In situ detection of collisionless reconnection in the Earth's magnetotail

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Magnetic reconnection is the process by which magnetic field lines of opposite polarity reconfigure to a lower-energy state, with the release of magnetic energy to the surroundings. Reconnection at the Earth's dayside magnetopause and in the magnetotail allows the solar wind into the magnetosphere[1,2]. It begins in a small 'diffusion region', where a kink in the newly reconnected lines produces jets of plasma away from the region. Although plasma jets from reconnection have previously been reported[3–7], the physical processes that underlie jet formation have remained poorly understood because of the scarcity of *in situ* observations of the minuscule diffusion region. Theoretically, both resistive and collisionless processes can initiate reconnection[8–14], but which process dominates in the magnetosphere is still debated. Here we report the serendipitous encounter of the Wind spacecraft with an active reconnection diffusion region, in which are detected key processes predicted by models[8–13] of collisionless reconnection. The data therefore demonstrate that collisionless reconnection occurs in the magnetotail.

When magnetic field lines of opposite polarity convect toward each other they reconnect and change configuration in a small diffusion region centred around a magnetic X-line (Fig. 1). Outside the diffusion region, in the inflow as well as the high-speed jet regions, the magnetic field lines are 'frozen' to the plasma. In the diffusion region, however, the field lines diffuse from the plasma, allowing the opposite field lines to merge and change partners (Fig. 1b). The occurrence of reconnection depends critically on the plasma processes within the diffusion region. Essentially all of the experimental tests for its occurrence, however, pertain to observations outside the diffusion region. Much of our knowledge of processes in the diffusion region thus derives solely from theoretical modelling[8–15].

According to theory, reconnection can be accomplished either by resistive or by collisionless mechanisms. The classical collision rate in the magnetosphere is low, but anomalous resistivity could be provided by increased wave activity[15–17]. If the resistive scale size is larger than the ion scale size (the ion skin depth—see Fig. 1 for definition), reconnection is accomplished by resistive diffusion of ions and electrons at the resistive scale and no separation between ions and electrons occurs. If, on the other hand, the resistive scale size is smaller than the ion skin depth, collisionless effects become dominant, and a separation of ions and electrons (the Hall effect) occurs as the ions are first unfrozen from the magnetic field (at the larger ion scale) while the electrons continue to carry the field lines toward the X-line and eventually diffuse at the smaller electron scale[14]. The separation between electrons and ions in the ion diffusion region gives rise to a system of currents, termed the 'Hall current' (see Fig. 1b), which in turn induces a quadrupolar out-of-plane Hall magnetic field pattern[1]. The Hall quadrupolar fields should be recognizable by a spacecraft traversing the magnetotail reconnection region, from one side of the X-line to the other, as a reversal of the out-of-plane component (y-component) of the magnetic field, with an amplitude of ~30% of the background magnetospheric field[18]. Electrons carrying the Hall current are expected along the boundary separating the lobe and the plasma sheet[19–21].

Out-of-plane magnetic fields have recently been detected by the Geotail spacecraft in the high-speed flow region outside the diffusion region both in the near-Earth tail[21] and at the dayside magnetopause[22]. These fields are presumably the extensions of the Hall magnetic fields originating inside the diffusion region. But as long as such signatures are obtained only outside the diffusion region one cannot tell with certainty whether the observed signatures are the cause or consequence of reconnection. Only *in situ* detection of Hall signatures in the diffusion region would unambiguously point to the dominance of collisionless effects in magnetic reconnection.

The Wind spacecraft made a fortuitous direct encounter with the ion diffusion region on 1 April 1999. As the spacecraft travelled away from the Sun through the Earth's magnetotail (see Fig. 1), at about 60 Earth radii behind the Earth it detected a period of Earthward-directed plasma jets followed by an interval of tailward-directed jets, with proton flow speed reaching 400 km s^{-1} (Fig. 2b). The velocities of both the Earthward and tailward jets are in agreement with the predicted slingshot effect resulting from reconnection[7]. This flow interval was embedded in a 10-hour interval of quasi-steady reconnection[7]. The detection of the reversal of the reconnection jets implies that the spacecraft moved from the Earthward side to the tailward side of an active reconnection X-line (Fig. 1b). The spacecraft remained in the reconnection layer as it crossed from one side of the X-line to the other, as evident from the uninterrupted transition from Earthward to tailward flow (Fig. 2a), so the spacecraft must have crossed the diffusion region. If the crossing from one side of the X-line to the other had occurred outside the diffusion region, the spacecraft would have detected an interval of slow flow in the z-direction only, which corresponds to the reconnection inflow region[7]. It can be inferred from the mostly negative sign of the x-component of the magnetic field, B_x, that the spacecraft stayed predominantly on the southward side of the plasma sheet midplane (the neutral sheet) during the crossing near the X-line, as schematically shown in Fig. 1b.

We now describe the Hall electron and magnetic field signatures obtained in the diffusion region implying that collisionless (rather than resistive) effects dominate in this event.

As the spacecraft travelled from the region of Earthward jets to the region of tailward jets while remaining mostly below the plasma sheet midplane, it observed a decrease followed by an increase in y-component of the magnetic field, B_y. The amplitudes of these changes were about 4.5 nT superposed on a background B_y field of 6 nT. The sense of the field reversal for this spacecraft trajectory is in precise agreement with the predicted quadrupolar out-of-plane Hall magnetic field configuration[8,23] (Fig. 1b). Even more convincing, shortly after the flow reversal Wind twice crossed briefly to the northward side of the neutral sheet, as apparent from the positive sign of the B_x component, before returning to the southward side. During the two brief excursions into the northern hemisphere the B_y component actually turned negative, as required by the model shown in Fig. 1b. The observed Hall magnetic field amplitude of 4.5 nT corresponds to about 40% of the total magnetic field magnitude (about 12 nT), close to the prediction based on a two-dimensional hybrid simulation[18]. The presence of nearly symmetric bipolar B_y field superposed on a background B_y field of 6 nT (50% of the total field) is consistent with theoretical predictions that the presence of a guide field does not change the quadrupolar Hall field pattern in a significant way[12,24].

In addition to the Hall magnetic field signatures, a low-energy (<300 eV) electron beam aligned with the magnetic field and directed towards (implying a current away from) the X-line was observed just before the flow reversal (Fig. 3). The electron beam was observed only for a 2-minute interval preceding the flow reversal when the B_x component was large and negative, which indicates that the spacecraft was near the boundary between the plasma sheet and the lobe in the southern hemisphere. The sense of the electron beam and the confinement of this beam to the plasma sheet/lobe boundary are consistent with these electrons being the Hall current carriers (see Fig. 1b).

A dip in the density was detected just preceding the time of the flow reversal (Fig. 2a). A density depletion along the separatrices[9] and at the centre of the diffusion region[10,12] has been predicted in recent simulation models. The observed density depletion (Fig. 2a) is not centred at the time of the flow reversal and would correspond more to a dip along the separatrices, although a brief entry into the lobe is also a possible interpretation.

The length of the ion diffusion region (along the x-axis) is difficult to estimate from single spacecraft observations. If, however, one assumes the X-line to be stationary in space while the spacecraft moves at a speed of about 1 km s^{-1} in the negative x-direction one obtains a diffusion region length of 1,300 km, or roughly 2 ion skin depths, for a crossing duration of 21 minutes. The true length is larger or smaller depending on whether the X-line moved with or against the spacecraft trajectory.

Waves with power between the lower hybrid resonance and the ion cyclotron frequency were observed (not shown) throughout the many hours of observed high-speed jets. The magnetic spectral energy density was similar inside and outside the diffusion region. Although these waves could be interpreted as whistlers generated in the collisionless diffusion region[9], we cannot rule out that the waves could be locally generated by processes outside the diffusion region.

The observations presented here constitute a rare encounter with an active reconnection diffusion region in the Earth's magnetotail where Hall effects indicative of collisionless reconnection were detected. The event was embedded in a 10-hour interval of quasi-steady reconnection. Evidence for Hall effects has also been reported outside the diffusion region in highly time-varying reconnection closer to the Earth[19,21] and at the dayside magnetopause[22], and perhaps in the diffusion region in the polar cusp (J. D. Scudder,

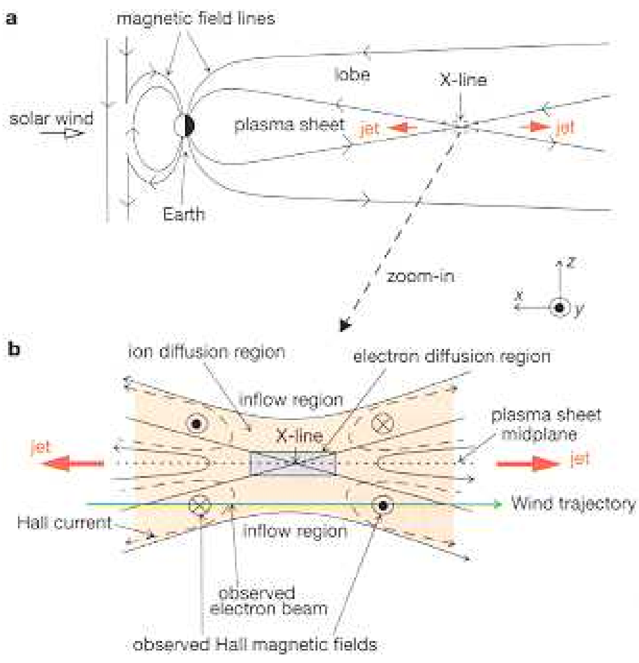

Figure 1 Schematics of magnetic reconnection in the Earth's magnetosphere. **a**, The noon–midnight plane of the magnetosphere showing dayside magnetopause and magnetotail reconnection. In the magnetotail, oppositely directed magnetic field lines in the northern and southern lobe regions convect towards the low-latitude plasma sheet, touch each other and reconnect at an X-point or X-line (in the out-of-plane y-direction). In the process magnetic energy is converted into kinetic energy in the form of bi-directional plasma jets directed towards and away from the Earth. **b**, Zoom-in on the region surrounding the X-line. In the collisionless regime, oppositely directed field lines convect towards each other from the top and the bottom of the figure and reconnect at a distance of the order of the ion skin depth (defined as $m/(ne^2\mu_0)$ where m is the mass of the species, n is the plasma density, e is the charge, and μ_0 is the permeability in vacuum) from the X-line. The skin depth in the plasma sheet is about 700 km for ions and 20 km for electrons. The ion diffusion region is marked by the shaded red area, and the smaller electron diffusion region is shown as a grey box. In the ion diffusion region, the separation between ions and electrons at the ion scale creates a system of Hall currents. These in turn induce a quadrupolar out-of-plane magnetic field pattern[8] which was observed by the Wind spacecraft as it travelled from the Earthward to the tailward side of the X-line. Electron motion consistent with the Hall current was also detected near the boundary between lobe and plasma sheet as expected from the schematic. The coordinate system is defined such that x points towards the Sun, z is normal to the current sheet, and y is directed out of the plane.

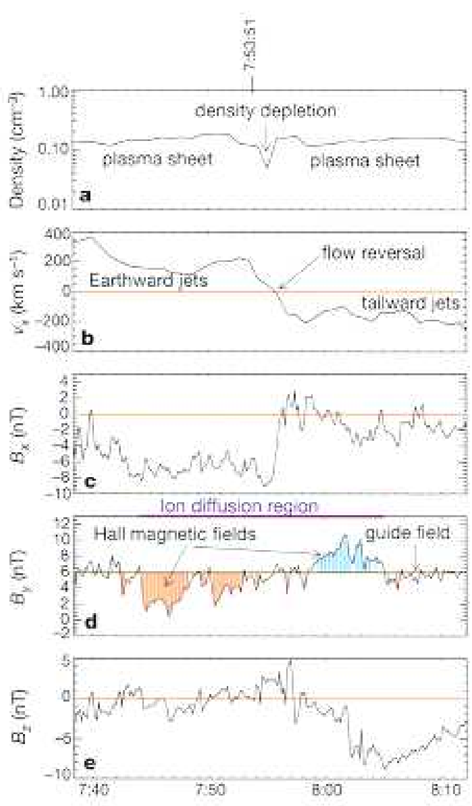

Figure 2 Observations by Wind in the ion diffusion region. The ion diffusion region (marked) is identified from the B_y component as the region of large 'out-of-plane' Hall magnetic fields surrounding the flow reversal. **a**, The plasma density, which was at the typical plasma sheet values throughout the interval except for a brief (~1 minute) dip to lower density just before the flow reversal. **b**, The x-component of the proton flow velocity, showing bi-directional jets and a flow reversal. **c**–**e**, The three components of the magnetic field. The direction normal to the current sheet was determined by minimum variance analysis[28] of the magnetic field data. Bipolar B_y field variations with polarities consistent with the Hall magnetic field pattern (Fig. 1b) were detected as the spacecraft crossed from the Earthward side to the tailward side of the flow reversal region. To highlight the bipolar B_y signature, magnetic field deviations (from the guide field) larger than 1.5 nT are shaded blue for negative changes and red for positive enhancements.

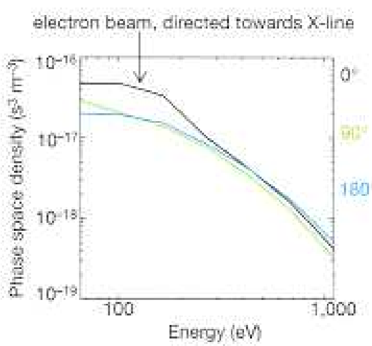

Figure 3 Detection by Wind of a low-energy electron beam carrying the Hall current. The electron distributions at 0°, 90° and 180° to the magnetic field were obtained at 7:53:51 Universal Time (UT), just before the flow reversal when the spacecraft was in the southern hemisphere (below the plasma sheet midplane) near the boundary between the lobe and the plasma sheet. The electron distribution is isotropic at all energies, except for the appearance of a field-aligned electron beam with energy up to 300 eV. The detection of the field-aligned (0°) electron beam implies that the beam was directed towards the X-line, consistent with the prediction that the Hall current should be directed away from the X-line at this location (see Fig. 1b).

personal communication). Together these observations indicate that magnetic reconnection in the entire magnetosphere operates in the collisionless regime at least some, if not most, of the time.

According to theory[9–13], reconnection proceeds at a much faster rate when it is mediated by collisionless rather than resistive effects, with predicted (dimensionless) collisionless reconnection rates reaching ~0.2 (refs 9–13). A collisionless reconnection regime in the Earth's magnetosphere thus implies much higher rates of solar wind entry than depicted by present-day global numerical simulation models of interactions between the solar wind and magnetosphere, which assume resistive reconnection[25–27].

The detection of Hall effects in the ion diffusion region implies the importance of collisionless (non-resistive) effects in reconnection. But the processes that ultimately cause the electrons to diffuse from the magnetic field in the much smaller electron diffusion region remain one of the main unsolved problems in reconnection research. The identification of electron processes requires high-resolution measurements capable of resolving electron-scale structures and dynamics. Such observations could then be used to verify a recent rather surprising theoretical finding, based on two-dimensional reconnection configurations, that ion-scale Hall effects ultimately determine the reconnection rate, irrespective of which electron-scale processes eventually cause the electrons to diffuse from the magnetic field[9–13]. □

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