On the signatures of magnetic islands and multiple X-lines in the solar wind as observed by ARTEMIS and WIND

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Abstract

We report the first observation consistent with a magnetic reconnection generated magnetic island at a solar wind current sheet that was observed on 10 June 2012 by the two ARTEMIS satellites and the upstream WIND satellite. The evidence consists of a core magnetic field within the island which is formed by enhanced Hall magnetic fields across a solar wind reconnection exhaust. The core field at ARTEMIS displays a local dip coincident with a peak plasma density enhancement and a locally slower exhaust speed which differentiates it from a regular solar wind exhaust crossing. Further indirect evidence of magnetic island formation is presented in the form of a tripolar Hall magnetic field, which is supported by an observed electron velocity shear, and plasma density depletion regions which are in general agreement with multiple reconnection X-line signatures at the same current sheet on the basis of predicted signatures of magnetic islands as generated by a kinetic reconnection simulation for solar wind-like conditions. The combined ARTEMIS and WIND observations of tripolar Hall magnetic fields across the same exhaust and Grad–Shrafranov reconstructions of the magnetic field suggest that an elongated magnetic island was encountered which displayed a $4R_E$ normal width and a $43R_E$ extent along the exhaust between two neighboring X-lines.

Keywords: solar wind, magnetic islands, reconnection

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

1. Introduction

The Sun is known to eject large-scale coronal mass ejections (CMEs) into interplanetary space (e.g., Gosling 1990, Kunow et al 2006) which typically generates a forward shock and a sheath region of compressed plasma ahead of an expanding large-scale magnetic flux rope with its helical magnetic fields anchored on the Sun (e.g., Zurbuchen and Richardson 2006). These flux rope structures of solar origin generally include an anomalously low ion plasma temperature (e.g., Gosling 2010). CME-related flux ropes can expand to a few tenths of an Astronomical Unit (AU) in radial size by the time they arrive at a heliocentric distance of 1 AU ($1 AU = 1.496 \times 10^8$ km) from the Sun, such that it may take them anywhere from several hours up to a day at their solar wind speed to convect past a given point in near-Earth space. Small-scale flux ropes also exist in the solar wind (e.g., Moldwin et al 1995, 2000, Gosling et al 2010). However, the generation mechanism for a subset of such flux ropes with a typical duration of an hour or so is less clear with some evidence suggesting a solar source region (e.g., Tu et al 1997, Mandrini et al 2005, Feng et al 2008). Magnetic reconnection is another mechanism first proposed by Moldwin et al (1995, 2000) to produce hour-long duration flux ropes at solar wind current sheets. However, no reconnection exhausts,
or other signatures of magnetic reconnection, have yet been reported in connection with small-scale flux ropes in the solar wind to conclusively support reconnection as their generation mechanism. The first evidence of reconnection occurring in the solar wind was reported in the form of accelerated ion flow within magnetic field reversal regions by Gosling et al (2005). Tian et al (2010) discovered this type of reconnection exhaust at the boundaries of a subset (42%) of hour-long duration flux ropes. However, exhausts identified at flux rope boundaries could very well represent magnetic flux annihilation within flux ropes of any age or size and irrespective of their origin as they interact with the ambient interplanetary magnetic field. A more conclusive signature of magnetic reconnection than the presence of an ion exhaust alone is therefore necessary to verify whether flux ropes can form at current sheets in the solar wind.

This report interprets the observed plasma and magnetic field structure across a solar wind reconnection exhaust as plausible signatures of multiple reconnection X-lines on the basis of a 2.5-dimensional kinetic reconnection simulation (Lapenta et al, 2010, Markidis et al, 2012), since two X-lines is a minimum requirement to form a topological O-line (magnetic island) embedded within a reconnection exhaust region. Evidence is provided in the form of ARTEMIS observations (Angelopoulos 2008) that supports the presence of a magnetic island across an active current sheet in the solar wind on 10 June 2012. WIND observations (Lepping et al, 1995, Lin et al, 1995) far upstream of ARTEMIS provide additional support consistent with the presence of multiple X-lines. The temporal duration of the observed reconnection exhaust ranges from 34 s at ARTEMIS to 74 s at WIND which corresponds to (1.2–2.7) × 10^8 km spatial scales at the observed solar wind speed. This is small compared with hour-long duration flux ropes. We refer to flux ropes as magnetic islands in this study since the simulation is two-dimensional (2D) in space and three-dimensional (3D) in all other quantities.

2. Observations in the solar wind on 10 June 2012

THEMIS (Time History of Events and Macroscale Interactions during Substorms) is a five spacecraft mission launched on 17 February 2007 and originally dedicated to substorm physics in the Earth’s magnetotail (Angelopoulos 2008). In 2009 it was decided to move the apogee of the two outer probes (THB and THC) into an orbit around the Moon to avoid dangerously long solar eclipses closer to the Earth. THB and THC left their geocentric orbits on 31 January 2010 (THB) and 28 March 2010 (THC), respectively. The two probes are now referred to as the ARTEMIS mission, since their lunar orbit insertions on 27 June (THB) and 17 July (THC) 2011. The Moon periodically brings this orbiting pair of satellites far out into the solar wind at a distance of 60 Earth radii (1 RE = 6378 km) from the Earth. At 12:31–12:33 UT on 10 June 2012 the two probes were in the solar wind upstream of the Moon when a magnetic field discontinuity swept past them with THB at (x, y, z) = (−9.5, −59.3, 5.7)R_E and THC at (x, y, z) = (−10.8, −57.0, 4.9)R_E in a geocentric solar ecliptic (GSE) coordinate system, where x points from the Earth to the Sun, and z points to the ecliptic north pole. Neither probe was near the Earth’s bow shock or the lunar wake (e.g., Trávníček et al 2005) behind the Moon, which was located at (x, y, z) = (−11.4, −59.8, 5.6)R_E at this time. The same magnetic field discontinuity was encountered at (x, y, z) = (233.2, −97.9, 11.7)R_E by the WIND satellite at 11:29 UT and far upstream of THC. Figure 1 displays the positions of the three satellites and the Earth relative to THC in the GSE coordinate system.

Figure 2 displays the magnetic field observations from the flux gate magnetometer (FGM) instrument (Auster et al 2008) on board THC as well as ion and electron observations from the electro-static analyzer (ESA) plasma instrument (McFadden et al, 2008) during a 15 min long interval between 12:20:30 to 12:35:30 UT on 10 June 2012. The magnetic field and velocity components are displayed in LMN coordinates based on a cross-product normal N = B_L × B_E/[|B_L|×|B_E|] where B_L and B_E are the average external magnetic fields on either side of the magnetic field rotation that THC encountered around 12:32 UT. The M-direction is defined as the unit vector of the cross-product between N and the maximum variance direction of the magnetic field (Sonnerup and Scheible 1998) across the field rotation. L = M × N completes the orthogonal LMN system. A clear B_L rotation is shown in figure 2(b) which we interpret as a current sheet with a normal oriented along N_{GSE} = (−0.86, 0.24, 0.45). This normal is directed 33° from the average solar wind velocity \mathbf{V}_{GSE} = (−403, −17, −5) km s\(^{-1}\) as measured by THC before the current sheet. The orientation of the LMN system of the inferred current sheet is displayed in figure 1 relative to the GSE system as well as the \mathbf{V}_{GSE} solar wind velocity as the current sheet approaches WIND.

Figure 2(c) shows that a solar wind-type ion reconnection exhaust with maximum \(\Delta V_{\perp} = 46 \text{ km s}^{-1}\) and average \(\Delta V_{\perp} = 38 \text{ km s}^{-1}\) flow enhancement was present at this current sheet from 12:31:52 to 12:32:26 UT (black vertical
dotted lines) and relative to the background flow. The exhaust was directed along the negative $\mathbf{L}_{GSE} = (0.41, -0.21, 0.89)$ axis while the anti-parallel $B_L$ component of the magnetic field rotated from $B_{L1} = -2.1$ nT before the exhaust to $B_{L2} = 1.8$ nT after the exhaust. A constant and strong background guide field was present along the negative $\mathbf{M}_{GSE} = (0.31, 0.95, 0.08)$ axis with a $B_M = 5.5$ nT magnitude corresponding to $B_M/B_L = 2.8$ and a relatively small 40° magnetic field shear angle which explains the absence of any significant magnetic field decrease (see figure 2(a)) across the exhaust.

The 34 s wide ion exhaust is consistent with an Alfvénic acceleration as expected for magnetic reconnection in the solar wind (e.g., Gosling et al 2005) and demonstrated here by the red trace in figure 2(c) which follows from a velocity prediction $V_L = V_{L0} + \Delta V_L$ based on tangential momentum balance (Paschmann et al 1986) where $\Delta V_L (t) = \pm (B_L(t)/\rho(t) - B_{L0}/\rho_0) \times (\rho_0/\mu_0)^{0.5}$ is a time-dependent function of the $B_L$ magnetic field weighted by the proton mass-density $\rho = Nm_p$ and $\mu_0$ is the permeability of free space. The prediction was applied separately from the two external reference locations (red vertical dotted lines), where all reference values ($V_{L0}, B_{L0}, \rho_0$) were evaluated, toward a joint position within the exhaust. The predicted $\Delta V_L$ speed was found to range between 36 and 40 km s$^{-1}$ from the two external sides and relative to the external $V_{L0}$ reference speed which compares favorably with the observed average 38 km s$^{-1}$ exhaust speed. The steady $V_{L3} = 338$ km s$^{-1}$ solar wind speed along the current sheet normal (see figure 2(e)) can be used to translate the 34 s exhaust duration into an estimated $\Delta D_N = 1.8\ R_E = 60L_i$ normal width where $L_i = 194$ km is the ion inertial length based on the average external plasma number density.

The same exhaust velocity prediction is superposed on the L-component of the measured electron velocity ($V_{EL}$) in figure 2(f) that was corrected by 40 km s$^{-1}$ to agree with the external ion velocity $V_{IL}$. This correction corresponds to a small $\Delta E_N = 0.22$ mV m$^{-1}$ offset to the observed $-\mathbf{v} \times \mathbf{B}$ solar wind electric field ($E_N = -1.17$ mV m$^{-1}$). There is a very good agreement between the observed electron flow enhancement $\Delta V_{EL} < 0$ (black) at THC and the predicted $\Delta V_{IL}$ speed (red) across the current sheet which confirms that ions and electrons are accelerated to the same Alfvénic speed in solar wind exhausts. However, there is an additional super-Alfvénic $\Delta V_{EL} = 59$ km s$^{-1}$ electron flow enhancement centered at 12:31:20 UT as compared with the available background Alfvén speed $V_{EL} = 38$ km s$^{-1}$ where $V_{AL} = B_L/(\rho \mu_0)^{0.5}$ is measured before this velocity change. The super-Alfvénic electron velocity is highlighted as the 19 s wide region I in figure 2 that THC encountered before the main exhaust (region III). The ion velocity $V_{IL}$ displayed a much weaker velocity change at this time, suggesting that the flow difference between the ions and electrons in region I may represent an in-plane electron current along the L-direction. Figure 2 also highlights two intermediate regions II and IV where $\Delta V_{EL}$ was weakly positive as compared with $\Delta V_{IL} < 0$ in regions I and III such that an in-plane electron velocity shear exists between regions I–II, II–III, and III–IV.

The measured electron number density profile across the event (figure 2(g)) indicates a rather deep density depletion $N_{min} = 1.0$ cm$^{-3}$ within the initial super-Alfvénic electron flow region I as compared with the observed adjacent background density $N_b = 1.4$ cm$^{-3}$ before the exhaust and $N_b = 1.3$ cm$^{-3}$ after the exhaust. The plasma number density increased to a maximum density $N_{max} = 2.0$ cm$^{-3}$ at the center of the exhaust region III. A second, and nearly twice as wide, density depletion region is observed to span most of region IV on the opposite side of the exhaust with a minimum $N_{min} = 1.1$ cm$^{-3}$ observed just inside the exhaust boundary.

Figure 3 presents a subset of the corresponding measurements recorded by the THB satellite at an upstream $\Delta R_{GSE} = (1.3, -2.2, 0.8)R_E$ distance from THC. This separation corresponds to $(\Delta R_{L1}, \Delta R_{M1}, \Delta R_{K}) = (1.7, -1.7, -1.3)R_E$ or $\Delta R_{L_{MAX}} = (56, -55, -43)L_i$. The THB observations were shifted forward in time by 20.5 s to provide an optimum match with the observations recorded at THC which is in general agreement with the estimated $\Delta R_N/V_N = 24.3$ s delay based on satellite separation and
were characterized by an enhanced (negative) guide field with \( \Delta B_M \) for these \( \Delta V_{\text{BL}} \) observations. The panels display: (a) \( L \)-component of the ion velocity \( V_{\text{IL}} \); (b) \( B_L \) magnetic field; (c) \( B_M \) magnetic field; (d) \( L \)-component of the electron velocity \( V_{\text{EL}} \); and (e) plasma number density.

Figure 3. THB observations (red) compared with THC observations (black) on 10 June 2012. The THB measurements were shifted forward in time by 20.5 s to provide an optimum correlation of the \( B_L \) magnetic field observations. The panels display: (a) \( L \)-component of the ion velocity \( V_{\text{IL}} \); (b) \( B_L \) magnetic field; (c) \( B_M \) magnetic field; (d) \( L \)-component of the electron velocity \( V_{\text{EL}} \); and (e) plasma number density.

solar wind speed. Figures 3(a) and (b) confirm that THB observed the same \( V_{\text{IL}} \) ion exhaust and \( B_L \) field rotation signatures as THC. More importantly, figure 3(d) shows that THB also observed the \( V_{\text{EL}} \) electron exhaust as well as the super-Alfvénic electron velocity channel prior to the exhaust, only \( \Delta R_L = 56 L_i \) from THC, and coincident with a deep density depletion region. THB recorded a very similar density profile as THC across the exhaust including a second density depletion region on the opposite side of the exhaust. Figure 3(c) shows that the exhausts at both ARTEMIS satellites were characterized by an enhanced (negative) guide field with a maximum \( B_M = 6.0 \text{nT} \) magnitude that displayed a localized magnitude decrease. This \( B_M \) dip also coincided with a locally 11 km s\(^{-1}\) slower \( V_{\text{IL}} \) jet speed as compared with the prediction (see figure 2(c)). Two \( B_M = 5.3 \text{nT} \) magnitude suppressions were also present on each side of the exhaust during which a compressed \( B_L = 2.5 \text{nT} \) field was observed. The super-Alfvénic electron velocity enhancements were observed by both ARTEMIS satellites toward the outer edge of the first \( B_M \) suppression region. Figure 4 presents a schematic overview of these \( \Delta B_M \) and \( \Delta V_{\text{EL}} \) observations as recorded in the four regions I–IV which are consistent with out-of-plane Hall magnetic field perturbations (Sonnerup 1979, Terasawa 1983) supported by an in-plane Hall current carried by the electron velocity. The narrow \( \Delta B_M > 0 \) regions that exist along the exhaust boundary for the negative \( B_M \) guide field may be consistent with the presence of two reconnection X-lines at this current sheet whereby each X-line generates an \( E \times B \) Poynting flux due to the exhaust directed Hall electric field \( (E) \) and the Hall magnetic field that propagates this \( \Delta B_M > 0 \) Hall field signal toward the other X-line (Shay et al 2011). This is the first time that Hall electron velocity signatures have been reported in the solar wind although similar signatures have been reported from within the Earth’s magnetotail (Teh et al 2013).

Figure 5 shows the time-shifted WIND observations using a constant 63 min delay to match the onset of the magnetic field rotation at THC. An ion reconnection exhaust that satisfied the predicted Alfvénic acceleration was present at the same current sheet as later observed by THC. However, the exhaust was observed for 74 s at WIND (11:28:45 to 11:29:59 UT) which corresponds to a \( \Delta D_N = 4.3 \text{Re} = 144 L_i \) normal width using the locally measured average solar wind speed \( V_N = 370 \text{km s}^{-1} \) and \( L_i = 190 \text{km} \). The exhaust was thus approximately twice as wide at WIND as compared with the \( \Delta D_N = 1.8 \text{Re} = 60 L_i \) normal width at THC. Figure 5(c) shows that WIND observed a very similar \( \Delta B_M \) magnetic field signature as recorded at THC, and it was superposed on a background guide field of the same magnitude. The exhaust region \( B_M \) field reached a similar \( B_M = 6.0 \text{nT} \) peak magnitude. However, there was no central \( B_M \) dip as observed by THC and the region was wider at WIND than it was at THC. A wider \( \Delta B_M < 0 \) region is consistent with the expectation that the central Hall field should extend across the full width of the exhaust (e.g., Karimabadi et al 1999) which was wider at WIND. Figure 5(d) displays a very close overall agreement of the plasma number densities recorded at WIND and THC including the peak density in the exhaust region. However, although WIND confirmed a density depletion upon exiting the exhaust, it is clear that the density depletion observed before entering the exhaust at THC was absent 63 min earlier at WIND with a relative upstream


result from spontaneous tearing of the initial Harris sheet. Although some of the parameters in the simulation differ from the prevailing conditions for the event on 10 June 2012, it is expected that the contrast between the signatures near a dominant X-line and those in the vicinity of islands will carry over into other parameter regimes. The simulation is characterized by a maximum Harris-sheet number density \( N_0 \) in a 200 \( \times \) 30L\(_i\) simulation domain where \( L_i = c/\omega_{pi} \) is the ion inertial length with \( \omega_{pi} \) being the ion plasma frequency based on \( N_0 \). The simulation employed a mass ratio \( m_i/m_e = 256 \), an electron thermal velocity \( V_{eTH}/c = 0.0045 \), where \( c \) is the speed of light corresponding to an electron temperature \( T_e = 10 \) eV typical of the solar wind, and a temperature ratio \( T_e/T_i = 0.2 \). An out-of-plane (guide) magnetic field \( B_M = 0.50B_L \) was employed where \( B_L \) is the reconnecting in-plane component of the magnetic field along the reconnection exhaust direction while \( B_M \) is the in-plane component of the magnetic field along the current sheet normal. This right-handed orthogonal system is defined such that \( M = N \times L \). The simulation was further initialized using \( V_{AB}/c = 0.0022 \) where \( V_{AB} \) is the Alfvén speed based on the background density \( N_0 = 0.20N_0 \) and the asymptotic magnetic field \( B_0 \) at \( \omega_{ci}t = 0 \) such that \( B_0^2 = (B_{LO}^2 + B_{MO}^2) \) and \( \omega_{ci} \) is the ion cyclotron frequency.

Figure 6(a) displays the normalized out-of-plane magnetic field relative to the background field \((\Delta B_M)\) in color with solid lines being the in-plane magnetic field for a 100 \( \times \) 15L\(_i\) section of the reconnection plane at time step \( \omega_{ci}t = 19.788 \). Multiple magnetic islands have formed between topological X-lines. The islands are characterized by density enhancements (see figure 6(d) and axial \( \Delta B_M > 0 \) core field enhancements which are associated with the asymmetric quadrupolar magnetic field (Sonnerup 1979, Terasawa 1983) perturbation \((\pm \Delta B_M)\) that forms around active X-lines with oppositely directed ion exhausts (see figure 6(b)). A prominent feature of the core region of all the islands in this kinetic simulation is the presence of a localized dip of the axial Hall magnetic field which is accompanied by a significant plasma density increase. Karimabadi et al (1999) presented a very similar magnetic field structure within the core regions of magnetic islands on the basis of a hybrid reconnection simulation (kinetic ions, fluid electrons) to understand the generation of strong axial core fields within magnetotail plasmoids for a finite guide field \( B_M = 0.27B_L \).

The spatial \( \Delta B_M \) asymmetry of the Hall magnetic field, which is clearly seen in figure 6(a) around a dominant X-line at \( x_L = 0L_i \), is due to the external guide field \( B_{MO} > 0 \) such that a wide Hall field region \((B_M = B_{MO} + \Delta B_M)\) develops across the exhaust where \( \Delta B_M \) is aligned with \( B_{MO} \) (here \( \Delta B_M > 0 \)), while narrow Hall field regions develop along the exhaust boundary where \( \Delta B_M \) is opposite to \( B_{MO} \) (here \( \Delta B_M < 0 \)). The L-component of the electron velocity \((V_{el})\) normalized by \( V_{AB} \) (see figure 6(c)) confirms that these are Hall field \( \Delta B_M \) perturbations due to in-plane Hall currents supported by super-Alfvénic electrons. The narrow Hall field regions in particular are supported by opposite \( V_{el} \) flows in relative close proximity (see figures 6(a) and (c)). The asymmetric widths of the Hall field regions described here for \( B_{MO} > 0 \) will be in the opposite sense for \( B_{MO} < 0 \) and instead result in a wide \( \Delta B_M < 0 \)

Figure 5. WIND observations (red) compared with THC observations (black) on 10 June 2012. The WIND observations were shifted forward in time by 63.05 min. Panels from the top display: (a) \( V_L \) velocity; (b) \( B_L \) magnetic field; (c) \( B_M \) magnetic field; (d) plasma number density; and (e) total magnetic field strength.

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\Delta R_{GSE} = (244.0, -40.9, 6.8)R_E \text{ separation from THC. This GSE separation translates into an } LMN \text{ system separation of }\Delta R_{LMA} = (114.9, 37.6, -216.0)R_E \text{ and thus a very large apparent } \Delta R_Y = 114.9 R_E = 3856 L_i \text{ separation along the exhaust. The } LMN \text{ system that we have employed here is clearly acceptable over these distances, since } \Delta R_N = 216.0R_E \text{ and } V_N = 370 \text{ km} \text{s}^{-1} \text{ predicts an estimated 62 min time delay between the exhaust encounters which is very close to the observed 63 min delay considering the different exhaust widths at THC and WIND.}
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3. Magnetic island signatures from a kinetic reconnection simulation

The observed solar wind exhausts on 10 June 2012 share a number of characteristics in common with the results of a 2.5-dimensional fully kinetic implicit particle-in-cell (PIC) simulation (Lapenta et al 2010, 2011) as reported by Markidis et al (2012) of magnetic reconnection in a plasma with parameters similar to what is observed in the solar wind at 1 AU. This PIC simulation, which was initialized using two oppositely directed Harris-type current sheets, is particularly relevant to the interpretation of the solar wind observations as the current sheets evolve to contain both strong semi-isolated X-lines, where an initial perturbation was imposed, as well as chains of magnetic islands separated by weaker X-lines that
Figure 6. Kinetic reconnection simulation results in the presence of a finite guide field: (a) Out-of-plane $B_M$ magnetic field relative to a background finite guide field; (b) $L$-component of the normalized ion velocity; (c) $L$-component of the normalized electron velocity; (d) Ion number density relative to the background density. Black contours in all panels display the in-plane magnetic field. Vertical dashed lines at $x_L = -46$ (green), $x_L = -19$ (white) and $x_L = -8$ $L_i$ (black) mark three virtual spacecraft fly-throughs along the current sheet normal direction.

region across the exhaust and a narrow $\Delta B_M > 0$ Hall field along the exhaust boundary as observed by ARTEMIS and WIND on 10 June 2012. Figure 6(a) illustrates how the narrow 1–2 $L_i$ Hall fields adjacent to the exhaust region can extend over a considerable 20–50 $L_i$ distance from a given X-line and beyond neighboring X-lines. Regions may therefore develop along the exhaust direction where two oppositely propagating and narrow Hall signatures from two separate X-lines coexist on either side of the exhaust. This may be a characteristic signature for the presence of multiple X-lines and magnetic islands since the Hall field remained in its quadrupole state close to a dominant X-line. Figure 6(d) illustrates another signature that may be related to the presence of multiple X-lines in the form of a narrow plasma density depletion region adjacent to the exhaust boundary. These depletions are correlated with strong electron flows along the magnetic field as observed by ARTEMIS. They are believed to result from the approximate conservation of magnetic field-aligned electron flux and typically form on the opposite side of the exhaust relative to a narrow Hall field depression in the vicinity of a single X-line. However, it appears from this simulation that they may also coexist with narrow Hall magnetic fields in agreement with the ARTEMIS observations when multiple X-lines are present.

The detailed signatures of the normalized magnetic field, $L$-components of the ion and electron velocity normalized by the Alfvén speed, and the plasma number density relative to the background density are shown in figure 7 for the three virtual satellite fly-through examples in figure 6. The classic quadrupole Hall magnetic field around a single X-line (figure 7(a), left) appears as a bipolar $B_M$ signature across an individual exhaust where the asymmetric normal widths of the two $\Delta B_M$ regions are due to the finite guide field. The Hall field perturbations in the vicinity of a magnetic island (figure 7(a), middle) may in contrast appear as a tripolar $B_M$ signature with two narrow guide-field depressions (here $\Delta B_M < 0$) adjacent to a wide guide-field enhancement at the center of the active current sheet. Each $B_M$ depression also coincides with a $B_L$ field compression as observed on 10 June 2012 such that the magnetic field strength remains essentially constant. A crossing through the core region of an island (figure 7(a), right) is characterized by a dip of the central guide-field enhancement which coincides with a very strong density compression. Both ARTEMIS satellites observed a similar $B_M$ dip coincident with a strong density enhancement. The narrow Hall field depressions, whether found toward the edge of an exhaust close to a single X-line or close to a magnetic island, are associated with oppositely directed and super-Alfvénic electrons along the direction of the exhaust as shown in figure 7(b) where the normalized $V_{eL}$ was scaled by a factor of 10. A deep plasma density depletion region at 40–60% of the background density may also develop on either side of magnetic islands, and occasionally within channels of strong Hall electron velocity shear as shown in figure 7(c) (middle). It should be noted that oblique in-plane trajectories may be found across this simulated current sheet that only display the two Hall field depressions on either side of the exhaust without strong density depletions or vice versa which may explain the
absence of a density depletion on one side of the exhaust at WIND.

4. Discussion

The primary observational difficulty for the direct identification of magnetic islands in the solar wind is related to the fact that islands are expected to move at the Alfvén speed, or even slower, if there are other islands in their vicinity to prevent their free motion from their assumed active X-lines. This is slow compared to the super-Alfvénic solar wind such that islands moving along the exhaust, which is frozen in to the solar wind, are not expected to display one of the most classic signatures of flux ropes that exist at planetary magnetopause surfaces, namely a bipolar signature of the magnetic field component normal to a magnetopause current sheet (e.g., Russell and Elphic 1979) which is due to the faster motion of a flux rope past a satellite than the speed of the current sheet. Moreover, the kinetic simulation results displayed in figures 6 and 7 suggest that a single spacecraft traversing a regular exhaust without the presence of islands may not look too different from a crossing of a magnetic island. For instance, flux ropes at the Earth’s magnetopause and plasmoids in the Earth’s magnetotail often display an enhanced plasma number density and an enhanced axial magnetic field in the presence of a finite guide field (e.g., Karimabadi et al 1999, Hietala et al 2013, and references therein). These same signatures are commonly observed across solar wind exhausts, such as the 10 June 2012 event discussed here, where the axial core field of an island may be identified with the enhanced Hall magnetic field across the exhaust region as previously suggested from hybrid simulations reported by Karimabadi et al (1999) for flux ropes in the Earth’s magnetotail. Density enhancements are frequently encountered across solar wind exhausts as well. Some additional signature is therefore required to differentiate a magnetic island structure within an exhaust from a regular solar wind exhaust. One such signature appears to be a tripoal Hall magnetic field which consists of a central Hall field enhancement sandwiched between two narrow Hall field suppressions supported by in-plane Hall electron currents as observed by ARTEMIS on 10 June 2012. Another example could be density depletion regions on both sides of the exhaust that coincide with the narrow Hall field suppression regions as observed by ARTEMIS on 10 June 2012 since these signatures should not be coincident for a single X-line.

Karimabadi et al (1999) performed hybrid reconnection simulations for both single- and multiple X-line cases and for the same guide field $B_M/B_L = 0.27$ ratio. In both cases, guide field $B_M$ dips formed on the two sides of the exhaust region which are reminiscent of the tripolar Hall field of the kinetic simulation. The question is to what extent a fully kinetic simulation of a single X-line for solar wind conditions would generate this $B_M$ suppression signature along all four separatrices emanating from the single X-line as suggested by the hybrid simulation. Figures 6 and 7 clearly show that an asymmetric but standard quadrupole Hall field was sustained within the ion diffusion region of a dominant X-line late in the kinetic simulation and for a stronger $B_M/B_L = 0.50$ ratio. This dominant X-line is a reasonable proxy for a single X-line leading us to conclude that a tripolar Hall field is more likely in the presence of a finite guide field and multiple X-lines than in the presence of an isolated X-line, all else being equal.

Despite significant differences between this solar wind-like kinetic simulation of magnetic islands and the hybrid simulation of magnetotail plasmoids for isothermal electrons, they both reproduced a very similar magnetic field structure within the island core regions in the presence of a guide field which is characterized by a local dip of the axial Hall magnetic
field enhancement. The observed $B_M$ magnetic field at the two ARTEMIS probes (see figure 3(c)) displayed a very similar localized $B_M$ dip of the Hall field enhancement at the very center of the exhaust region where the plasma density displayed a local maximum (see figure 3(e)). The local $B_M$ dip also coincided with an ion $v_L$ velocity deceleration (see figure 3(a)) relative to the predicted exhaust velocity (see figure 2(c)). A related phenomenon of jet flow diversion ahead of an island obstacle can be seen in figures 6 and 7 of the kinetic simulation at $x_L = -19L_e$ and $7 < x_N < 11L_e$ and near other islands. It is therefore quite possible that both ARTEMIS probes traversed the central region of an exhaust-generated magnetic island in the solar wind on 10 June 2012. The WIND satellite did not observe a local dip of the exhaust $B_M$ enhancement. However, the ion velocity toward one side of the center of the exhaust (see figure 5(a)) indicated an apparent flow braking signature at a time when the guide field reached its maximum value which indicates the presence of an island at WIND as well. It is not entirely surprising that WIND failed to observe a local $B_M$ dip at the center of the exhaust given its expected relatively smaller area of island core regions as compared with a generally larger area of $B_M$ enhancements within individual islands as suggested in figures 6 and 7.

Figure 8 presents the results of a Grad–Shrafranov (GS) reconstruction (Sonnerup and Guo 1996, Hau and Sonnerup 1999) of the magnetic field observed by WIND and THC for a time period centered at each reconstruction exhaust under the assumption that the structures are essentially 2D locally and magnetohydrostatic. The same technique has been applied to large-scale flux rope encounters in the solar wind (e.g., Hu and Sonnerup 2001) as well as flux ropes at the Earth’s magnetopause (e.g., Hasegawa et al 2006). Here we used the locally observed solar wind velocity as the co-moving frame velocity under the assumption that the structure is essentially frozen in to the solar wind, while using the negative $M_{GSE}$-axis as the third invariant $zs$-axis of the reconstruction maps.

*Figure 8.* Grad–Shrafranov reconstructions of the GSE magnetic field observed at (a) WIND and (b) THC. Black contours correspond to the reconstructed $xy$-plane magnetic field and color corresponds to the out-of-plane $B_z$ magnetic field. White arrows are the measured in-plane magnetic field and blue arrows are the measured in-plane ion velocity along the $zs$-axis of the co-moving frame of the field maps. The coordinate systems of the maps employed $zs = (0.951, -0.310, -0.013)$ at WIND and $zs = (0.951, -0.309, -0.032)$ at THC which were derived as the oppositely directed unit vectors of the $xy$-plane projections of $V_s = (-439.0, -17.2, -6.4) \text{ km s}^{-1}$ at WIND and $V_s = (-401.8, -13.9, 1.2) \text{ km s}^{-1}$ at THC. Here $V_s$ is the mean of two 1 min averages of the solar wind $V_{GSE}$ adjacent to each exhaust. The invariant (out-of-plane) direction is $zs = -M_{GSE}$ or $zs = (-0.310, -0.947, -0.078)$ for both reconstruction planes.

The white arrows correspond to the observed magnetic field vectors along the (negative) spacecraft trajectory ($zs$-axis) in the $xy$-plane of the reconstruction while blue arrows are the measured ion velocity vectors superposed on the magnetic field maps in the solar wind frame of reference. The exhausts are localized to the current sheet where the out-of-plane magnetic field reproduces what we interpret as an axial Hall field enhancement (red) and Hall field depressions (blue) appear on either side of the exhaust. The reconstructed field map at WIND supports the presence of a magnetic island with a core dimension of about $4R_E$ while the magnetic field map at THC suggests the presence of a nearby topological X-line within the exhaust.

*Figure 9.* ARTEMIS (THB: red; THC: green) and WIND (blue) spacecraft positions are shown in the $NL$-plane relative to the THC position at 12:32 UT on 10 June 2012. The solar wind velocity is shown as the red vector and the $M_{GSE} = N_{GSE} \times L_{GSE}$ axis is positive into the plane. Oblique dotted lines illustrate the trajectories of WIND and THC along the negative solar wind velocity. Sinusoidal curves show schematic representations of a proposed chain of magnetic islands encountered at WIND and THC. Dotted (solid) sinusoidal curves at THC illustrate the island chain with zero (finite) drift speed along the exhaust and relative to its position at WIND. The direction of the in-plane magnetic field is shown as arrows for an island chain at THC while the island chain at WIND depicts asymmetric quadrupole Hall magnetic field perturbations into and out of the $NL$-plane around each X-line and relative to the background negative guide field.
schematic only, and they are likely 10 times too wide based on the GS reconstruction of the island that WIND encountered which suggests a size of about $4R_E$ along the spacecraft trajectory. The two chains of islands near the ARTEMIS spacecraft correspond to the two scenarios of zero island drift along the exhaust direction (dotted sinusoidal curves) and a finite drift to the right at the observed Alfvén exhaust speed $V_{EL} = -38\text{ km s}^{-1}$ (solid sinusoidal curves) in the solar wind frame of reference. The pair of dotted lines shown at oblique angles indicates the spacecraft trajectories of WIND and THC along a direction opposite to the solar wind velocity vector. The separation between the two spacecraft along the horizontal (exhaust) $L$-direction is as small as $\Delta R_L = 8.7R_E = 285L_E$ when the $26^\circ$ angle between the $ML$-plane solar wind velocity and the $N_{GSE}$-direction is taken into consideration and if we assume no drift motion of the islands. The same island may have been encountered in this scenario by both spacecraft if it was $4R_E$ wide along the current sheet normal and at least twice the $8.7R_E$ separation or $18R_E$ along the exhaust based on the GS map which suggests that WIND traversed the island near its center. However, it is possible that the island moved along the exhaust direction in the solar wind frame at some fraction of the observed exhaust flow speed ($V_{EL} = -38\text{ km s}^{-1}$) during the 63 min that separated the observations. This is supported by the measurements which indicate a small $11\text{ km s}^{-1}$ deceleration of $V_{EL}$ at the center of the two exhausts. The observed differences of the exhaust normal width ($\Delta D_N$) also support a finite drift scenario, since $\Delta D_N$ was nearly half as wide at THC ($1.8R_E$) as it was at WIND ($4.3R_E$). This $\Delta D_N$ difference is difficult to reconcile with figure 9 and a THC position $8.7R_E$ to the right side of the WIND trajectory if the spacecraft encountered the same island in a zero-drift scenario. This is reinforced by the GS map at THC which suggests that THC may have encountered an island much closer toward one X-line than what is possible in the zero-drift assumption. A maximum $38\text{ km s}^{-1}$ drift speed corresponds to a total $22.4R_E$ distance covered in 63 min such that THC would have traversed the island $22.4 - 8.7 = 13.7R_E$ closer to the X-line to the left side of the WIND trajectory in figure 9.

The different normal widths can be used with some assumption of the reconnection rate to estimate the distance to the X-line from the two spacecraft. Denoting the full opening angle of the exhaust at the X-line as $\beta = 2\times\alpha$ we have that the reconnection rate $\tan(\alpha) = \Delta D_N/2\Delta D_L$. A fast reconnection rate of 0.10 results in THC being $\Delta D_L = 9.0R_E$ from the X-line and WIND being $\Delta D_L = 21.5R_E$ from the same X-line. This corresponds to a $12.5R_E$ separation between the spacecraft which is close to the $13.7R_E$ estimate based on the assumption that the island moved at the $38\text{ km s}^{-1}$ Alfvén speed along the exhaust. The $12.5R_E$ spacecraft separation suggests an effective slower island drift speed of $36\text{ km s}^{-1}$ along the exhaust direction compared with the maximum $38\text{ km s}^{-1}$ exhaust speed. This is consistent with the observation of a small exhaust deceleration at the center of the exhausts at the two spacecraft which may be due to the exhaust running into the slower moving island ahead of it. The reconnection rate would have to be revised from 0.10 to 0.09 if the island actually moved at the exhaust speed. The total distance between two neighboring X-lines can be estimated to be about twice the $\Delta D_L = 21.5R_E$ distance to one X-line from WIND or $43R_E$ if it is further assumed that WIND traversed close to center of the island on the basis of the GS reconstruction. In summary, it is quite possible that WIND and ARTEMIS encountered the same elongated island which was moving close to the exhaust Alfvén speed in the frame of the solar wind on 10 June 2012. However, individual X-lines do not necessarily need to drift together with the magnetic islands as was indicated for simplicity in figure 9.

5. Conclusions

The general agreement between the detailed predictions of magnetic islands and multiple X-lines based on a kinetic reconnection simulation for a solar wind electron temperature and a finite guide field, and the solar wind exhaust event that ARTEMIS and WIND recorded on 10 June 2012 strongly suggest that one or more magnetic islands can form due to magnetic reconnection in the solar wind. The direct evidence consists of an enhanced core magnetic field with a local $B_M$ dip coincident with a plasma density enhancement as well as an indication that the exhaust flow is slowing down ahead of the island obstacle. Indirect signatures were also present to support the possible existence of multiple X-lines at the same current sheet. These consist of a tripolar out-of-plane Hall magnetic field signature supported by an in-plane electron shear velocity as well as density depletion signatures that coincide with the adjacent dips of the out-of-plane Hall magnetic field on either side of the exhaust at ARTEMIS. The encounter of one elongated magnetic island by WIND and ARTEMIS was further supported by a GS reconstruction of the magnetic field which suggests that the island was about $4R_E$ wide with a possible $43R_E$ distance between neighboring X-lines. The different normal exhaust widths at WIND and THC is consistent with a fast reconnection rate and an island drift speed along the measured exhaust flow direction which is only somewhat slower than the observed Alfvén exhaust speed. Further analysis is required to investigate any possible impact that three-dimensional geometries may have on the propagation of Hall magnetic field signatures from neighboring X-lines in the solar wind.

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References

Angelopoulos V 2008 The THEMIS mission Space Sci. Rev. 141 5
Auster H U et al 2008 The THEMIS fluxgate magnetometer Space Sci. Rev. 141 235

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Feng H Q, Wu D J, Lin C C, Chao J K, Lee L C and Lyu L H 2008 Interplanetary small- and medium-sized magnetic flux ropes during 1995–2005 J. Geophys. Res. 113 A12105

Gosling J T 1990 Coronal mass ejections and magnetic flux ropes in interplanetary space Physics of Magnetic Flux Ropes (Geophysical Monograph Series vol 58) ed C T Russell et al (Washington, DC: American Geophysical Union) p 343

Gosling J T 2010 The structure and evolution of the three-dimensional solar wind Heliophysics: Evolving Solar Activity and the Climates of Space and Earth ed C J Schrijver and G L. Siscoe (Cambridge: Cambridge University Press) pp 217–42

Gosling J T, Skoug R M, McComas D J and Smith C W 2005 Direct evidence for magnetic reconnection in the solar wind near 1 AU J. Geophys. Res. 110 A01107

Gosling J T, Teh W L and Eriksson S 2010 A torsional Alfvén wave embedded within a small magnetic flux rope in the solar wind Astrophys. J. Lett. 719 L36

Hasegawa H, Sonnerup B U O, Owen C J, Klecker B, Paschmann G, Balogh A and Réme H 2006 The structure of flux transfer events recovered from Cluster data Ann. Geophys. 24 603

Hau L N and Sonnerup B U O 1999 Two-dimensional coherent structures in the magnetopause: recovery of static equilibria from single-spacecraft data J. Geophys. Res. 104 6899

Hietala H, Eastwood J P and Isavnin A 2013 Sequentially released tilted flux ropes in the Earth’s magnetotail Plasma Phys. Control. Fusion submitted

Hu Q and Sonnerup B U O 2001 Reconstruction of magnetic flux ropes in the solar wind Geophys. Res. Lett. 28 467

Krimhahadi H, Krauss-Varban D, Omidi N and Vu H X 1999 Magnetic structure of the reconnection layer and core field generation in plasmoids J. Geophys. Res. 104 12313–26

Kunow H, Crooker N U, Linker J A, Schwenn R and von Steiger R 2006 Foreword Space Sci. Rev. 123 1

Lapenta G, Markidis S, Divin A, Goldman M and Newman D 2010 Scales of guide field reconnection at the hydrogen mass ratio Phys. Plasmas 17 082106

Lapenta G, Markidis S, Divin A, Goldman M V and Newman D L 2010 Bipolar electric field signatures of reconnection separatrices for a hydrogen plasma at realistic guide fields Geophys. Res. Lett. 38 L17104

Lepping R P et al. 1995 The WIND magnetic field investigation Space Sci. Rev. 71 207

Lin R P et al. 1995 A three-dimensional plasma and energetic particle investigation for the Wind spacecraft Space Sci. Rev. 71 125

Mandrini C H, Pohjolainen S, Dasso S, Green L M, Démoïn L P, van Driel-Gesztelyi L, Copperwheat C and Foley C 2005 Interplanetary flux rope ejected from an x-ray bright point: the smallest magnetic cloud source-region ever observed Astron. Astrophys. 434 725

Markidis S et al. 2012 Collisionless magnetic reconnection in a plasmoid chain Nonlinear Process. Geophys. 19 145

McFadden J P, Carlson C W, Larson D, Ludlam M, Abiad R, Elliott B, Turin P, Marckwordt M and Angelopoulos V 2008 The THEMIS ESA plasma instrument and in-flight calibration Space Sci. Rev. 141 277

Moldwin M B, Phillips J L, Gosling J T, Scime E E, McComas D J, Bame S J, Balogh A and Forsyth R J 1995 Ulysses observation of a noncoronal mass ejection flux rope: evidence of interplanetary magnetic reconnection J. Geophys. Res. 100 19903

Moldwin M B, Ford S, Lepping R, Slavin J and Szabo A 2000 Small-scale magnetic flux ropes in the solar wind Geophys. Res. Lett. 27 57

Paschmann G et al. 1986 The magnetopause for large magnetic shear: AMPTE/IRM observations J. Geophys. Res. 91 11099

Russell C T and Elphic R C 1979 ISEE observations of flux transfer events at the dayside magnetopause Geophys. Res. Lett. 6 33

Shay M A, Drake J F, Eastwood J P and Phan T D 2011 Super-Alfvénic propagation of substorm reconnection signatures and Poynting flux Phys. Rev. Lett. 107 065001

Sonnerup B U O 1979 Magnetic field reconnection Solar System Plasma Physics vol 3, ed C F Kennel, L J Landerotti, E N Parker (Amsterdam: North-Holland) pp 45–108

Sonnerup B U O and Guo M 1996 Magnetopause transects Geophys. Res. Lett. 23 3679

Sonnerup U O and Scheible M 1998 Minimum and maximum variance analysis Analysis Methods for Multi-Spacecraft Data (ISSI Scientific Report Series SR-001) ed G Paschmann and P W Daly (Noordwijk, The Netherlands: European Space Agency Publications Division) pp 185–220

Teh W L, Nakamura R, Fujimoto M, Kronberg E A, Fazakerley A N, Daly P W and Baumjohann W 2013 Electron dynamics in the reconnection ion diffusion region J. Geophys. Res. 117 A12225

Terasawa T 1983 Hall current effect on tearing mode instability Geophys. Res. Lett. 10 475

Tian H, Yao S, Zong Q, He J and Y Q 2010 Signatures of magnetic reconnection at boundaries of interplanetary small-scale magnetic flux ropes Astrophys. J. 720 454

Trávníček P, Hellinger P, Schriver D and Bale S D 2005 Structure of the lunar wake: two-dimensional global hybrid simulations Geophys. Res. Lett. 32 L06102

Tu C Y, Marsch E, Ivory K and Schwenn R 1997 Pressure enhancement associated with meridional flow in high-speed solar wind: possible evidence for an interplanetary magnetic flux rope Ann. Geophys. 15 137

Zurbuchen T H and Richardson I G 2006 In situ solar wind and magnetic field signatures of interplanetary coronal mass ejections Space Sci. Rev. 123 31