GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L19109, doi:10.1029/2008GL035297, 2008

Recent in-situ observations of magnetic reconnection in near-Earth space

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Received 10 July 2008; revised 21 August 2008; accepted 28 August 2008; published 11 October 2008.

[1] The paper presents a brief review of recent in-situ observations of reconnection in space, with emphasis on results pertaining to the question of anti-parallel versus component reconnection, the implied spatial and temporal scales, the location of the reconnection sites, particle acceleration, reconnection rates, the dependence on plasma β, and the properties of the diffusion region.

Citation: Paschmann, G. (2008), Recent in-situ observations of magnetic reconnection in near-Earth space, *Geophys. Res. Lett.*, *35*, L19109, doi:10.1029/2008GL035297.

1. Introduction

[2] Magnetic reconnection is a phenomenon of great importance in solar system plasmas and, presumably, in astrophysical plasmas, because it converts energy stored in magnetic fields into particle kinetic energy and changes the magnetic field topology, allowing effective exchanges of mass, momentum and energy between differently magnetized plasma regions. For reconnection to occur, the 'frozen-in field' condition of magneto-hydrodynamics (MHD) must break down in a localized region, commonly called the 'diffusion region', of the current sheet separating the plasmas. There the magnetic field lines that are flowing in from both sides become 'cut' and 'reconnected' as shown in Figure 1, forming a X-type configuration. Associated with the inflow is an electric field pointing out of the plane of the diagram parallel to the X-line. In component reconnection, the magnetic field also has a component (the 'guide field') into or out of the plane of Figure 1.

[3] Once reconnected, the field lines form two oppositely directed wedges of field loops threading the current sheet, bounded by the field lines mapping into the X-line, called 'separatrices'. The magnetic tension of these loops accelerates the inflowing plasma away from the reconnection site on both sides. Detection of these plasma jets in crossings of the outflow regions, also referred to as reconnection exhausts, often at large distances from the reconnection site, forms the easiest measurable reconnection signature in space plasmas. The reconnection rate is commonly specified by the inflow velocity, or the normal magnetic field, scaled to the Alfvén velocity or to the magnetic field in the inflow region, respectively.

[4] This paper presents a brief review of reconnection research based on recent in-situ measurements at the magnetopause, in the magnetotail, and in the solar wind and magnetosheath. Papers earlier than 2005 are referred to only when needed to establish the context and, with a few exceptions, the literature on remote sensing observations is not included.

2. Magnetopause

[5] Reconnection between the interplanetary magnetic field (IMF) and Earth's magnetic field at the magnetopause has long been inferred to occur, first from indirect observations of its global consequences such as the resulting solar wind plasma entry into the magnetosphere, and the setup of magnetospheric convection, but later also from direct in-situ observations at the magnetopause itself. Because of the large differences in plasma density on the two sides of the magnetopause, magnetopause reconnection is usually quite asymmetric. Under such conditions, the outflow region is bounded on the high-density side by a current layer akin to a rotational discontinuity (RD) or standing Alfvén wave. For a discussion of the structure of the magnetopause undergoing reconnection and for some of the early observations, see *Cowley* [1995] and *Sonnerup et al.* [1995].

[6] New information has been obtained regarding the location and orientation of the X-line. In a statistical study of 176 accelerated flow events at low latitudes on the dayside during dawn-dusk directed IMF observed by Double Star TC-1, it was found that the direction of the flows, northerly (southerly) for TC-1 locations north (south) of the X-line, was consistent with an X-line through the sub-solar point [*Pu et al.*, 2007]. This paper also showed that, for the same dawn-dusk orientation of the IMF, Cluster crossings at high dayside latitudes were consistent with a nearly north-south directed X-line. For dawn-dusk oriented IMF, reconnection with nearly north-south directed X-lines occurring near the low-latitude dawnside magnetopause has also been reported [*Paschmann et al.*, 2005].

[7] Further evidence for an X-line through the sub-solar point was presented in another study of 239 low-latitude TC-1 crossings for southward and dawn-dusk directed IMF [*Trenchi et al.*, 2008]. This study found that the orientation of the X-line was tilted by 45° for a dawn-dusk oriented IMF, as expected for component reconnection. From a combination of space- and ground-based observations, *Wild et al.* [2007] have also inferred a tilted X-line passing through the sub-solar region.

[8] Because the TC-1 observations were obtained fairly close to the X-line so that the local magnetic shear must have been close to the shear at the X-line, the *Pu et al.* [2007] and *Trenchi et al.* [2008] studies provide further evidence that reconnection does not require a magnetic shear angle of 180°, but can occur if the shear angle is 90°. By tracing the location of the X-line from cut-off velocities observed in the cusp, *Trattner et al.* [2007] have inferred that the majority of events was also consistent with component reconnection.

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0094-8276/08/2008GL035297$05.00

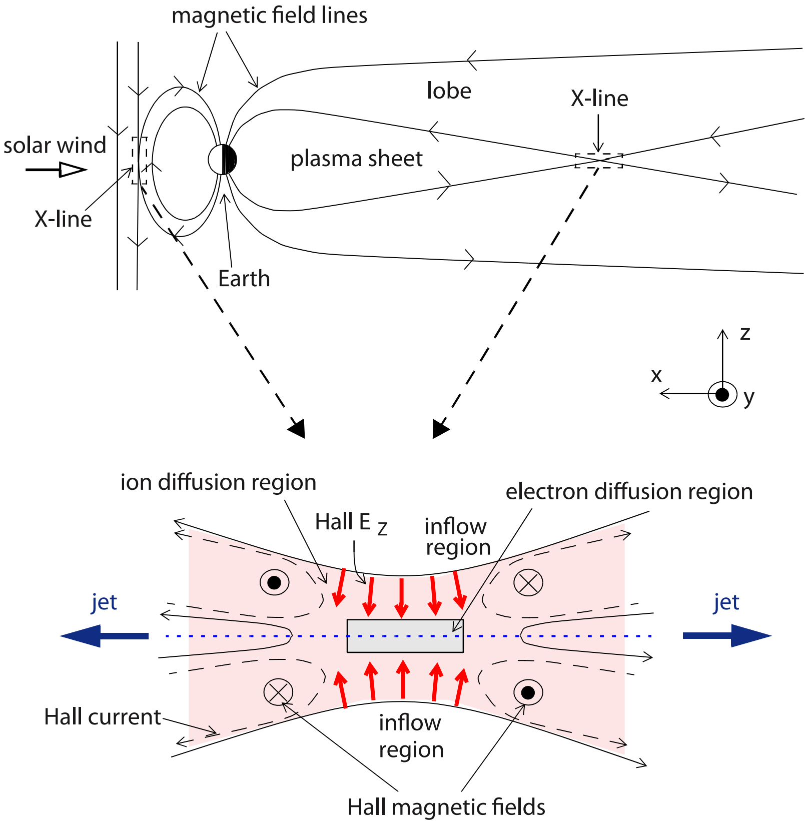

Figure 1. Magnetic reconnection in Earth's magnetosphere. (top) Noon-midnight cut, showing magnetopause and magnetotail reconnection sites, the former for southward IMF. (bottom) Zoom-in on the region around the X-line, with the ion and electron diffusion regions indicated by the shading and the rectangular box, respectively. The quadrupolar Hall magnetic field is pointing in and out of the plane of the figure. The Hall electric field is shown by the red arrows, while the blue arrows mark the oppositely directed jets in the outflow regions. Note that entry and acceleration occur all the way along the current sheet. Figure courtesy of Marit Oieroset.

[9] Simultaneous measurements with two satellites, one positioned in the subsolar magnetopause, the other at the dawn flank of the magnetopause, showed that, at least for southward IMF, the X-line can extend over the entire dayside magnetopause [*Phan et al.*, 2006a].

[10] For northward IMF, reconnection can occur tailward of the polar cusps where the draped interplanetary and the terrestrial field lines will have anti-parallel components. If such an IMF field line becomes reconnected in both hemispheres, closed magnetic flux tubes are added to the dayside magnetosphere, creating a boundary layer of magnetosheath plasma on closed magnetic field lines, as originally suggested by *Song and Russell* [1992] and first observed by *Onsager et al.* [2001]. Further evidence for the occurrence of such dual-lobe reconnection has been reported from in-situ observations of counterstreaming electrons [*Lavraud et al.*, 2006; *Bavassano Cattaneo et al.*, 2006; *McFadden et al.*, 2008], but also from simultaneous imaging of the cusp aurora in both hemispheres [*Østgaard et al.*, 2005]. Using multi-point measurements from THEMIS, *Øieroset et al.* [2008] showed that, by this process, a thick boundary layer (up to 0.9 R_E) can develop near the subsolar point.

[11] Recent measurements have strengthened earlier findings that magnetopause reconnection can be quasi-stationary. *Retinò et al.* [2005] presented a case with accelerated flows meeting the Walén relation [e.g., *Sonnerup et al.*, 1995] in 50 crossings occurring over a 4-hour period. Similar results were reported by *Zheng et al.* [2005] and *Nykyri et al.* [2006]. There is also new evidence regarding transient magnetopause reconnection in the form of so-called flux-transfer events (FTEs). *Dunlop et al.* [2005] reported dual-spacecraft observations of FTEs moving in opposite directions originating from a common X-line. *Hasegawa et al.* [2006] presented 2-D maps of the magnetic field of several FTEs, based on Grad-Shafranov reconstruction, which show that the FTEs consist of one or more magnetic flux ropes, with field lines bulging out on both sides, plus a strong core-field. *Owen et al.* [2008] interpret Cluster observations of 'crater'-like FTEs (i.e., FTEs with reduced magnetic field at the center) in terms of transient and patchy reconnection near the subsolar region.

[12] The statistical study by *Trenchi et al.* [2008] found a significant dependence of the occurrence of reconnection jets on the magnetosheath plasma β, the ratio of plasma to magnetic field pressure. While the average β for their non-reconnection cases was ~4, the average for the reconnection cases was ~1.7, although there was a large overlap between the β distributions. Regarding particle acceleration, *Zhang et al.* [2008] report a case with energetic electrons and ions peaking at the center of the magnetopause current sheet.

Reconnection rates at the magnetopause have been reported in several recent papers [*Hasegawa et al.*, 2006; *Mozer and Retinò*, 2007; *Teh et al.*, 2007; *Rosenqvist et al.*, 2008], confirming earlier reports that values are typically of order 0.1.

3. Magnetotail

[13] There is plenty of evidence for the occurrence of reconnection across the current sheet in the geomagnetic tail [e.g., *Cowley*, 1984]. Given the anti-parallel direction of the magnetic fields in the northern and southern tail lobes, and the generally similar plasma conditions on the two sides of the tail current sheet, the reconnection configuration is expected to be symmetric. Under these conditions, the outflow regions should be bounded by slow shocks, but except for a positive identification presented by *Eriksson et al.* [2004], no new evidence for such slow shocks has been reported in the recent literature.

[14] Reconnection sites in the near-Earth magnetotail vary over a wide range of distances. A statistical study by *Nagai* [2006] of Geotail observations in the range 10–31 R_E show the X-line distance to be controlled by the solar wind energy input, with the X-line closer to Earth when the input is higher. X-lines as close as 10–12 R_E, embedded within a thick region of closed plasma sheet field lines, have been reported by *Sergeev et al.* [2008]. Measurements of the reconnection rates in the magnetotail have been rare, but *Xiao et al.* [2007] have found values between 0.07 and 0.15.

[15] Observations by the ISEE 3 spacecraft in the distant magnetotail during substorms have shown energetic electron and ion bursts in the lobes adjacent to the plasma sheet, interpreted as originating from the near-Earth X-line [e.g., *Scholer et al.*, 1987, and references therein]. The first observation of energetic particles (300 keV electrons) within the diffusion region itself was reported from Wind observations by *Øieroset et al.* [2002]. Energetic electron observations by Cluster, with energies up to $\sim$100 keV, from within or near the diffusion region were reported by *Imada et al.* [2007], *Asano et al.* [2008], *Asnes et al.* [2008], and *Chen et al.* [2008]. *Imada et al.* [2007] suggest that the electrons are accelerated in a two-step process, with the first step at the X-line, and the second step in the outflow region away from the X-line. *Asano et al.* [2008] report electrons with energies >30 keV, but also conclude that they originate from just outside the diffusion region. *Asnes et al.* [2008] found bursts of electrons with energies up to >100 kev on the tailward side of the reconnection site. *Chen et al.* [2008], finally, report energetic electron bursts within a series of bipolar magnetic field signatures, interpreted as reconnection-associated magnetic islands, as proposed by *Drake et al.* [2006].

4. Solar Wind and Magnetosheath

[16] In 2005 *Gosling et al.* [2005] reported the detection of reconnection in the solar wind in the ACE data, occurring across current sheets embedded in the solar wind flow. Accelerated flows were observed within a Petschek-type reconnection outflow (‘exhaust’), emanating from a distant X-line and bounded on both sides by currents sheets that are akin to standing Alfvén waves or RDs. As conditions were fairly symmetric on the two sides, additional slow-mode shocks are expected, but not apparent in the measurements, although the increased density and ‘temperature’ and decreased field strength within the exhaust are qualitatively consistent with slow shocks. Counter-streaming ion beams, observed at the center, are evidence for the interpenetration of the plasmas from both sides, indicating the importance of kinetic effects. Dual-spacecraft observations of oppositely directed outflows, implying that an X-line was located between the two observing spacecraft, have been reported by *Davis et al.* [2006].

[17] Subsequent papers [see *Gosling*, 2007, and references therein] have established that such reconnection events are quite common and apparent in essentially all solar wind data sets, covering distances between 0.3 and 5 AU. Interestingly, a statistical study of 46 events observed by the Wind spacecraft shows a prevalence of local magnetic shear angles <90°, with the smallest angle being only 24°, and that a large fraction were embedded in solar wind having a proton $\beta < 1$, much lower than average. No evidence for the enhancement of energetic particle fluxes was found in seven events observed by ACE. However, if they were confined to thin sheets near the separatrices, they could have been missed. Interestingly, reconnection events were observed only very rarely in the thin current sheets embedded in the turbulent high-speed solar wind.

[18] Observations by multiple spacecraft indicate that the X-line can be quite long (at least several million kilometers) and be observed over periods of several hours [*Phan et al.*, 2006b; *Gosling et al.*, 2007a, 2007b].

[19] Recently, reconnection has also been observed in the magnetosheath. *Phan et al.* [2007a] observed reconnection signatures during a passage of a current sheet that had not shown any reconnection signatures when observed an hour earlier by ACE and Wind in the upstream solar wind, implying that reconnection was initiated in the magnetosheath. A similar case was discussed by *Maynard et al.* [2007]. Furthermore, it now appears that the small-scale current sheets found in the turbulent flows downstream from the quasi-parallel bow shock, may undergo reconnection as well [*Retinò et al.*, 2007; *Sundkvist et al.*, 2007]. These authors attribute the observed energetic ions to reconnection, but the so-called ‘diffuse’ ions, known to occupy the regions upstream and downstream of the quasi-parallel shock, make such an identification non-unique.

5. Diffusion- and Separatrix-Regions

5.1. Signatures

[20] Reconnection requires violation of the frozen-in condition $\boldsymbol{E} + (\boldsymbol{v} \times \boldsymbol{B}) = 0$ in some localized region, the diffusion region (see Figure 1). First, on a scale of the ion inertial length, $\lambda_i = c/\omega_{p,i}$ (where c is the speed of light and $\omega_{p,i}$ the ion plasma frequency), the ions are no longer magnetized, while the electrons remain tied to the magnetic field. Thus $\boldsymbol{E} + (\boldsymbol{v}_i \times \boldsymbol{B}) \neq 0$, but $\boldsymbol{E} + (\boldsymbol{v}_e \times \boldsymbol{B}) = 0$. Here $\boldsymbol{E}$ and $\boldsymbol{B}$ denote the electric and magnetic fields, and $\boldsymbol{v}_i$ and $\boldsymbol{v}_e$ the ion and electron flow velocities. This behavior follows because the Hall term in the generalized Ohm's law becomes significant: $\boldsymbol{E} + \boldsymbol{v}_i \times \boldsymbol{B} = (1/ne)\boldsymbol{j} \times \boldsymbol{B}$. By inserting the expression $\boldsymbol{j} = ne(\boldsymbol{v}_i - \boldsymbol{v}_e)$ for the electric current density, one then obtains $\boldsymbol{E} + \boldsymbol{v}_e \times \boldsymbol{B} = 0$.

[21] The most straightforward way to identify the ion diffusion region would then be to test above relations with the measured data. But as λ_i is only of order 100 km, the diffusion region is rarely resolved in current plasma measurements. Direct evaluation of the Hall term is also rarely possible because it requires knowledge of $\boldsymbol{j}$.

[22] In this situation one has to resort to more qualitative signatures, such as the detection of flow reversals or the Hall-induced magnetic and electric fields. Flow reversals are observed if the X-line moves such that a spacecraft makes a transition between the oppositely directed outflows. Quadrupolar magnetic field deflections out of the reconnection plane are caused by Hall currents, generated near the center of the diffusion region, and their closure by field-aligned currents. For a spacecraft pass across one of the outflow regions, only two of the quadrupolar field deflections would be sampled. But since these Hall fields extend some distance along the separatrices, their detection is evidence for a diffusion region encounter only if the opposite polarities are observed back-to-back. In the diffusion region there is also a strong bipolar Hall electric field normal to the current layer.

[23] Next, on the electron inertial length scale, λ_e, which is a factor of 43 smaller than λ_i and thus typically only a few km thick, the electrons are no longer magnetized either. Thus $\boldsymbol{E} + (\boldsymbol{v}_e \times \boldsymbol{B}) \neq 0$ because some or all of the remaining terms in the generalized Ohm's law are nonzero: $\boldsymbol{E} + (\boldsymbol{v}_e \times \boldsymbol{B}) = -(1/ne)\nabla \cdot P_e - (m_e/ne^2)\partial\boldsymbol{j}/\partial t + \eta\boldsymbol{j}$, where P_e is the electron pressure tensor, and η is the resistivity. In the electron diffusion region a nonzero $E_{\|} = \boldsymbol{E}\cdot\boldsymbol{B}$ must be present, but is difficult to measure.

[24] If one can estimate the spatial scales of the observed structures directly, from knowledge of the speed with which they pass the spacecraft, this can be used to support the diffusion region identification. However, structures with such scale sizes also occur in other regions, notably along the separatrix layers even at large distances from the X-line. Some authors have applied the term diffusion region to those regions as well [*Mozer*, 2005; *Vaivads et al.*, 2006]; here we will use the traditional definition in which the diffusion region surrounds the X-line.

5.2. Magnetopause Diffusion Region

[25] Pioneering work on the magnetopause diffusion region was provided by *Mozer et al.* [2002] and *Vaivads et al.* [2004]. *Mozer et al.* [2002] reported single-spacecraft (Polar) data taken during a subsolar magnetopause crossing with ≈180° shear angle, showing a pronounced bipolar Hall magnetic field and the first observation of the associated normal electric field. The evidence for a true ion diffusion region encounter was an interval where $\boldsymbol{E} \times \boldsymbol{B}/B^2$ disagreed with $\boldsymbol{v}_{i,\perp}$ but agreed with $\boldsymbol{v}_{e,\perp}$, and that the scale-size was just a few λ_i. *Vaivads et al.* [2004] presented measurements by Cluster within the ion diffusion region for a crossing tailward of the polar cusp, confirming the presence of the Hall magnetic and electric field signatures and demonstrating from the simultaneous four-point measurements that these are truly spatial structures, of $\approx 4\ \lambda_i$ width. They further showed that the normal electric field was approximately accounted for by the Hall term.

[26] More recently, observations of the Hall magnetic field signatures have been reported by *Pu et al.* [2005] and *Zhang et al.* [2008]. The *Pu et al.* [2005] case was from a partial low-latitude Double Star TC-1 crossing that showed a sharp reversal of the flow direction in the middle of the crossing, and thus was probably a true ion diffusion region encounter. The *Zhang et al.* [2008] case was a high-latitude Cluster crossing that was interpreted as an ion diffusion region encounter, based on the inferred scale size of $\approx 5\ \lambda_i$, but also on an observed difference between $\boldsymbol{E}$ and $-(\boldsymbol{v}_i \times \boldsymbol{B})$, although that difference was only about 30%. Observations tailward of the northern cusp suggest that reconnection is a source of kinetic Alfvén waves [*Chaston et al.*, 2005].

[27] Contrary to the general situation at the magnetopause, conditions were nearly symmetric for the crossings discussed by *Mozer et al.* [2002] and *Vaivads et al.* [2004]. For highly asymmetric density and magnetic field-strength conditions, *Mozer et al.* [2008] have reported the unipolar Hall magnetic and electric field signatures expected under such conditions.

[28] Other recent investigations have dealt with the structure of the narrow layers along the separatrices at some distance from the diffusion region. *Mozer* [2005] reported numerous events with electron-scale dimensions and significant $E_{\|}$ located mainly at the magnetospheric separatrix. *Retinò et al.* [2006] also discuss the separatrix on the magnetospheric side, an estimated 50 λ_i tailward of the X-line and about 5 λ_i wide, but having considerable substructure. *Khotyaintsev et al.* [2006] discuss observations of the separatrix region on the magnetospheric side, interpreted to be associated with the bulge created by a burst of reconnection at a distance of about 2 R_E. They show that the observed strong normal electric fields are mainly caused by the Hall term.

5.3. Magnetotail Diffusion Region

[29] The first identifications of the Hall currents and magnetic fields associated with magnetotail reconnection were provided by single-spacecraft measurements on Geotail [*Nagai et al.*, 2001] at 25–30 R_E distance and on Wind [*Øieroset et al.*, 2001] at 60 R_E. Recent observations have been obtained with Cluster and thus concern reconnection inside of 19 R_E, the apogee of Cluster.

[30] The most complete observations, i.e., flow reversals, together with the characteristic Hall magnetic and electric field signatures, were reported by *Wygant et al.* [2005], *Borg et al.* [2005], *Eastwood et al.* [2007], and *Runov et al.* [2008]. *Wygant et al.* [2005] were the first to identify the Hall-related bipolar normal electric fields for magnetotail reconnection. *Borg et al.* [2005] demonstrated the consistent direction of the Hall electric fields and their extension into the separatrix regions. *Eastwood et al.* [2007] presented further support for the identification of the ion diffusion region by showing that $\boldsymbol{E} + (\boldsymbol{v}_i \times \boldsymbol{B})$ is nonzero. *Runov et al.* [2008] also showed that, for short intervals, $\boldsymbol{E}$ and $\boldsymbol{v}_i \times \boldsymbol{B}$ differ, and that the current sheet has a thickness of $\approx 2\ \lambda_i$, both facts supporting the ion diffusion region identification. *Runov et al.* [2008] also showed that the quadrupolar magnetic field is observed even where the frozen-in condition is approximately satisfied, demonstrating that the quadrupolar field is not attributable to the Hall effect directly, but to the field-aligned currents closing the electron currents in the Hall zone. *Cattell et al.* [2005] reported the discovery of large-amplitude solitary waves, identified as

'electron holes', well-correlated with electron beams, along the separatrices close to the diffusion region.

[31] Flow reversals, together with the characteristic Hall magnetic signatures appear in papers by *Alexeev et al.* [2005], *Nakamura et al.* [2006], *Laitinen et al.* [2007], *Asano et al.* [2008], and *Asnes et al.* [2008]. *Alexeev et al.* [2005] deduced the electric currents directly from differences between ion and electron flows, and showed that they are consistent with Hall currents on the earthward side of the X-line, while no such clear picture emerged on the tailward side. The interval discussed by *Nakamura et al.* [2006] included crossings having significant guide-fields. The paper by *Asano et al.* [2008] shows 'flat-top' electron distributions occurring in narrow regions (of several λ_i width) in the outer reaches of the ion diffusion region. They also report electron beams near the separatrices directed towards the X-line, consistent with the expected Hall current closure, as originally reported by *Fujimoto et al.* [1997].

[32] Cases with just unidirectional fast flows, together with Hall magnetic field signatures, are presented by *Henderson et al.* [2006] and *Xiao et al.* [2007]. The paper by *Henderson et al.* [2006] includes the first attempt to directly evaluate the $\nabla \cdot P_e$ term in the generalized Ohm's law, based on the differences in P_e measured at the four Cluster spacecraft. This term is found to be dominated (by a factor of 5) by the Hall-term, suggesting that the electron diffusion region, where $\nabla \cdot P_e$ is expected to be important, was not actually encountered. *Xiao et al.* [2007] estimate a width and length of the diffusion region as 0.9 λ_i and 3.3–5.1 λ_i, respectively.

5.4. Solar Wind and Magnetosheath Diffusion Regions

[33] No diffusion region observations have been reported for the solar wind, but there is one such observation in the magnetosheath [*Phan et al.*, 2007b], the evidence being the sudden polarity changes of the bipolar Hall magnetic and electric field signatures at the center of the current sheet. From an estimate of the current at the center, a super-Alfvénic electron jet, of ~9 λ_e width, is inferred. Consistent with this narrow width, these electrons were not magnetized, as evidenced by a substantial difference between their inferred perpendicular velocity and $\boldsymbol{E} \times \boldsymbol{B}/B^2$. From the wedge angle of the outflow region, together with the known velocity of the structure, the distance away from the X-line at which the spacecraft encounter with the electron jet occurred was determined as 63 λ_i. In spite of this extraordinary extent of the electron diffusion region, the estimated reconnection rate was large, 0.07.

6. Summary

6.1. New Regions

[34] Recent observations have added two more regions, the solar wind and the magnetosheath, where reconnection is occurring. In these regions, the boundary conditions are significantly different from those at the magnetopause and magnetotail; furthermore, the reconnection structures in these regions are convected past the observer at essentially constant speed, facilitating the determination of their spatial scales.

6.2. Spatial and Temporal Scales

[35] Reconnection in the solar wind appears to be quasi-steady and large-scale. By contrast, reconnection in the near-Earth magnetotail is more transient, with X-lines probably much shorter than the width of the magnetotail. At the magnetopause, reconnection occurs in two modes: quasi-steady, with X-lines spanning up to the entire dayside magnetopause, or transient, in the form of FTEs that involve flux ropes with possibly quite limited X-line extent.

6.3. X-line Location and Orientation

[36] At the magnetopause there is clear evidence that for southward or dawn-dusk directed IMF, the X-line passes through the vicinity of the subsolar point, in agreement with the expectation that reconnection would be initiated where the magnetosheath flow becomes stagnant. The finding that the X-line is inclined by about 45° for dawn-dusk field directions is consistent with the so-called component reconnection model. For dawn-dusk directed IMF, reconnection has been observed also at high latitudes on the dayside, as well as at the flanks, with nearly north-south directed X-lines. For northward IMF, reconnection has been demonstrated to occur tailward of one or both of the polar cusps, in the latter case leading to the formation of a boundary layer of magnetosheath plasma on closed magnetic field lines.

6.4. Component Versus Anti-parallel Reconnection

[37] The observations in the solar wind and at the magnetopause demonstrate that reconnection can occur in the presence of substantial guide fields. There is no requirement that the shear angle between the magnetic fields on the two sides of the current layer must be 180°; it can be 90° or even considerably less. This is particularly relevant for the magnetopause, where there are always locations at which the fields are anti-parallel, regardless of the IMF direction, but nature does not appear to prefer those locations, even though reconnection would be more efficient for 180° shear.

6.5. Reconnection Rates

[38] Reconnection rates have been inferred for number of reconnection events at the magnetopause, the magnetotail, the solar wind, and the magnetosheath, with values of order 0.1, which are considered to signify fast reconnection.

6.6. Plasma β Dependence

[39] There have been earlier indications, but now there is additional evidence from both solar wind and magnetopause observations, for reconnection to favor low values of the plasma β in the inflow regions,

6.7. Particle Acceleration

[40] Reconnection is commonly considered to be a means for accelerating particles to high energies. It is thus interesting that no such particles have been reported for the solar wind reconnection events, perhaps because they might be confined to very thin sheets and thus not resolved. Recent observations in the magnetotail have shown the presence of energetic electrons near the diffusion region, but there are indications that they gain their energy in a two-step process, with the first step at the reconnection site itself, and the second step in the outflow region away from the X-line. There is also evidence for electron acceleration in association with magnetic islands.

6.8. Diffusion- and Separatrix-Regions

[41] The many recent observations within or near the diffusion region have significantly expanded our knowl-

edge of its basic properties, by identifying the detailed structure of the Hall magnetic and electric fields; by directly measuring the Hall term and showing that it can balance the electric field in the ion diffusion region; by a first attempt to directly evaluate the divergence of the electron pressure tensor; by the discovery of a very long ($\sim 60\ \lambda_i$), but narrow super-Alfvénic electron jet embedded in the outflow region. The unfreezing of the ions from the magnetic field has only been established in a few fortuitous cases, the problem being the general inability of present plasma measurements to resolve the narrow ion diffusion region structures.

[42] **Acknowledgments.** The author thanks Bengt Sonnerup for helpful comments and suggestions.

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