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The changing topology of the duskside magnetopause boundary layer in relation to IMF orientation

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Abstract

On 7 December 2000, Cluster made an extended outbound radial traversal of the duskside magnetopause boundary layer. The long duration of the crossing, during which Cluster spent several hours within $2R_E$ of the nominal magnetopause, allows us to deconvolve the structure of this boundary layer in its dependence on interplanetary parameters. We present evidence that as the interplanetary magnetic field (IMF) changed in discontinuous jumps from southward to northward, the magnetic topology of the boundary layer evolved from open to closed. Reconnection signatures, including enhanced flows observed locally at Cluster and ion energy dispersion signatures observed by FAST near Cluster's magnetic footpoint, appeared while the IMF was southward. When the IMF turned nearly due northward, Cluster observed 75-s (Pc 4) oscillations which we attribute to the Kelvin–Helmholtz instability.

Keywords: Boundary layers; Solar wind–magnetosphere coupling; Multispacecraft measurements; Reconnection; Kelvin–Helmholtz instability

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1. Introduction

The boundary layer (BL) at the magnetopause is the interface between plasmas of magnetospheric and solar wind origin. This interface can be driven by reconnection, implying an open BL, or by viscous interactions such as the Kelvin–Helmholtz (KH) instability, which implies a closed BL. It has been a matter of ongoing debate to decide when the BL is open, when it is closed, and what processes of mass, energy and momentum transfer take place in the two cases.

Because the characteristics of the BL depend strongly on IMF and solar wind conditions, it is useful to examine the BL under changing interplanetary conditions. This is, however, a difficult undertaking because it requires that a traversal of the boundary layer last long enough to encompass these changing conditions. A boundary layer traversal satisfying these conditions

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occurred on 7 December 2000, when the Cluster spacecraft crossed the duskside BL just tailward of the terminator while the magnetopause was expanding slowly outwards. Some aspects of the magnetic field data from the magnetopause crossing on this day were investigated by Kauristie et al. (2001), who concluded that the magnetopause was viscously driven at the time of the crossing.

2. Event geometry; interplanetary conditions

Cluster was outbound at a radial distance 13–16R_E and slightly tailward of the dusk terminator ($X_{\mathrm{GSM}} \approx -2.5R_E$) in the northern hemisphere ($\lambda_{\mathrm{GSM}} = 25\text{–}30°$). Our interpretation of the early part of this crossing is aided by two fortuitous magnetic conjunctions with the FAST satellite. The magnetic footpoints of Cluster and FAST, when mapped to the ionosphere at 100 km altitude, show a close conjunction between the spacecraft at 11:45 UT over northwestern Russia and a more distant one on the following FAST orbit near 14:00 UT, this time over Scandinavia.

Solar wind plasma and magnetic field parameters during the event are shown in Fig. 1. An estimated lag time from ACE to Cluster of 75 ± 5 min is included. During the period of interest (~11:30–16:00 UT) the IMF changed direction from due south to sporadic intervals of due north orientation. This rotation was achieved by a sequence of discontinuous jumps in all components. The solar wind dynamic pressure decreased gradually, prolonging Cluster's stay in the BL to several hours. The position of Cluster with respect to a model magnetosphere (Shue et al., 1998) is shown in Fig. 2. From ~1145 to 1700 UT, Cluster was within $2R_E$ of the model (undisturbed) magnetopause (where quantity $D_r = 0$), crossing at a relative speed of just ~1 km s^{-1}.

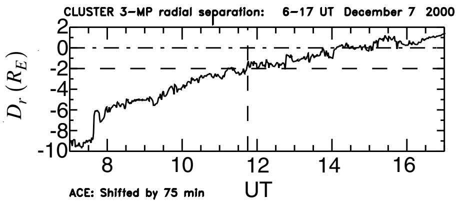

Fig. 2. Radial distance from the Shue et al., 1998 model magnetopause to the Cluster spacecraft. Negative distances mean Cluster is inside the model magnetopause.

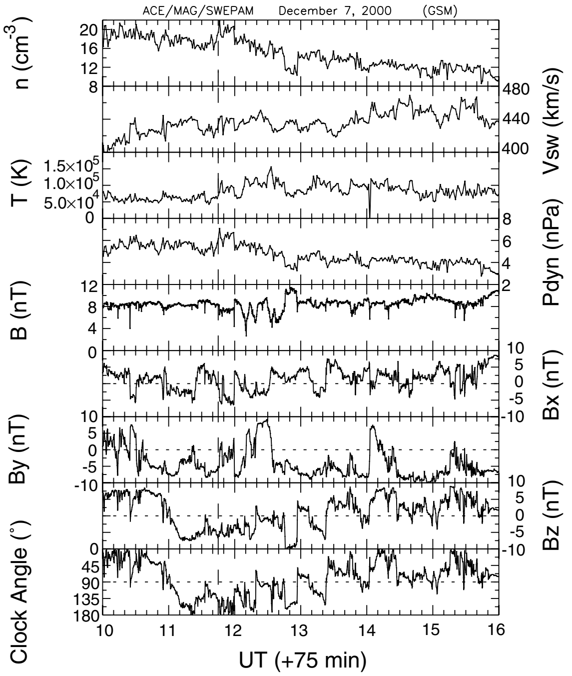

Fig. 1. Interplanetary conditions for this event. From top to bottom the figure shows the proton density, bulk speed, temperature, dynamic pressure, total field and its GSM components, and the IMF clock angle.

3. Cluster and FAST observations

3.1. Southward IMF

Fig. 3 shows Cluster ion spectrometry (CIS) (Rème et al., 1997) and fluxgate magnetometer (FGM) (Balogh et al., 1997) data from Cluster 3 (Samba) during the interval of southward IMF, about 11:30–13:30 UT.

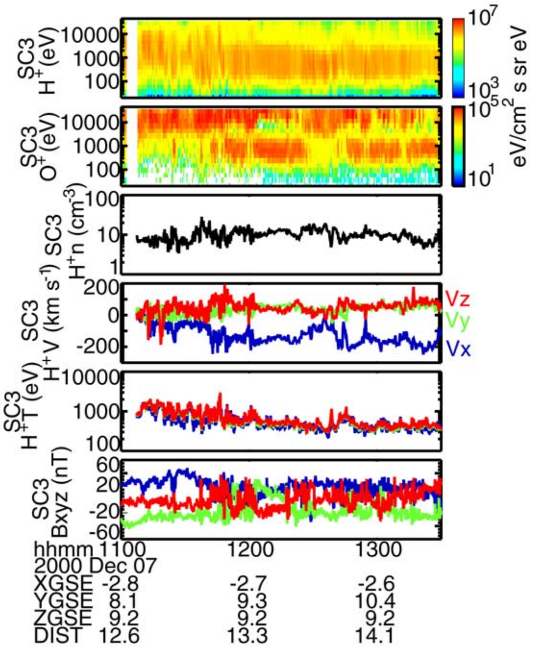

Fig. 3. Cluster 3 CIS and FGM data from the southward IMF portion of the event. From top to bottom: proton and O$^+$ energy spectrograms, proton density, velocity, and temperature, and magnetic field.

The coexistence of plasma populations characteristic of the plasma sheet and of the magnetosheath suggests that Cluster was indeed inside the BL at these times.

Southward IMF favors a reconnection-driven BL, and signatures of reconnection do indeed appear in the data. Fig. 4 shows 12 min of Cluster data around the time of the Cluster–FAST conjunction (arrowed). The signatures indicating that reconnection was occurring are: (i) enhanced flows up to near the local Alfvén speed (dashed line) at 11:42 UT which are directed mainly antisunward ($\Delta v_x < 0$) and northward ($\Delta v_z > 0$); and (ii) rotations in the magnetic field at 11:42 UT when the flow enhancement starts. Note also the heated plasma at the magnetic depression occurring at 11:45:30–11:46:30 UT.

Confirmation that these are indeed reconnection-related processes in the BL comes from FAST (see Carlson et al., 1998, for a description of the mission) where, at a geocentric altitude of ~1.5 R_E, a dispersed ion energy-latitude signature is observed at ~11:45–11:46 UT, as shown in Fig. 5, panel 3. In reality, there are two partially overlapping signatures, the one at higher energy starting later and lasting longer. Comparing with Cluster data, we see that the later injection is that of ions heated at the magnetopause where the field depression occurs.

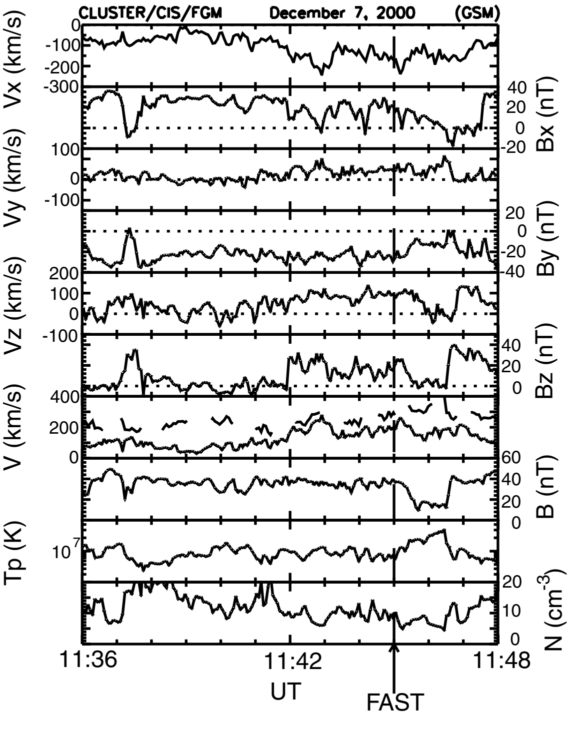

Fig. 4. An expanded view of 12 min of CIS and FGM data. From top to bottom: (pairwise) flow and field components (GSM), the total flow and field, the proton temperature, and the density. The dashed line in the V panel is the local Alfvén speed.

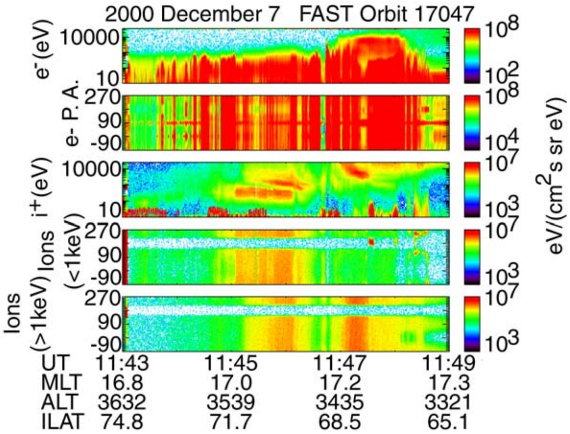

Fig. 5. FAST particle data from the outbound northern passes of orbit 17047, when FAST passed near the same field lines as Cluster. From top to bottom: spectrograms of electron energy, electron pitch angle, ion energy, ion pitch angle (below 1 keV), ion pitch angle (above 1 keV), and mass per charge.

3.2. Northward IMF

We turn now to the later period of northward IMF. Cluster 3 H^+ and O^+ spectrograms for the period 13:50–14:30 UT are shown in Fig. 6. As Cluster approached the magnetopause, two distinct types of oscillations were observed. The first, covering about four cycles of a large-amplitude ~200 s oscillation, makes the whole BL oscillate over the spacecraft. This oscillation will be the subject of a future work. Shortly thereafter, waves with a ~75 s period appeared and persisted for about 15 min. The spacecraft samples alternately the low energy magnetosheath particles and a mixture of low and high energy particles (LLBL). This is a magnetopause surface wave. These waves were detected by all four spacecraft with no significant phase shift, indicating a wavelength much longer than the spacecraft separation of ~1500 km. Taking a phase speed equal to two-thirds the magnetosheath speed, we obtain a wavelength of ~2R_E. The IMF pointed strongly north while these waves occurred, and the

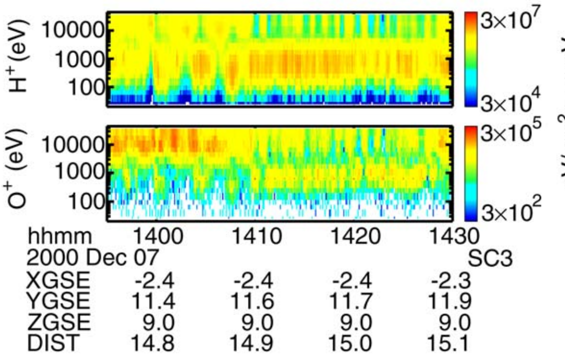

Fig. 6. Cluster 3 CIS H^+ and O^+ energy spectrograms from the period of northward IMF.

waves stopped when the IMF rotated away from due north. These points suggest a Kelvin–Helmholtz (KH) origin, implying a closed LLBL topology at this time.

4. Discussion

In the earlier interval when the IMF was mainly south, there were at two conjugate heights data features widely considered to indicate reconnection. In addition, FAST also showed evidence of an overlapping dispersion which correlated well in time with the plasma heated at a magnetic depression in the LLBL. We suggest the latter to be a slow shock feature making part of a reconnection layer. A reconnection layer structure including both a rotational discontinuity (responsible for the first ion dispersion) and a slow shock (responsible for the second) was presented by Rijnbeek et al. (1989) and by Walthour et al. (1994). Clearly, however, while the data are qualitatively consistent with this idea, its validation requires a quantitative analysis which we present elsewhere.

In the later interval, when the IMF was mainly north, a magnetopause surface wave was observed. We now interpret this waves in terms of an incompressible theory of the KH instability acting at the dayside magnetopause (Farrugia et al., 1998). In that work the IMF was assumed to have a strong northward component and account was taken of the properties of the plasma depletion layer next to the sunward magnetopause which tends to form under such conditions (Phan et al., 1994). This incompressible theory suggested that narrow bands of low shear form at the magnetopause where KH waves are generated. For an IMF pointing north-west (as here), the KH-active strips would lie at dusk in the northern hemisphere and at dawn in the southern hemisphere. Once the waves emerge from these active strips they travel antisunward, rippling the tail magnetopause. This we suggest is the causative mechanism of these waves at Cluster 3. This result is also consistent with earlier work (Kauristie et al., 2001).

To conclude, we have shown a long crossing by Cluster normal to the duskside magnetopause lasting long enough for the IMF to rotate slowly from south to north and for the same LLBL to go from an open to a closed topology. We have presented evidence of a reconnection layer in the first interval and of KH instability in the second.

Acknowledgements

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