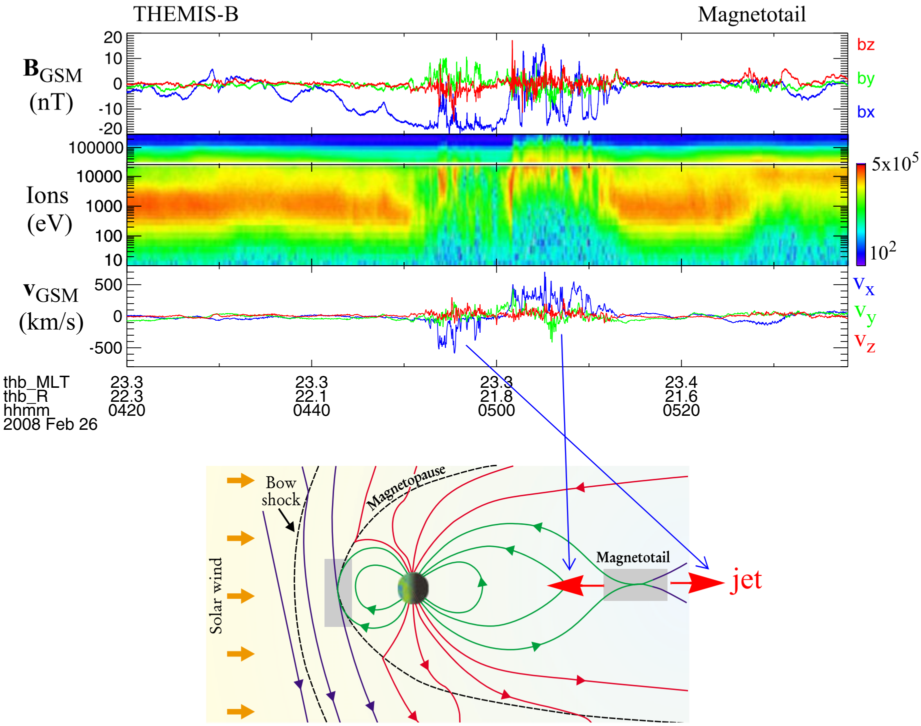

Fig. 7 Crossings of the magnetotail current sheet by one of the THEMIS spacecraft, showing bursty high-speed jets that switch direction from tailward to Earthward, in association with the passage of the reconnection X-line. *Top*: time-series of the three components of the measured magnetic field; energy-time spectrogram of the ions from 10 to 10^5 eV; the three components of the plasma bulk velocity. *Bottom*: schematic that illustrates the underlying configuration. Adapted from Angelopoulos et al. (2008)

these jets in the magnetic flux pile-up regions Earthward of the reconnection site is a strong candidate for electron acceleration (see Sect. 2.4.3).

Another transient reconnection feature in the magnetotail are magnetic flux ropes or plasmoids. On the largest scales, there are the plasmoids that are formed between the near-Earth and distant X-lines, subsequently propagating down-tail (Hones 1979), which can be remotely sensed because they compress the lobe magnetic field (Slavin et al. 1984). On the smallest scales, there are flux ropes that are formed by reconnection at multiple X-lines (e.g., Slavin et al. 2005). Recent multi-point measurements with the Cluster and THEMIS spacecraft have allowed to probe their internal structure (Eastwood et al. 2005; Imber et al. 2011; Beyene et al. 2011; Kiehas et al. 2012).

2.4.3 Electron Acceleration

The potential for accelerating electrons to high energies is one of the most appealing features of magnetic reconnection. In-situ measurements offer a unique opportunity to check the reality of this expectation.

At the magnetopause the identification of acceleration and heating is hindered by the energetic particles of magnetospheric origin that can enter the outflow region and mix with the incident solar wind plasma. There is as yet no evidence to suggest that reconnection in the solar wind ever produces substantial particle acceleration (Gosling 2011). However, observations in the magnetotail have clearly shown the association of energetic electrons up to several hundred keV with reconnection (Terasawa and Nishida 1976; Baker and Stone 1976).

The initial acceleration appears to occur in the diffusion region itself, as first reported by Øieroset et al. (2002) and later confirmed by Retinò et al. (2008). The smallness of the diffusion region limits its effectiveness for the overall acceleration. In the case presented by Øieroset et al., the energy density in the energetic electrons was less that 1 % of the energy density in the ion jets. But once these accelerated electrons have escaped the diffusion region and enter the outflow region, other processes can take over.

Hoshino et al. (2001) were the first to consider the magnetic flux pileup region, created when the fast reconnection outflow jets collide with the pre-existing plasmas at rest, as the site for the second step in the electron acceleration. Strong observational evidence for this scenario has been provided by the Cluster and THEMIS multi-point measurements in the outflow region close to the diffusion region (Imada et al. 2007; Ashour-Abdalla et al. 2011; Khotyaintsev et al. 2011; Vaivads et al. 2011). Regarding the actual mechanism, there is observational evidence for betatron and/or Fermi acceleration (Hada et al. 1981; Ashour-Abdalla et al. 2011; Khotyaintsev et al. 2011; Fu et al. 2011). Cluster multi-point measurements have also provided evidence for electron acceleration in association with magnetic islands (Chen et al. 2008b) and for island (or flux-rope) coalescence (Retinò et al. 2008).

The finding that much of the electron acceleration seems to occur not within the diffusion region itself, but through jet braking in the outflow is reminiscent of scenarios envisioned for acceleration in the solar corona (e.g., Tsuneta 1995; Shibata et al. 1995).

It should be noted that particle acceleration in cosmic plasmas was the subject of the first ISSI workshop in this series. In the volume resulting from that workshop, the chapter by Birn et al. (2012) provides a detailed discussion of both in-situ observations as well as simulation studies of ion and electron acceleration in Earth's magnetotail.

2.5 Solar Wind

Current sheets associated with directional discontinuities in the magnetic field are ubiquitous in the solar wind. That they can undergo reconnection and exhibit the associated plasma jetting has been discovered only fairly recently (Gosling et al. 2005). Study of these reconnection events offers valuable new insights because the boundary conditions are more stable and more symmetric than at the magnetopause, while the magnetic shear is as variable. There is also the advantage that the solar wind rapidly advects any embedded structure past an observing spacecraft. One thus obtains nearly instantaneous snapshots of the configuration, in contrast to the magnetopause and magnetotail current sheets, which are constantly reversing their motion. In the meantime, it has been established (see Gosling 2011) that such reconnection events are quite common and apparent in essentially all solar wind data sets, covering distances between 0.3 and 5 AU.

2.5.1 Structure, Flows, and Kinetic Effects

The overall structure is determined by plasma inflow across the RDs on both sides, with a wedge-shaped outflow (exhaust) region in between, as depicted on the left in Fig. 8. Because of the two back-to-back RDs, the entire structure appears as a bifurcated current sheet. On the right in Fig. 8, the observations for a pass through such a structure are presented. Because the inflow velocity on the two sides points in opposite directions, while the normal magnetic

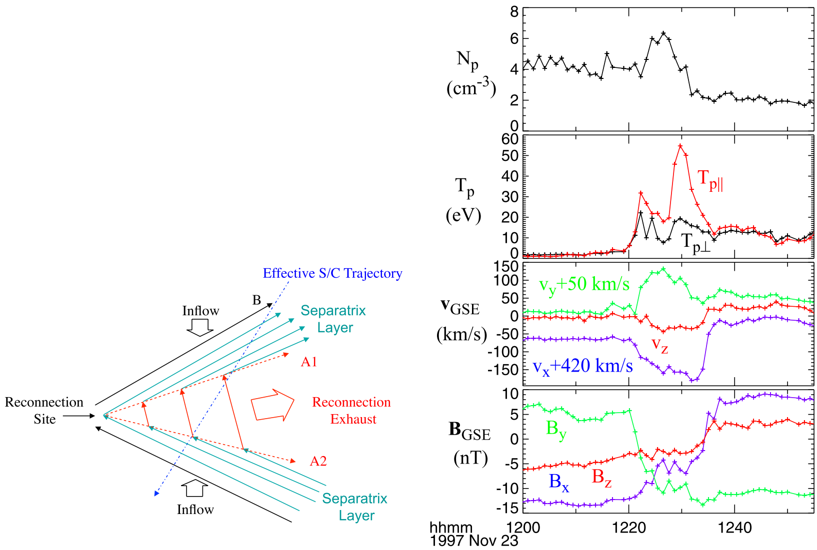

Fig. 8 *Left*: Schematic showing a slightly asymmetric solar wind reconnection configuration, consisting of an outflow region (exhaust), bounded on either side by thin current sheets labelled A1 and A2 that are akin to standing Alfvén waves, i.e., RDs. For simplicity, only one of the outflows emanating from the reconnection site is shown. *Right*: Observations by the ACE spacecraft during a crossing of a structure as depicted on the *left*. From top to bottom, the figure shows the plasma density, the parallel and perpendicular proton temperatures, the three components of the bulk velocity, and the corresponding magnetic field components, both in GSE coordinates (Adapted from Gosling et al. 2005)

field must be continuous and thus points in the same direction on both sides, the velocity and magnetic field variations at the boundaries are correlated on one side and anti-correlated on the other, as evident from Fig. 8. The outflow speed is much lower than at the magnetopause because the Alfvén velocity in the solar wind is much smaller. Nevertheless the observed flows closely meets the predictions from the Walén-relation. Multi-spacecraft observations of oppositely directed outflows, implying that an X-line was located between the observing spacecraft, have been reported by Davis et al. (2006) and Gosling et al. (2007c).

Under symmetric conditions, a slow shock (SS) is expected to occur inside the RDs on both sides of the exhaust. Although the enhanced proton density and temperature and decreased magnetic field strength observed in the central portion of the exhaust are qualitatively consistent with this expectation, the transitions across the boundaries of the exhaust in Fig. 8 are rather thick (a few hundred ion inertial lengths.) Sharper exhaust boundaries, reminiscent of slow shocks, have been seen in other solar wind exhausts (Phan et al. 2006a), although it is often found that these boundaries consist of merged RDs and slow-shocks (Teh et al. 2009; Sasunov et al. 2012). Sasunov et al. did, however, also report an event with a well-separated RD and SS pair. A remarkable result of the solar wind reconnection observations is the persistence of well-defined exhaust boundaries even at very large distances downstream from the X-line, of order of thousands or tens of thousands of ion inertial lengths.

In Sect. 2.2.3, interpenetrating beams were mentioned as one of the possible kinetic effects. In ideal MHD, the plasmas inflowing from the two sides do not mix, but are kept separated by a contact discontinuity. In practice this does not occur, as illustrated in Fig. 9, which shows the accelerated beams from the two sides interpenetrating in the middle of the

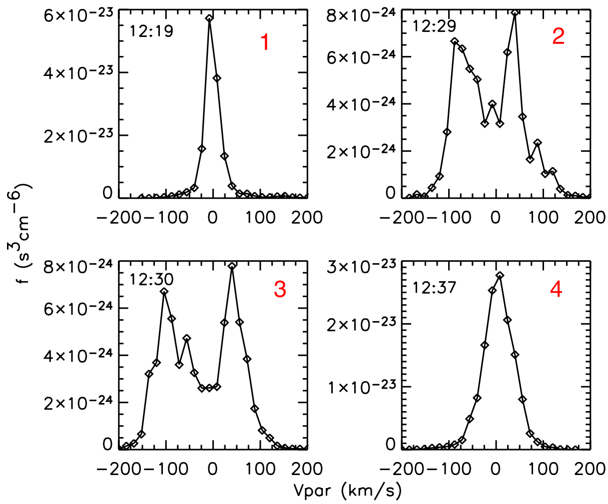

Fig. 9 Selected samples of the proton distribution function in the solar wind frame obtained before (*upper left panel*), during (*upper right* and *lower left panels*), and following (*lower right panel*) the reconnection exhaust crossing from Fig. 8 (From Gosling et al. 2005)

event (Gosling et al. 2005). The two beams have velocities separated by roughly twice the Alfvén speed, as expected from reconnection.

2.5.2 *Prevalence of Low Shear*

Solar wind reconnection events exhibit a prevalence of local magnetic shear angles $<90°$, with the smallest reported angle being only 11° (Gosling 2011), confirming the conclusion from the magnetopause observations that even large guide fields do not prevent reconnection.

2.5.3 *Spatial and Temporal Scales*

The presence of extended current sheets with stable boundary conditions in the solar wind allows studies of the large-scale properties of reconnection. Multi-spacecraft observations have indicated that solar wind reconnection events can have large spatial and temporal scales. The X-line can extend to several million kilometers (or tens of thousands of ion inertial lengths) and be observed over periods of several hours (or thousands of Alfvén transit times). An example is shown in Fig. 10 (Phan et al. 2006a). In one instance, the observing spacecraft remained in the exhaust as long as 3 hours (Gosling et al. 2007a). Even more extreme events, observed by many widely-spaced spacecraft, including STEREO-A and STEREO-B, have been reported by Gosling et al. (2007b) and Lavraud et al. (2009). The latter study suggests that reconnection rates might not have been constant over the duration of the event.

2.6 Magnetosheath

In the magnetosheath downstream from the quasi-parallel bow shock, the shocked solar wind plasma is highly turbulent. Figure 11 shows (on the right) the rapid fluctuations in magnetic field magnitude and direction, implying the occurrence of thin current sheets, which are necessary for reconnection to occur. In the lower left of the figure, the suggested formation of such current sheets between magnetic islands is illustrated. Analysis of high-resolution

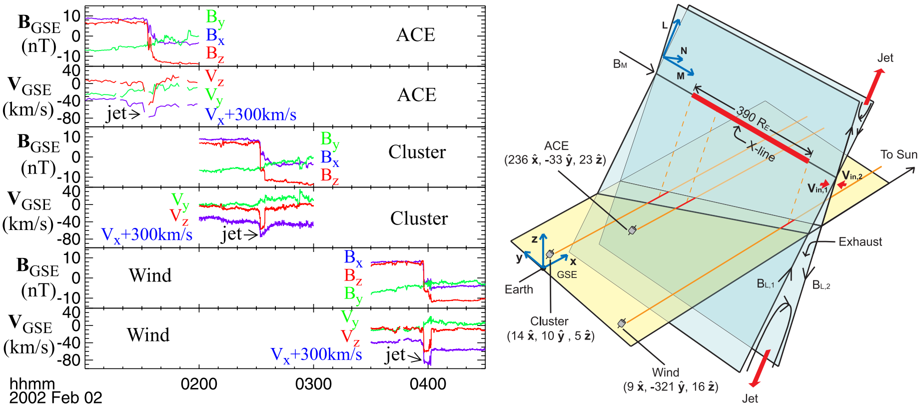

Fig. 10 A solar wind event observed sequentially by the widely spaced ACE, Cluster, and Wind spacecraft, implying that reconnection was occurring over large spatial and temporal scales. *Left*: The *top two panels* show the magnetic field and plasma flow velocities from ACE, and the subsequent panels show the same quantities for one of the Cluster spacecraft and for Wind. *Right*: Schematic of the encounters by ACE, Cluster and Wind with the exhaust region and its boundaries (*blue planes*) emanating from an extended (390 R_E) reconnection X-line The *yellow plane* is the ecliptic. Spacecraft positions (in R_E) are given in geocentric solar ecliptic coordinates (Adapted from Phan et al. 2006a)

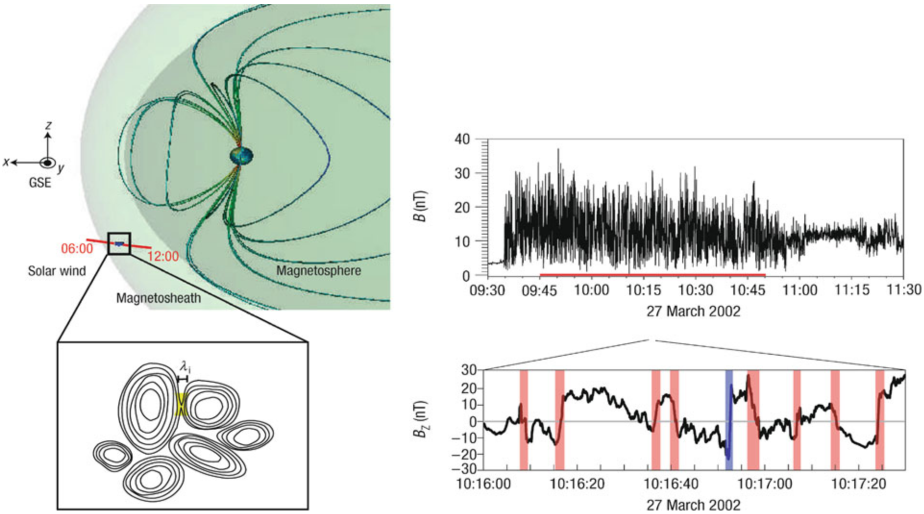

Fig. 11 *Left*: Cluster spacecraft crossing of a quasi-parallel bow shock and schematic illustration of current sheet formation between magnetic islands in the downstream magnetosheath. *Right*: time-series of magnitude and main component of the measured magnetic field, showing evidence of many current sheets (Adapted from Retinò et al. 2007)

multi-point measurements from Cluster (Retinò et al. 2007) for one such current layer crossing have revealed the microphysical (Hall-current) signatures that are evidence for magnetic reconnection (see Sect. 3.1). If reconnection occurs in a large percentage of these turbulent current sheets, the process could play an important role in the dissipation of turbulent energy (Sundkvist et al. 2007).

Reconnection in the magnetosheath has also been observed on larger scales. Thick (non-reconnecting) solar wind current sheets are compressed when they convect across the bow shock and further compressed as they pile up against the magnetopause. The thinning of the current sheet can trigger reconnection. This scenario was revealed by hybrid and MHD simulations (Lin and Xie 1997; Maynard et al. 2002; Omidi et al. 2009) and confirmed by multi spacecraft observations (Phan et al. 2007b). The interaction of current sheets with the bow shock and the magnetopause may have applications beyond the near-Earth space. It has been suggested that similar interactions could also occur across the termination shock and/or at the heliopause of our solar system producing anomalous cosmic rays (Drake et al. 2010), or in striped wind compression across termination shocks in pulsar wind nebulae (Lyubarsky 2003).

2.7 Other Planets

Reconnection signatures have been reported for the magnetospheres of five other planets, mostly based on in-situ magnetic field measurements.

Mercury, with its small intrinsic magnetic field and its closeness to the Sun, has a small magnetosphere, although its basic structure resembles that of Earth's. MESSENGER observations have revealed reconnection signatures at the magnetopause and in the magnetotail. In one instance, minimum variance analysis of the magnetic field implied that the magnetopause appeared as a rotational discontinuity, with a finite B_n that translated into a reconnection rate of 0.13 (Slavin et al. 2009).

Venus has no intrinsic magnetic field, but a magnetotail is formed by the draped IMF. There formation of a plasmoid due to magnetic reconnection has been observed recently by the Venus Express spacecraft (Zhang et al. 2012b).

At Mars, the Hall magnetic fields that are a signature of the reconnection diffusion region have been detected at tail and flank current sheets (Eastwood et al. 2008; Halekas et al. 2009), indicating that reconnection is occurring, as discussed in Sect. 3.1. Flux ropes have been observed there as well (Eastwood et al. 2012).

Jupiter has the largest planetary magnetosphere, its dynamics being dominated by planetary rotation rather than by the solar wind. Yet there is significant solar wind interaction, as manifested by a long magnetotail. In the magnetotail, magnetic signatures of localized and transient reconnection have been observed (Russell et al. 1998), and some auroral features have also been interpreted as resulting from magnetotail reconnection (Radioti et al. 2011). In a direct transfer of insights obtained for Earth's magnetosphere, magnetopause reconnection rates at Jupiter have been estimated using empirical relationships between solar wind parameters and reconnection voltages obtained for Earth, scaled to Jupiter conditions (Nichols et al. 2006).

Like Jupiter, Saturn has a large rapidly rotating magnetosphere, but reconnection might still play a role in its dynamics. In one magnetopause crossing, a non-zero normal component of the magnetic field has been reported from minimum variance analysis of the magnetic field, implying a reconnection rate of 0.10 (McAndrews et al. 2008). Interestingly, in another direct transfer of knowledge gained at Earth (see Sect. 2.8.2), Masters et al. (2012) have suggested that the higher plasma β in the magnetosheath of Saturn should prevent magnetopause reconnection except for large shear angles. The case reported by McAndrews et al. had indeed a fairly large magnetic shear (149°).

2.8 General Characteristics

In this section, we will discuss some general characteristics of reconnection that the in-situ observations have revealed.

2.8.1 Occurrence Frequency

Not all crossings of the magnetopause, magnetotail, or solar wind current sheets show evidence of reconnection. In fact, the majority of current sheet crossings in the solar wind and in the magnetotail show no reconnection signatures, while at the dayside magnetopause the occurrence rate of reconnection signatures is about 50 % (Paschmann et al. 1986). This raises the question what conditions must be fulfilled for reconnection to occur. The next section discusses such conditions.

2.8.2 Onset Conditions

Current Sheet Thickness For reconnection to occur, the current sheet must be sufficiently thin. In collisionless plasmas, it appears that the current sheet thickness has to be one ion inertial length or smaller, in order to initiate reconnection (e.g., Cassak et al. 2006).

According to the general understanding of magnetotail dynamics, the tail current sheet is usually too thick for reconnection to start. The bursty nature of near-Earth magnetotail reconnection suggests that sufficient thinning occurs only sporadically. Regardless of the cause for thinning, ISEE and Cluster multi-spacecraft observations have provided evidence for sub-ion-inertial-length current sheets just prior to magnetotail reconnection and associated substorm onset (e.g., Sanny et al. 1994; Runov et al. 2008).

The dayside magnetopause current sheet is usually thin due to the constant compression of the solar wind against the dayside magnetosphere. However, as mentioned earlier, half of the magnetopause crossings display no reconnection signatures even when the magnetic shear is high. This indicates that a thin current sheet is a necessary but not sufficient condition for reconnection.

Magnetic Shear and Plasma β While it is clear that current sheets must be sufficiently thin for reconnection to occur, the plasma β, i.e, the ratio of plasma to magnetic pressure, has long been suspected to be an important additional constraint. Early magnetopause observations (Paschmann et al. 1986) had suggested that β in the inflow (magnetosheath) region may be a controlling factor, with reconnection more likely to occur for small values of β. It now appears, based on recent solar wind and magnetopause observations, that it is not β alone that controls reconnection, but a combination of β (more precisely the difference between the β values on the two sides) and the magnetic shear (Phan et al. 2010, 2013, in press). The left part of Fig. 12 shows that for low $\Delta\beta$ reconnection occurred at current sheets with both low and high magnetic shear angle, whereas for large $\Delta\beta$ reconnection occurred only for high magnetic shear angles. The plot on the right shows that β itself does not organize the data as well as $\Delta\beta$. These observations are in quantitative agreement with a theoretical prediction (Swisdak et al. 2003, 2010) that reconnection is suppressed in high β plasmas at low magnetic shear angle due to diamagnetic drift of the reconnection X-line caused by plasma pressure gradients across the current sheets.

2.8.3 Reconnection Rates

Reconnection rates are notoriously difficult to obtain from in-situ observations because they require knowledge of the normal component of the magnetic field, B_n, or the plasma flow, v_n, which are both small and depend on precise knowledge of the current sheet orientation. Similar restrictions apply to the determination of the reconnection electric field, E_t. For the magnetopause, Fuselier and Lewis (2011) have compiled some of the reported values in

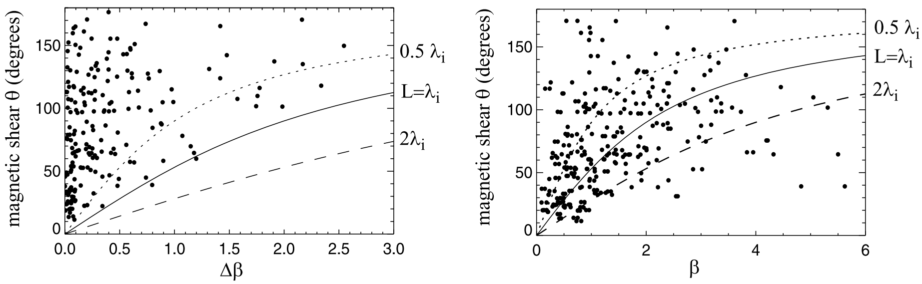

Fig. 12 *Left*: Plot of magnetic shear angle versus the difference of the plasma-β on the two sides of a set of 197 solar wind reconnection exhausts. The *three curves* are theoretical predictions from Swisdak et al. (2010) for different choices of the scale size, L (in units of the ion inertial length, λ_i), of the density gradient at a reconnection diffusion region. Reconnection should be suppressed below these curves. *Right*: Similar plot, but for β (Adapted from Phan et al. 2010)

the literature, ranging between <0.01 and 0.2. For one extended magnetopause reconnection event, Fuselier et al. (2010) have reported an average value of 0.08. Rosenqvist et al. (2008) have determined reconnection rates for the multiple magnetopause crossings shown in Fig. 4, and obtained values between 0.01 and 0.3, with an average of 0.14. For individual solar wind and magnetosheath events, values of ∼0.03 and ∼0.07, respectively, were inferred (Phan et al. 2006a, 2007b). The large variations in the reported values do not necessarily imply intrinsic variability of the reconnection rates, but may simply represent the (hard to quantify) uncertainties in the determinations. Note that simulations of fast reconnection give typical rates of 0.1–0.2 (Shay et al. 1998).

3 Microphysics

Magnetic reconnection is a cross-scale phenomenon. While the process is initiated in a small *diffusion region*, where ion and electrons are demagnetized, the consequences of reconnection are large-scale, as discussed in Sect. 2.

The manner in which the particles demagnetize is closely related to the relative importance of the different scale sizes: the resistive scale, the ion scale, and the electron scale. In the diffusion region the plasma frozen-in condition must be violated, implying that some of the terms on the r.h.s. of the generalized Ohm's law must be non-zero. Ohm's law can be written as (e.g., Rossi and Olbert 1970):

$$\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B} = \eta \boldsymbol{j} + + \frac{1}{ne} \boldsymbol{j} \times \boldsymbol{B} - \frac{1}{ne} \nabla \cdot \boldsymbol{P}_e + \frac{m_e}{ne^2} \left[\frac{\partial \boldsymbol{j}}{\partial t} + \nabla \cdot (\boldsymbol{j}\boldsymbol{v} + \boldsymbol{v}\boldsymbol{j}) \right] \tag{3}$$

where $\boldsymbol{E}$ and $\boldsymbol{B}$ denote electric and magnetic fields, $\boldsymbol{v}$ is the velocity of the particle species, and $\boldsymbol{j}$ is the current density. Each of the terms on the right hand side of Eq. (3) can break the frozen-in condition and are associated with different scale sizes. Here $\eta \boldsymbol{j}$ is the resistive term, $\frac{1}{ne} \boldsymbol{j} \times \boldsymbol{B}$ is the Hall, or ion, term, $\frac{1}{ne} \nabla \cdot \boldsymbol{P_e}$ is the divergence of the electron pressure term, and $\frac{m_e}{ne^2}[\frac{\partial \boldsymbol{j}}{\partial t} + \nabla \cdot (\boldsymbol{j}\boldsymbol{v} + \boldsymbol{v}\boldsymbol{j})]$ is the electron inertia term. Thus the first term becomes important on the resistive scale, the second term is associated with the ion scale, and the last two terms become important on the electron scale.

If the resistive scale is larger than the ion scale, both electrons and ions demagnetize on the same scale, the resistive scale. However, if the resistivity is so small that the resistive

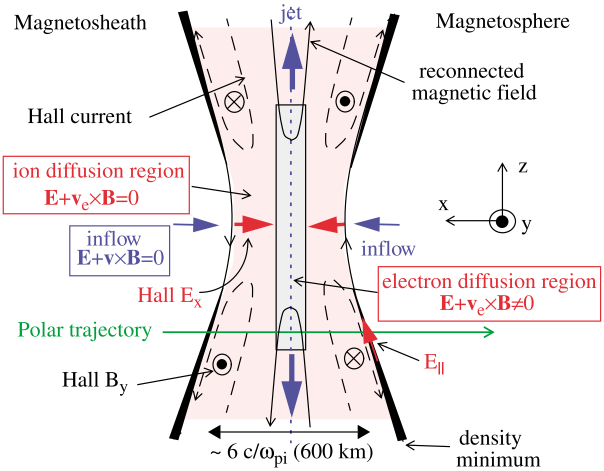

Fig. 13 The geometry of the diffusion region. Ions are decoupled from the electrons and magnetic field in the ion diffusion region, creating Hall magnetic and electric field patterns. Electrons are demagnetized in the much smaller electron diffusion region. The *green arrow* indicates the trajectory of the Polar spacecraft while collecting the data shown in Fig. 14(A) (From Mozer et al. 2002)

term can be ignored, the ions will demagnetize at the ion scale, due to the $\frac{1}{ne}\boldsymbol{j} \times \boldsymbol{B}$ (Hall) term, while the electrons will stay magnetized longer, until they reach the much smaller electron scale where they become demagnetized due to one of the electron terms. The ion and electron separation in the diffusion region leads to a system of Hall currents, which in turn induce the quadrupolar Hall magnetic fields, as shown in Fig. 13. A Hall electric field develops in the ion diffusion region and is directed towards the current sheet on both sides of the current sheet (Fig. 13). The $V_{e,y} = E_z \times B_x/B^2$ drift and its pulling of the magnetic field in the negative y direction results in the quadrupolar Hall B_y (Mandt et al. 1994; Shay et al. 1998; Pritchett 2005).

The quadrupolar Hall currents and magnetic fields are symmetric in magnitude on the two sides of the current sheet only when reconnection is symmetric, i.e. when the plasma on the two sides of the current sheet are similar. When reconnection is asymmetric, i.e. the reconnecting plasmas are different, the Hall currents and magnetic field patterns are also asymmetric, with larger magnitude Hall fields on the low-density side of the current sheet (Pritchett 2008). Reconnection is usually asymmetric at the Earth's magnetopause, and symmetric in the Earth's magnetotail. If a guide field is present, the Hall magnetic field will be superposed onto this guide field and therefore appear to be asymmetric even if reconnection is symmetric (Karimabadi et al. 1999; Pritchett and Coroniti 2004).

Until recently, much of our knowledge of processes in the diffusion region was derived solely from theoretical modeling. The small size of the diffusion region made it very challenging to observe in situ with a spacecraft. The width of the ion diffusion region is of the order of the ion inertial length, λ_i, which is only ∼50 km at the Earth's dayside magnetopause and ∼1000 km in the magnetotail. The length of the diffusion region is predicted to be 10 times larger. The electron diffusion region width is the electron inertial length, λ_e, which is 43 times smaller, only ∼1–2 km at the magnetopause and ∼25 km in the magnetotail. In this section we discuss recent findings from spacecraft encounters with both the ion-scale and the electron-scale diffusion region, as well as observations from additional reconnection-related regions where electron-scale physics has been found to be important. Finally, we discuss briefly the upcoming NASA Magnetospheric Multi-Scale (MMS) mission, which is dedicated to studies of electron-scale physics in reconnection.

3.1 The Ion Diffusion Region

In collisionless reconnection, the ion diffusion region is the region where ions are demagnetized while electrons are not, resulting in a Hall current and induced Hall magnetic fields, as discussed above and illustrated in Fig. 13. Confirming the presence of the Hall effect with in-situ spacecraft observations is significant since it implies that the resistive scale is smaller than the ion inertial length, and the ions and electrons are demagnetized at different scales. While the quadrupolar Hall currents and Hall magnetic field in the diffusion region were first predicted theoretically (Sonnerup 1979), the first in situ spacecraft observations of these phenomena were made approximately two decades later.

Hall Currents The first observational confirmation of the predicted ion and electron decoupling in the diffusion region were made along the separatrix layers. The separatrices are the surfaces defined by all magnetic field lines crossing the reconnection X-line, thus representing the most recently reconnected field lines. In Fig. 2, the field lines labeled S1 and S2 are cuts through the separatrix surfaces. Fujimoto et al. (1997) and Nagai et al. (2001) reported observations by the Geotail spacecraft along magnetotail separatrices of low-energy electrons streaming towards the X-line, while higher energy electrons were streaming away from the X-line. The directions of the low energy electrons were consistent with them being the Hall current carriers.

Hall Magnetic Fields In addition to observing the Hall current carrier along the separatrices, Nagai et al. (2001) reported associated out-of-plane magnetic fields consistent with the predicted directions of the Hall magnetic field. Subsequently, Hall magnetic fields were detected inside the diffusion region itself by the Wind spacecraft in Earth's distant magnetotail (Øieroset et al. 2001). The diffusion region was identified from the plasma jet reversal, which coincided with a reversal in the normal component of the magnetic field, indicating that the spacecraft crossed a reconnection diffusion region, going from the earthward to the tailward jet. Coinciding with these reversals, the out-of-plane magnetic field component also reversed sign and the observed polarities were consistent with the predicted polarities of the quadrupolar Hall magnetic field (see Fig. 14(C)).

Mozer et al. (2002) reported a fortuitous diffusion region encounter by the Polar spacecraft at the dayside magnetopause. We note that this event was a rare case when reconnection was nearly symmetric at the Earth's magnetopause, thus the Hall magnetic field pattern would still be quadrupolar, similar to the magnetotail Hall pattern. However, in contrast to the Wind crossing along the outflow direction of the tail diffusion region, the Polar crossing was normal to the current sheet, going from the magnetosheath to the magnetosphere south of an X-line, as indicated by the green horizontal line in Fig. 13, the out-of-plane magnetic field reversed sign from positive to negative, consistent with the predicted directions of the Hall magnetic fields (Fig. 14(A)).

A Cluster multi-spacecraft encounter with a diffusion region at the dayside magnetopause was reported by Vaivads et al. (2004), also showing out-of-plane magnetic fields consistent with the Hall magnetic field directions (Fig. 14(B)). In this multi-spacecraft encounter, two spacecraft observed the Hall magnetic field simultaneously in two of the quadrants, hence establishing even more firmly that the observed out-of-plane magnetic fields were spatial, not temporal structures. From the four-point timing analysis, the spatial scale shown along the bottom of Fig. 14(B) was determined, giving a current layer thickness of a few ion inertial lengths.

Confirming the presence of the Hall magnetic field in all four quadrants in one single event is challenging, even with multi-spacecraft observations. To overcome this difficulty,

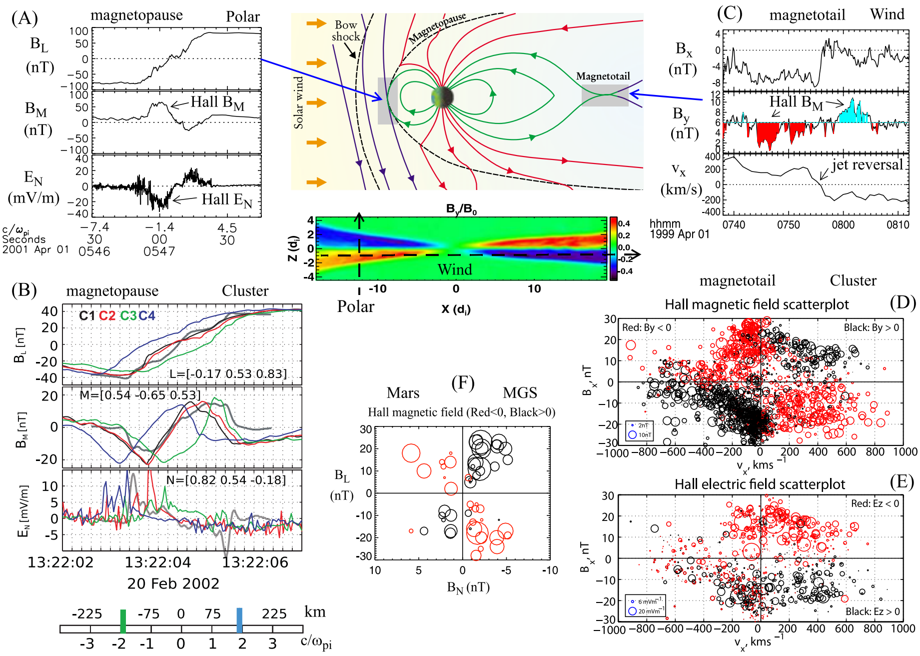

Fig. 14 Hall magnetic and electric fields, as observed at the magnetopause and magnetotail reconnection sites shown in the cartoon at the *top center*. (**A**) Magnetopause crossing by the Polar spacecraft, showing the Hall and reconnecting magnetic field components and the Hall electric field (adapted from Mozer et al. 2002). (**B**) Magnetopause crossing by the four Cluster spacecraft, showing the reconnecting magnetic field component, the out-of-plane magnetic field component, and the electric field normal to the magnetopause (adapted from Vaivads et al. 2004). (**C**) Crossing of the magnetotail current sheet by the Wind spacecraft, showing he bipolar Hall magnetic field and the reversal in the Earthward directed flow velocity (adapted from Øieroset et al. 2001). (**D**) Hall magnetic field B_y versus reconnecting magnetic field B_x and reconnection jet velocity V_x. Black corresponds to $B_y > 0$ and red to $B_y < 0$. (**E**) Hall electric field versus B_x and V_x. Black corresponds to $E_z > 0$ and red to $E_z < 0$. The size of the symbols indicates the magnitude of the data points (adapted from Eastwood et al. 2010b). (**F**) Hall magnetic fields observed by the Mars Global Surveyor (MGS) spacecraft, in a format similar to part (**D**), except that B_n is used to distinguish the two sides of the X (MGS data courtesy of J. Halekas). *Center*: simulation of the diffusion region, with the Hall field directions in *red* (courtesy M. Shay)

Eastwood et al. (2010b) performed a statistical study, using Cluster multi-point observations of 18 diffusion region encounters in the Earth's magnetotail, which, taken together, covered all four quadrants multiple times. The observed out-of-plane magnetic fields in these events were indeed consistent with the predicted Hall magnetic field in all four quadrants, as shown in Fig. 14(D).

The events included in Eastwood et al. (2010b) did not have any significant guide field. By contrast, Eastwood et al. (2010a) studied a separate diffusion region encounter by Cluster where a moderate guide field (20 % of the reconnecting field) was present and showed that the Hall magnetic and electric fields were asymmetric and shunted away from the current sheet, consistent with simulations.

In addition to the studies already mentioned, there has been several other reports of in-situ spacecraft encounters with the diffusion region, both in the Earth's magnetotail (e.g., Runov et al. 2003; Wygant et al. 2005; Borg et al. 2005; Nakamura et al. 2006; Asano et al. 2008), at the Earth's magnetopause (e.g., Pu et al. 2005; Zhang et al. 2008), in the magnetosheath (Phan et al. 2007a), and even at other planets (e.g., Eastwood et al. 2008; Halekas and Brain 2010). Figure 14(F) shows the amplitude of the out-of-plane magnetic field for 28 current sheet crossings at Mars. The observed polarities of the out-of-plane magnetic fields surrounding diffusion regions at Mars are consistent with the predictions for the Hall quadrupolar magnetic field, indicating that ion-electron decoupling also occur in reconnection at Mars (Halekas et al. 2009).

Hall Electric Fields Electric fields with directions consistent with the predicted direction of the Hall electric field (Shay et al. 1998; Pritchett 2005) has been reported in connection with observations of the Hall magnetic field, both at the Earth's magnetopause (Mozer et al. 2002; Vaivads et al. 2004) and in the magnetotail (Wygant et al. 2005; Borg et al. 2005; Eastwood et al. 2010b). Examples are shown in Fig. 14(A) and (B). In their statistical study Eastwood et al. (2010b) recorded the normal electric field and showed that its direction was consistent with the predicted direction of the Hall electric field for all 18 events (Fig. 14(E)).

3.2 The Inner Electron Diffusion Region

Within the ion diffusion region there is a thin layer where electrons demagnetize (Fig. 13). This inner electron diffusion region is located in close vicinity of the reconnection X-line.

According to theory, the electron diffusion region is characterized by a large out-of-plane current centered at the electron jet reversal (Shay and Drake 1998; Hesse et al. 1999). The two lower panels in the left part of Fig. 15 show horizontal cuts through a simulation of the reconnection region, including the electron diffusion region shown in the top panel. As shown in the middle panel, there is a large difference between electron and ion outflow speeds. The bottom panel shows the electron and ion velocities in the out-of-plane direction. While very little variation is seen in the out-of-plane ion velocity, there is a large into-the-plane electron jet located right at the jet reversal. This into-the-plane electron jet indicates the presence of a strong out-of-plane current right in the center where the ion and electron jets reverse sign.

Because the inner electron diffusion region is 43 times smaller than the ion diffusion region, there have been few reports of encounters with this region until recently. Chen et al. (2008a), with guidance from kinetic simulations, reported the encounter of the inner electron diffusion region by the Cluster spacecraft. More recently, Nagai et al. (2011) reported a fortuitous encounter with the electron diffusion region in the Earth's magnetotail, when the Geotail spacecraft traversed from the tailward to the earthward side of a reconnection X-line (Fig. 15, right). Panel (c) shows the electron and ion velocities in the outflow direction as the dotted and solid line, respectively. A large difference between electron and ion speeds is seen, similar to that in the simulation (Fig. 15, left). Furthermore, right at the jet reversal there was a strong into-the-plane electron jet, a key characteristic of the inner electron diffusion region.

The observed strong into-the-plane electron jet indicates that the spacecraft encountered the inner electron diffusion region. However, only two data points were collected in the region of strong current. While this indicated that the electron diffusion region was indeed encountered, it is not sufficient to study the detailed electron physics in this region. Investigating the electron-scale processes in the electron diffusion region is the goal of the upcoming MMS mission, which will perform very high-resolution plasma and field measurements (see Sect. 3.5).

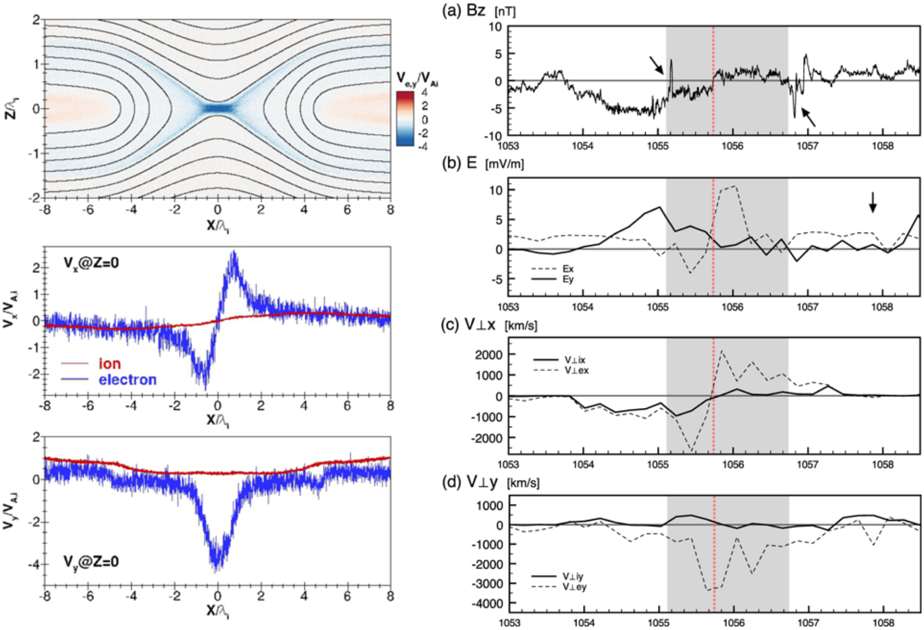

Fig. 15 *Left*: Simulations of a reconnection region. The *top panel* shows the diffusion region, with the electron part at the center. The *middle panel* shows the electron and ion velocities in the outflow direction, the *lower panel* the velocities in the out-of-plane direction, electrons in *blue* and ions in *red* (Figure courtesy of I. Shinohara). *Right*: Geotail observations on 15 May 2003. (**a**) Normal magnetic field B_z, (**b**) electric field E_x, E_y, and (**c**, **d**) plasma perpendicular velocities. The presumed X-line crossing is indicated by a *red vertical line*. From Zenitani et al. (2012), after Nagai et al. (2011)

3.3 Elongated Electron Jet Layer

Full particle simulations in large simulation domains revealed the existence of a long (tens of ion inertial length) super-Alfvénic electron jet connected to the inner electron diffusion region (Daughton et al. 2006; Karimabadi et al. 2007; Shay et al. 2007). Cluster detected such an electron jet (extending at least 60 ion inertial lengths) in a magnetosheath reconnection event under nearly symmetric boundary conditions (Phan et al. 2007a). Simulations showed that in the case of asymmetric reconnection with a guide field, the extended electron jet exists over a shorter length than for symmetric reconnection, and the jet exists on one side of the X-line only (Mozer and Pritchett 2009). In contrast to the inner electron diffusion region, the extended electron jet is not accompanied by dissipation (Hesse et al. 2008).

3.4 Electron Physics Along the Separatrices

Connected to the diffusion region are the separatrices, referred to earlier. Ion and electron decoupling have been observed in thin (electron scale) layers, associated with the separatrices, at distances far away from the traditional diffusion region surrounding the X-line (Mozer et al. 2003; André et al. 2004; Khotyaintsev et al. 2006). These layers of electron-ion decoupling along the separatrices are characterized by large density fluctuations and large electric fields both perpendicular and parallel to the magnetic field.

Solitary waves, which are bipolar electric field pulses traveling parallel to the magnetic field, have been observed on the magnetospheric side of the magnetopause current sheet

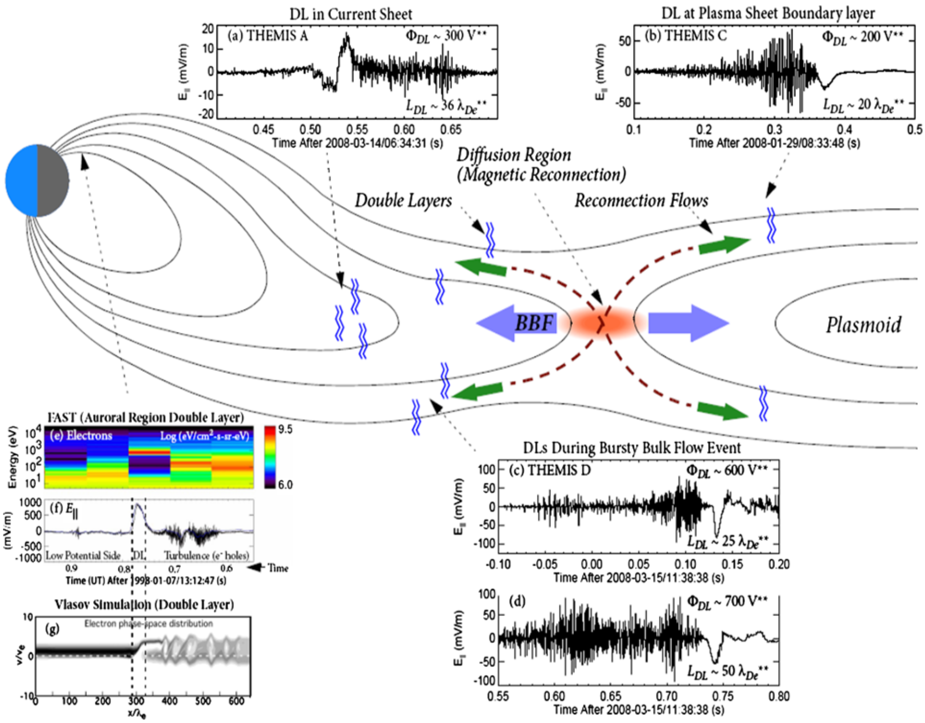

Fig. 16 FAST and THEMIS observations of double layers and electron holes in the magnetosphere. The occurrence regions are indicated in the cartoon. The data plots show time series of E_{parallel}, demonstrating that double layers and solitary waves have been observed in the magnetotail current sheet (*top*, *left*), in the plasma sheet boundary layer (*top*, *right*), in the auroral region (*bottom*, *left*) and in bursty bulk flows (*bottom*, *right*). THEMIS data plots adapted from Ergun et al. (2009). Figure courtesy of R. Ergun and L. Andersson

(Cattell et al. 2002), as well as in the Earth's magnetotail where they have been observed near the outer edge of the plasma sheet and in the current sheet itself (Cattell et al. 2005; Ergun et al. 2009; Andersson et al. 2009) (see Fig. 16). These waves, also referred to as electron holes, could play an important role in dissipation and diffusion if they occur in large numbers because they can affect the electron distribution function (Cattell et al. 2002).

3.5 NASA's Magnetospheric Multi-scale Mission

The ion diffusion region has now been encountered and explored by a variety of spacecraft, but the electron diffusion region is largely unexplored. This is primarily because current spacecraft instrumentation cannot resolve the electron diffusion region in detail. The upcoming Magnetospheric Multi-Scale (MMS) mission, scheduled for launch in 2014, consists of four spacecraft carrying identical plasma and field instruments with orders of magnitude higher time resolution plasma measurements than before (e.g., Burch and Drake 2009). The spacecraft will fly in a tetrahedral (pyramid) formation with close (as small as 10 km) separation, allowing them to determine three dimensional structures of the reconnection sites they encounter, both at the magnetopause and in the magnetotail. Achieving the MMS mission goal rests on the ability to unambiguously identify the inner electron diffusion region in the data. Studies of recent spacecraft encounters with the inner electron diffusion region have yielded methods for identifying this region (Zenitani et al. 2012; Scudder et al. 2012).

4 Summary

In-situ observations in planetary magnetospheres and the solar wind, in conjunction with theoretical modeling and simulations, have provided many insights into the reconnection process that we have described in this paper and summarize below.

Different Boundary Conditions The magnetopause, magnetotail, and solar wind reconnection sites complement each other because they allow to study reconnection for quite different boundary conditions and plasma regimes. At the magnetopause, conditions are usually highly asymmetric, with the density much lower and the magnetic field strength much higher on the magnetospheric side, while across the magnetotail and solar wind current sheets, plasma conditions are usually fairly symmetric. The magnetic shear, on the other hand, is highly variable across the magnetopause and solar wind current sheets, while nearly 180° across the magnetotail current sheet. The different boundary conditions affect the structure and dynamics of reconnection.

Signatures of Reconnection in the Outflow Region The dominant observational evidence for reconnection is the detection of the accelerated plasma bulk velocity at or near the Alfvén speed in the outflow (exhaust) region. A number of kinetic effects complement the fluid signatures, among them counterstreaming beams and cut-offs in the velocity distributions. Other basic reconnection signatures such as the normal magnetic field, plasma inflow and reconnection electric field are much more difficult to determine.

Nature of the Outflow Region Boundaries For asymmetric conditions, the dominant boundary feature is predicted to be a rotational discontinuity (RD). The RDs have been identified for the magnetopause through the outflow velocities meeting the Walén-relation. For symmetric conditions, the structure is expected to include slow shocks. In a few instances, these have been identified for magnetotail and solar wind reconnection. A remarkable result is the persistence of sharp and well-defined boundaries to very large distances downstream from the X-line.

Detection of the Reconnection Diffusion Region While most of the spacecraft encounters with the reconnection layer occur in the outflow (exhaust) region downstream of the diffusion region, the past decade has witnessed numerous reports of ion diffusion region encounters by spacecraft in the magnetotail, at the magnetopause and in the magnetosheath, as well as glimpses of the much smaller electron diffusion region. Advances in the theoretical understanding of the diffusion region, coupled with the spacecraft detections of the diffusion region, form the basis for the upcoming Magnetospheric Multi-Scale mission which will investigate the magnetic field breaking processes in the electron diffusion region using ultra-high-resolution plasma and field measurements on four spacecraft.

Reconnection Rates Reconnection rates are notoriously difficult to measure reliably because they are proportional to the normal components of the magnetic field or plasma flow, which are small and dependent on precise knowledge of the current sheet orientation. Nevertheless, some values have been reported, ranging between <0.01 and 0.2, where it is uncertain whether this range reflects true variability or simply the large uncertainties. On the other hand, the detections of Hall magnetic and electric fields in the diffusion region suggest that reconnection operates in the 'fast' regime in near-Earth space.

Spatial and Temporal Scales Reconnection in the near-Earth magnetotail associated with geomagnetic substorms is highly bursty, storing and explosively releasing magnetic energy similar to solar flares. In the solar wind and at the magnetopause there is evidence that reconnection can operate in a quasi-steady manner along extremely long X-lines. Thus in-situ observations have clarified that reconnection is not intrinsically transient, but can operate in a quasi-stationary, continuous fashion. It can operate over large spatial scales, but can also be patchy.

Flux Ropes Intermittent or continuous reconnection with modulated reconnection rate could produce flux ropes that are commonly observed at the magnetopause (referred to as Flux Transfer Events) and in the magnetotail (called plasmoids or magnetic islands). Their role in energizing particles has been suggested but has yet to be firmly established.

Reconnection Onset Conditions and Occurrence Frequency A large number of current sheet encountered by spacecraft in the magnetosphere and solar wind display no local signatures of reconnection. The question is what conditions need to be met for reconnection to occur. There is clear evidence that current sheets must be sufficiently thin (an ion inertial length or less). In addition to the thin current sheet requirement, a combination of plasma β (more precisely the difference, $\Delta\beta$, across the current sheet) and magnetic shear has a controlling effect. For small $\Delta\beta$, reconnection can happen even for low magnetic shear (or large guide field), while for large $\Delta\beta$, reconnection requires large shear. With these (and possibly additional) strict conditions it is not surprising that many current sheets do not undergo reconnection.

Anti-parallel Versus Component Reconnection A long-standing controversy that the in-situ observations have resolved is whether or not reconnection requires purely anti-parallel magnetic fields. The observations clearly show that it can happen in the presence of substantial guide fields.

Turbulent Reconnection Downstream of the quasi-parallel bow shock, the shocked solar wind (magnetosheath) plasma is highly turbulent and filled with thin current sheets, and some initial evidence for reconnection across such current sheets has been reported. However, the plasma measurements onboard current spacecraft do not have sufficient temporal resolution to firmly establish the occurrence rate of reconnection in these thin current sheets. The upcoming magnetospheric Multi-Scale mission, with its ultra-high-resolution plasma measurements, should be able to determine what fraction of the current sheets undergoes reconnection and whether the process plays a significant role in dissipating turbulent energy.

Electron Acceleration Multi-point measurements in and near the reconnection diffusion region have provided strong evidence for electron acceleration to hundreds of keV in a two- or multi-step process, beginning within the diffusion region itself, but becoming more pronounced when the electrons enter the outflow region, either in the flux pileup region created by flow jet braking, or within magnetic islands.

Reconnection at Other Planets In-situ magnetic field measurements have provided evidence for reconnection at five other planets (Mercury, Venus, Mars, Jupiter, and Saturn). Because the solar wind plasma-β value decreases systematically with increasing distance from the Sun, reconnection may be more frequent at inner planets and consequently may play a more important role in their interaction with the solar wind.

Acknowledgements At UC Berkeley, this research was funded in part by NSF grant AGS-1103303 and NASA grant NNX08AO83G.

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