Exhaust structures during magnetopause reconnection: Enabling inference of proximity to the X-line.

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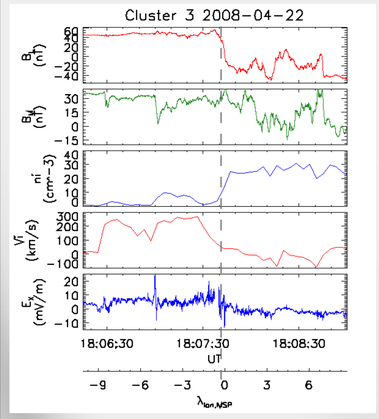
Abstract

In-situ observations of asymmetric reconnection at Earth's magnetopause have shown that the transition in density (n), the reconnecting component of the magnetic field (B_L), the normal component of the electric field (E_N), and the outflow jet (V_L) often occur at different locations when spacecraft travel from the magnetosphere to the magnetosheath. In this study, we use data from the Cluster spacecraft along with 2D and 3D particle-in-cell simulations to illustrate that the relative displacements between the transitions are mainly due to exhaust crossings at different proximities to the X-line. In the 2D simulation, n, B_L, and E_N transitions occur together only within 5 electron skin depths of the X-line and ion flow is earthward of the density gradient. In the 3D simulation, transitions occur together within the thin electron current layer, which varies in length along the direction of the main current. Deeper into the exhaust, the transitions separate from one another and break-up in an orderly fashion: n develops a plateau that, farther away, appears as a dip along the magnetosheath separatrix, the B_L transition gets progressively more gradual, E_N develops a broad peak directed toward the low density side, and the peak of V_L occurs between the density gradient and the B_L reversal. Relative offsets of transitions within the exhaust allow the inference of spacecraft proximities to the X-line.

Motivation

- We studied nine previously reported reconnection events to determine the relative offsets between B_L, n, E_N and V_L.
- The density gradient can be coincident with the B_L reversal or removed from it by 125 $\lambda_{i,MSP}$
- Peak V_L can occur from the B_L reversal to 2 $\lambda_{i,MSP}$ earthward of the density gradient
- The location of the DC **E**-field reversal depends on VL while the Hall **E** field can occur on either side of the density gradient.
- Different offsets are attributed to exhaust crossings at different proximities to the X-line.

Observations: Case 1



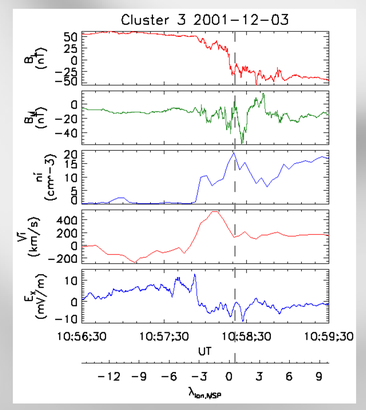
Exhaust Crossing in Close Proximity to the X-Line

- B_L reversal is steep and narrow (< $2\lambda_{i,MSP}$)
- Density gradient is coincident with B_L reversal
- DC electric field switches sign with B_L
- Ion jet is earthward of the density gradient

Notable Features

- E_N points sunward in the upstream region where the ion jet is located.
- Guide field points to dusk.

Observations: Case 2



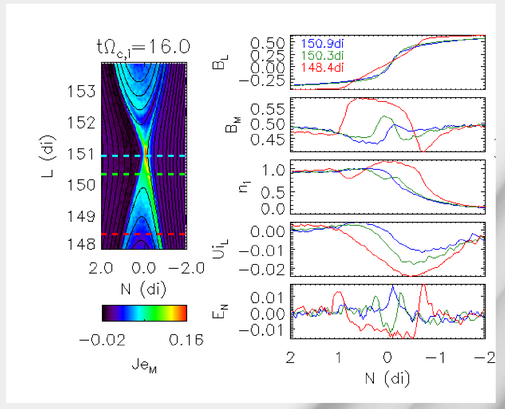
Exhaust Crossing Deeper Into Exhaust

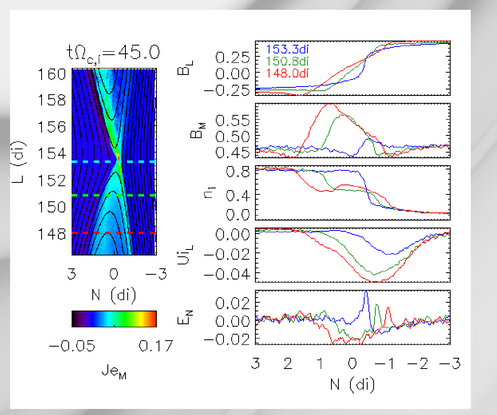
- B_L reversal is gradual and wide (~ $6\lambda_{i,MSP}$)
- Density gradient is removed from B_L = 0
- DC electric field reversal is also offset from B_L=0
- Ion jet occurs within the exhaust, between the density gradient and B_L reversal

Notable Features

- E_N is negative in the region of the ion jet
- Guide field is points to dawn

2D PIC Simulation





Spatial Evolution

- **Near the X-Line** (blue trace):
  - B_L, n, and E_N transition together and ion outflow is observed earthward of the density gradient, similar to Case 1.
  - Transitions occur together only within |N| < 5 d_i of the X-line
- **Downstream of the X-line**:
  - B_L reversal is more gradual and BM is more unipolar
  - A density dip forms along the length of the separatrix (red) with a peak above ambient MSH densities developing within the exhaust
  - Where the width of the density dip is comparable to the distance between separatrices, a plateau is observed (green)
  - Outflow crosses the separatrix and enters the exhaust
  - The negative **E** field in the upstream region (blue) tracks with the ion jet into the exhaust (green, red), broadening and intensifying with the jet.

Temporal Evolution

- Transition are still localized to within |N| < 5d_i of the X-line
- B_L steepens near the X-line. BM is strongly unipolar.
- Density dip broadens (red), plateau extends downstream (green)
- Same general trends as for $t\Omega_{c,i}$=16.

Comparisons to Observations

- Simulations and Case 1 depict opposing signs for the E_N peak upstream from the X-line.
  - The sign difference is due to opposite outflow directions (Cluster crosses the northern exhaust, but simulation cuts are across the southern exhaust).
- The guide field is dawnward for Case 2 and consequently the convective electric field is negative, indicating a guide-field dependence on E_N.
- Outflow is seen directly upstream from the X-line and is caused by ExB drift due to non-zero E_N and B_M there.

Conclusions

- Our results allow us to infer proximity to the X-line for any asymmetric reconnection exhaust crossing.
- Transitions of B_L, n, and E_N occur together only within the thin electron current layer surrounding the X-line, while the peak ion outflow is observed earthward of the density gradient.
- The ion jet, guide field, and normal electric field play an essential role in shaping the exhaust structure.

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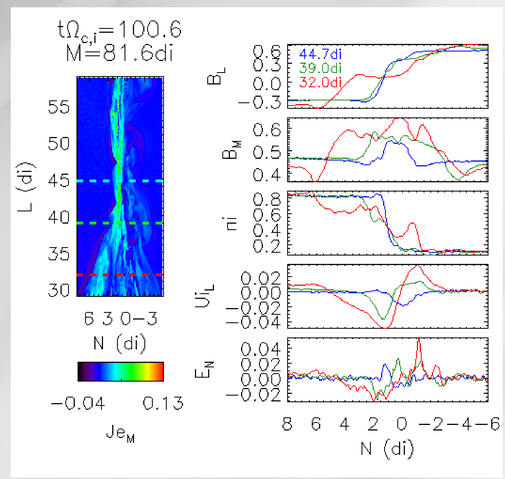
3D PIC Simulation



- Similar to 2D and Cluster observations, B_L, n, and E_N transition together only within the thin current layer surrounding the X-line and ion outflow is observed earthward of the density gradient
  - Thickness and length of the current sheet can vary in the M-direction.
  - Regions over which transition occur together vary with the size of the current sheet.
- Despite magnetic turbulence and flux ropes present in 3D, the basic reconnection structure agrees with 2D PIC and in-situ observations.