A magnetic reconnection X-line extending more than 390 Earth radii in the solar wind

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Magnetic reconnection in a current sheet is a magnetic to particle energy conversion process that is important in many laboratory[1], space[2,3] and astrophysical contexts[4-6]. It is not presently known whether reconnection is fundamentally a process that can occur over an extended region in space or whether it is patchy and unpredictable in nature[7]. Frequent reports of small-scale flux ropes and flow channels in Earth's magnetosphere associated with

reconnection[8-13] raise the possibility that reconnection is intrinsically patchy, each reconnection region extending at most a few Earth radii (R_E) even though the associated current sheets span many tens or hundreds of R_E. Here we report three-spacecraft observations of accelerated flow associated with reconnection in a current sheet embedded in the solar wind flow where the reconnection line extended at least 390 R_E (or 2.5 million km). Observations of this and 27 similar events imply that reconnection is fundamentally large scale. Patchy reconnection observed in the magnetosphere is likely to be a geophysical effect associated with fluctuating boundary conditions rather than a fundamental property of reconnection. Our observations also reveal, surprisingly, that reconnection can operate in a quasi-steady-state manner even when undriven by the external flow.

Until recently, in-situ observations of reconnection in space plasmas were made almost exclusively in the Earth's magnetosphere, in current sheets formed by the interaction between the solar wind and the geomagnetic field. Such current sheets have finite extents and their boundary conditions (determined by the solar wind magnetic field) often change rapidly. It is generally difficult to establish the presence of an extended reconnection X-line in the magnetosphere from in-situ measurements since that requires the presence of widely separated spacecraft detecting the same reconnection events. The chances for such conjunctions are exceedingly small because the spacecraft are seldom ideally positioned for such observations and because of the variable boundary conditions. The single event reported where 2 spacecraft (separated by 3 R_E) detected the same reconnection event at the magnetopause only allowed the deduction that the X-line was at least 3 R_E long[14]. Remote observations of proton auroras[15] and ionospheric convection[16] have hinted at the presence of a magnetopause X-line up to 40 R_E in length but that has not yet been confirmed by in-situ observations.

The recent discovery of reconnection exhausts in the solar wind[17,18] introduces a new laboratory where reconnection can be investigated by in-situ measurements. The solar wind reconnection events often are associated with interplanetary coronal mass ejections (ICMEs) and the magnetic field orientations on the two sides of the current sheets usually are well defined. The combination of extended current sheets with stable boundary conditions and the fact that the solar wind rapidly convects the exhausts past observing spacecraft make these solar wind reconnection events ideal for addressing the question of extended versus patchy reconnection without complications due to boundary effects.

On February 2, 2002, The Wind, ACE, and Cluster spacecraft were all in the solar wind (see Figure 1). Cluster was 14 R_E upstream (sunward) of the Earth. ACE was 222 R_E further upstream of Cluster, while Wind, in its furthest orbit from Earth during its 10-year mission, was located at 331 R_E dawnward of Cluster (and 321 R_E from the Sun-Earth line). Figure 2 shows that all 3 spacecraft detected the passage of the same bifurcated current sheet with accelerated plasma flow embedded in it. The total magnetic field rotation (or shear) across the bifurcated current sheet was 140^{o}. The observed plasma acceleration within the exhaust agreed with the reconnection prediction to within 5^{o} in direction and 10% in flow speed (see Figures 3c and 3d for more details). This is consistent with the plasma acceleration being accomplished by the magnetic tension force associated with linkage of the magnetic field across the exhaust. Furthermore, Figure 3 shows that the plasma density and temperature were sharply enhanced at the edges of the current sheet while the magnetic field strength was reduced. These signatures are consistent with the Petscheck[19] model of fast reconnection where the reconnection exhaust is bounded by Alfven and/or slow mode waves. The plasma and field signatures just described are typical of solar wind reconnection exhausts[17,18]. What is significant about this 2002-02-02 event is the fact that the reconnection exhaust was observed by 3 widely-separated spacecraft, which allows the deduction of a long reconnection X-line.

The extent of the X-line that can be measured depends on the orientation of the exhaust and of the X-line relative to the spacecraft. To obtain the X-line orientation one first needs to determine the exhaust geometry.

The bifurcated current sheet associated with the reconnection exhaust was convecting with the solar wind and was first detected at ACE at ~01:32 UT, followed by Cluster an hour later (at ~02:32 UT) and 2.5 hours later than at ACE by Wind (at ~03:57 UT). The fact that Cluster and Wind detected the current sheet 85 minutes apart even though both spacecraft were at nearly the same distance from the Sun (but 330 R_E apart in dawn-dusk direction) implies that the current sheet must make a large angle relative to the "east-west" (GSE-y) direction (see Figure 1). This angle is confirmed by the analysis of the current sheet geometry at Wind. The normal to the current sheet tilt was determined by the minimum variance analysis[20] of the magnetic field across the current sheet and was found to be ($0.71\,\hat{\mathbf{x}}$, $0.60\,\hat{\mathbf{y}}$, $-0.37\,\hat{\mathbf{z}}$) in GSE. The resulting error in the propagation time from ACE to Cluster is 4 minutes 20 seconds, or 7%. From ACE to Wind, the error is only 6 seconds, or 0.07%. This agreement demonstrates that the current sheet was indeed approximately flat on a scale of hundreds of Earth radii (or 0.01 AU) and that the current sheet normal was accurate. The small magnitude of the normal magnetic field (B_N) across the current sheet (Figure 3e) further confirms the accuracy of the current sheet normal.

The X-line orientation ($0.47\,\hat{\mathbf{x}}$, $-0.79\,\hat{\mathbf{y}}$, $-0.39\,\hat{\mathbf{z}}$) in GSE is obtained from the components of the magnetic field in the current sheet plane[21]. From the X-line orientation one can determine, based on the locations where the 3 spacecraft intersected the current sheet, that Cluster and Wind detected flow from positions along the X-line that were 390 R_E apart, while ACE detected flow from the X-line at an intermediate location (see Figure 1). This implies that the X-line extended at least 390 R_E (or $4 \cdot 10^4$ ion skin depths) and very likely a great deal further. If reconnection were patchy, one or more spacecraft most likely would not have encountered accelerated flow. Another fact that is consistent with a coherent and extended X-line is that the reconnection jets detected by all 3 spacecraft were directed in the same direction, implying that the X-line was north of all spacecraft. Patchy and random reconnection could result in different spacecraft detecting jets directed in different directions.

In addition to finding an extended X-line, the fact that the 3 spacecraft detected the reconnection exhaust over a period of 2.5 hours implies that reconnection must have been quasi-steady over at least that time span. This finding is similar to reports of quasi-steady reconnection at the Earth's magnetopause[22-24]. An important difference is that while reconnection is strongly driven at the magnetopause (by the solar wind impinging on the Earth's magnetosphere), reconnection in the present case appears to have been largely undriven. There was a discontinuity in the flow speed across the current sheet of 27 km/s; however, Figure 3c shows that much of the flow speed discontinuity was due to a 22 km/s shear in the flow component tangential to the current sheet which does not compress the current sheet. In the normal direction the velocity across the current sheet was nearly constant except for a small 5 km/s shift. The velocity shift was consistent with a normal inflow, in the frame of the current sheet, of $v_{N,rec}$= 2.5 km/s associated with reconnection (at the position of Wind). The fact that reconnection can be quasi-steady in the undriven regime is surprising and has not previously been reported to the best of our knowledge.

Finally, with a 12 nT magnetic field convecting into the reconnection region at 2.5 km/s (for a dimensionless reconnection rate, $v_{N,rec}/v_{Alfven}$, of 3.3%), the reconnection electric field was 0.03 mV/m. Along an X-line of at least 390 R_E, the minimum reconnection potential was thus 75 kV.

While we have shown detailed observations from a single event, our conclusions in terms of extended X-lines and steady reconnection are general. We have identified 27 additional events when both ACE and Wind were in the solar wind and detected essentially the same reconnection signatures, irrespective of how far apart (in space and time) the two spacecraft were. Common among all 28 events is that the plasma β (the ratio of plasma to magnetic pressure) in the ambient solar wind (outside the exhausts) is less than unity[17] ($\langle\beta\rangle_{28\ \mathrm{events}} = 0.4 \pm 0.2$), a condition that has been suggested to be necessary for the occurrence of reconnection[25]. In 4 of these cases, we have evidence for an X-line extending more than 100 R_E. We are aware of no counter examples where one spacecraft detected the reconnection signature and the other did not. The large number of dual-spacecraft detections of reconnection flow with no counterexamples strongly indicate that reconnection in the solar wind, and likely in other astrophysical domains as well, is fundamentally large scale and quasi-steady, leading to the release of large amount of magnetic energy.

Our finding also raises an interesting question: How does the reconnection X-line become so extended? We suspect that in the case of the solar wind, reconnection starts in a limited region in the solar wind current sheet closer to the Sun and spreads with time from its initiation region. By the time the current sheet reaches 1 AU, the X-line has reached hundreds of Earth radii or more. The true size of the solar wind X-line can be investigated by the upcoming NASA/STEREO mission, which will provide large spacecraft separations exceeding 1 AU in the GSE-y direction.

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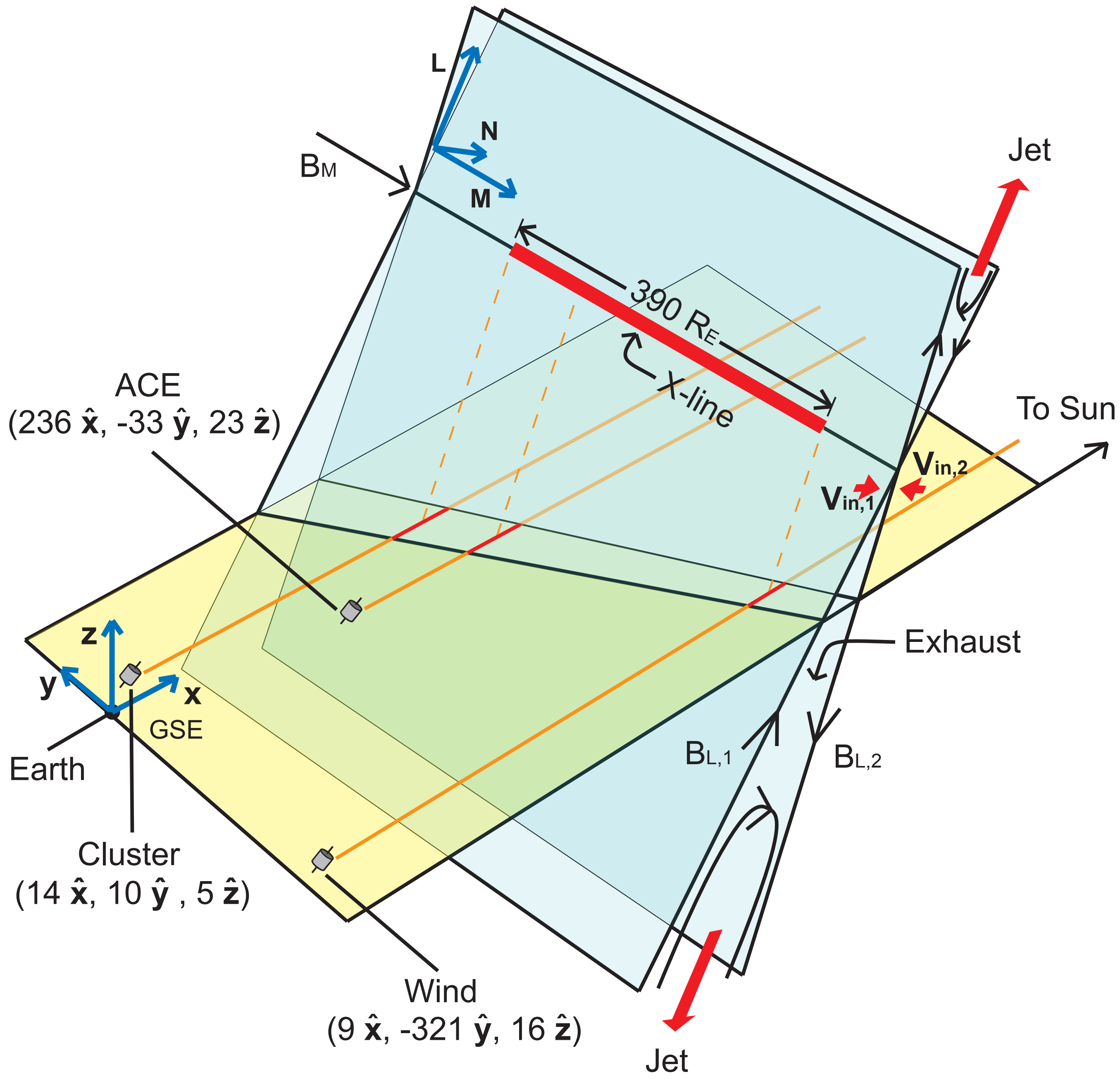
Figure 1. Schematic of the encounters of an extended (390 R_E) magnetic reconnection X-line in the solar wind by three spacecraft. Reconnection in the current sheet (in blue) occurs at the X-line between magnetic field lines with large anti-parallel components $B_{L,1}$ and $B_{L,2}$; the resulting bi-directional plasma jets (confined to the reconnection exhausts) can be observed far from the X-line. The ACE, Cluster and Wind spacecraft positions are shown in the unit of Earth radius and in geocentric solar ecliptic (GSE) coordinates with x-axis pointing from Earth to Sun, y-axis pointing toward dusk and z axis parallel to the ecliptic pole. All 3 spacecraft were relatively close to the ecliptic plane (in

yellow). ACE was 222 Earth radii (R_E) upstream of Cluster while Wind was 331 R_E dawnward of Cluster. Also shown is the LMN current sheet coordinate system with N along the overall current sheet normal, M along the X-line direction and L along the anti-parallel magnetic field direction. The current sheet normal, (0.71$\hat{\mathbf{x}}$, 0.60$\hat{\mathbf{y}}$, -0.37$\hat{\mathbf{z}}$) in GSE, is tilted 45^o relative to the Sun-Earth line. The X-line is oriented along (0.47$\hat{\mathbf{x}}$, -0.79$\hat{\mathbf{y}}$, -0.39$\hat{\mathbf{z}}$) in GSE. The thick solid red line is the (390 R_E) portion of the X-line whose effect is observed by the 3 spacecraft. The solid orange lines denote the spacecraft trajectory relative to the solar wind, with the red line portion marking the intersections of the exhaust with the spacecraft. The total reconnected magnetic flux is determined by the inflow velocity, V_{in}, the strength of the anti-parallel field components, and the length of the X-line (= $V_{in,1} \cdot B_{L,1} \cdot L_{X\text{-line}}$ or $V_{in,2} \cdot B_{L,2} \cdot L_{X\text{-line}}$). The angle of the diverging exhausts is exaggerated for illustration. The actual calculated angle is ~ 4^o.

Figure 2. Detections of the magnetic reconnection exhaust by the ACE, Cluster-3 and Wind spacecraft on 2002-02-02. a-b the magnetic field and plasma velocity in GSE measured by ACE, c-d, the magnetic field and velocity measured by Cluster-3, e-f, the magnetic field and velocity measured by Wind. The x component of the velocity in Panels b, d, and f has been shifted by +300 km/s. The red horizontal bars in panels a, c, and e indicate the durations of the encounters by the 3 spacecraft. The magnetic field rotated 140^o across the exhaust. The plasma flow in the exhaust was enhanced by ~50 km/s relative to the ambient solar wind flow speed. The velocity components were correlated (anti-correlated) with the components of the magnetic field at the leading (trailing) edge of the exhaust, as expected from reconnection sunward and northward of the spacecraft. It is concluded that all 3 (widely separated) spacecraft detected essentially the same reconnection signature. The abrupt

changes in the magnetic field B_z at the two edges and a plateau in the B_z profile in the middle of the current sheet indicate that the current sheet is bifurcated.

Figure 3. Quantitative comparison between the flow acceleration observed by the Wind spacecraft and the prediction from reconnection. a, the ion density. b, the parallel and perpendicular ion temperatures. c, the observed and (reconnection) predicted plasma flow speed. d, the observed and predicted (in black) plasma velocity in LMN coordinates. e, the magnetic field in LMN coordinates. The anti-parallel component of the magnetic field (B_L) was nearly equal in magnitude on the 2 sides of the exhaust. The guide field (along the **M** or X-line direction) was ~4 nT or 35% of the anti-parallel field. The flow velocity perpendicular to the magnetic field (v_N) was nearly constant (except for a small shift of 5 km/s) across the bifurcated current sheet. The 5 km/s shift in v_N corresponds to a normal reconnection inflow $v_{N,rec}$ of 2.5 km/s (or a dimensionless reconnection rate, $v_{N,rec}/v_{Alfven}$, of 3.3%). The flow predictions in panels c and d are based on the local magnetic field measurements and the reference velocity and magnetic field: $\mathbf{v}_{predicted} = \mathbf{v}_{reference} \pm (1-\alpha_{reference})^{1/2}(\mu_0\rho_{reference})^{-1/2}[\mathbf{B}\rho_{reference}/\rho - \mathbf{B}_{reference}]$ [25,26]. The positive (negative) sign is chosen for the leading (trailing) edge of the bifurcated current sheet. $\alpha = (p_{//}-p_{\perp})\mu_0/B^2$ is the pressure anisotropy factor, ρ is the plasma mass density. The left (right) dashed line in panels c and d denotes the reference times for the prediction of reconnection flow acceleration at the leading (trailing) edge of the exhaust. The leading and trailing edge predictions merge at 03:59 UT. The agreement between the predicted and observed flow is excellent in both the magnitude (Panel c) and the components of the velocity (Panel d). This level of agreement is similar to other reconnection exhaust events in the solar wind[17].



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Wind
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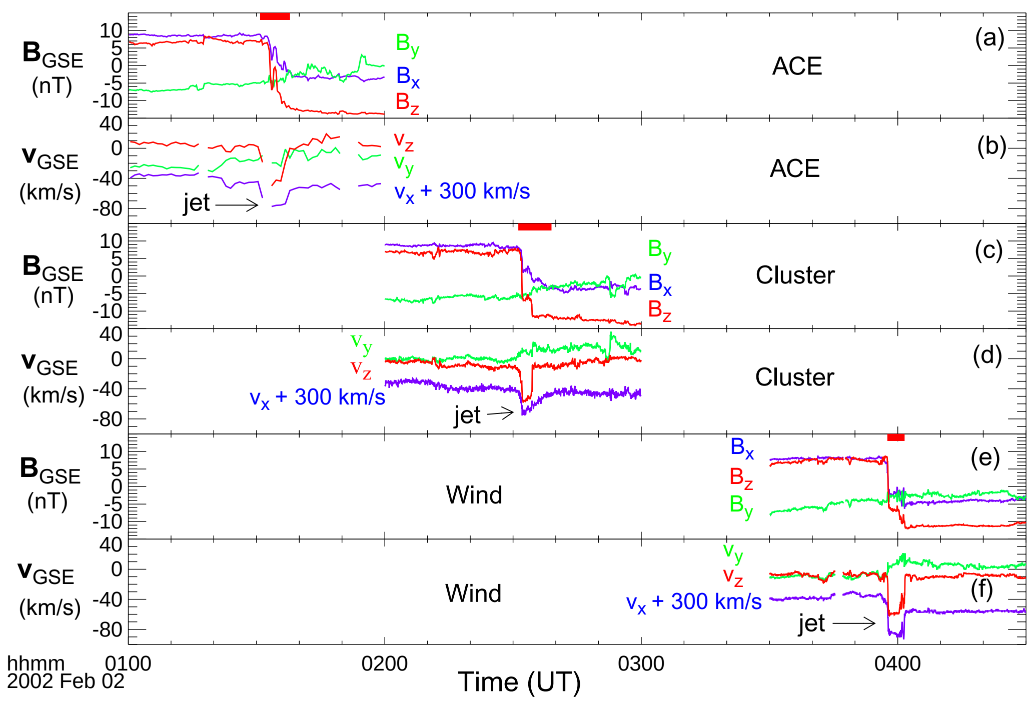

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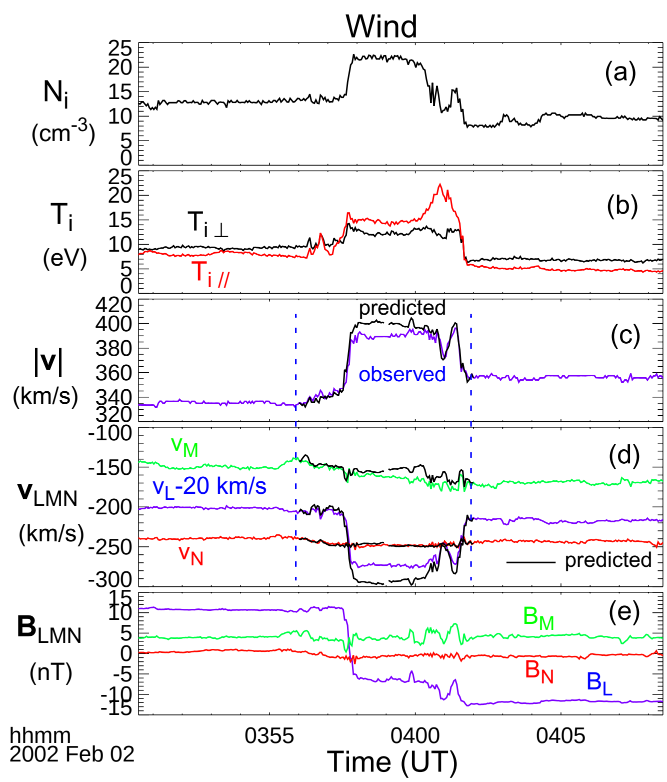
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