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Interaction between reconnection and Kelvin–Helmholtz at the high-latitude magnetopause

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Abstract

On March 23, 2002, Cluster satellites recorded an event, which has been interpreted as reconnection, during an outward crossing near the dawn side cusp region in the Northern Hemisphere. The event showed a large perturbation in the magnetic normal component, inconsistent with a one-dimensional reconnection layer configuration, and causing a poor result in a minimum magnetic variance analysis. The utilization of the plasma velocity or electric field data significantly improves the boundary normal analyses. Through the comparison between observational data and local three-dimensional MHD simulations, it is demonstrated that this perturbation is likely an indication of a strong boundary modulation by a KH wave. The event is used to examine several established and new boundary normal analysis methods.

Keywords: Kelvin–Helmholtz instability; Reconnection; Boundary normal analysis

1. Introduction

It is well accepted that magnetic reconnection plays a critical role in the solar-wind-magnetosphere coupling (Dungey, 1961), which has been often observed at the low-latitude dayside magnetopause for southward interplanetary magnetic field (IMF) conditions (Russell and Elphic, 1978; Sonnerup et al., 1981; Fuselier et al., 2011), as well as at the high-latitude magnetopause for northward IMF condition and dawnward/duskward IMF conditions (Kessel et al., 1996; Zhang et al., 2008). On March 23, 2002, during 11:33 UT and 11:45 UT, Cluster satellites recorded an event with significant plasma acceleration, which has been interpreted as magnetic reconnection, when they traveled from the cusp to the magnetosheath on the dawn side of the Northern Hemisphere (Zhang et al., 2008). The IMF was dominated by the magnetic B_Y component (GSE coordinates); consequently, the boundary normal direction is expected to be mostly along the Z direction. However, this magnetic field component had a large perturbation during the crossing, inconsistent with an approximate one dimensional magnetic reconnection layer configuration. A detailed analysis of this inconsistency is presented in the next section. Noting the presence of a large shear flow between the magnetosheath and the cusp in this event, we hypothesize that this large magnetic perturbation in the normal direction is likely caused by a large amplitude Kelvin–Helmholtz (KH) wave.

There are numerous research efforts focusing on the KH instability at the low latitude magnetopause during the northward IMF period (Miura and Pritchett, 1982; Fairfield et al., 2000; Otto and Fairfield, 2000; Hasegawa et al., 2004). In contrast, high-latitude KH waves have been barely investigated (Hwang et al., 2012; Merkin et al., 2013) and the observational signatures are not well

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explored. This study of the March 23, 2002 event will likely shed more light on the high-latitude KH instability, which, consequently, requires a better understanding of the boundary normal properties for such events. It has been demonstrated by Zhang et al. (2008) that this large magnetic perturbation generates a poor normal direction by the minimum variance analysis using the magnetic field (MVA-B) method (Sonnerup and Cahill, 1967). Therefore, a key question is, which method can provide an acceptable local coordinate system when magnetic reconnection is modulated by KH waves. Such waves are expected not only for the Earth but also for other magnetospheres where plasma data may not be reliable or available at all. Therefore, a second objective of this study is the insight which can be gained by magnetic field analysis alone for these types of events.

Following, we briefly review the event and compare the results from different boundary normal analyses in Section 2. Based on these results, we compare the observational signature with MHD simulation results in Section 3. A further comparison between the different boundary normal analysis methods using the simulation data is presented in Section 4. Section 5 is the discussion and summary.

2. Observational event analysis

In the interest of clarity, we need to introduce three different coordinate systems and their notations. Coordinates denoted by XYZ refer to the Geocentric Solar Ecliptic (GSE) coordinate system. By using lower case xyz coordinates we refer to the simulation coordinate system based on a reconnection configuration. Here the y direction (antiparallel direction) is along the antiparallel/reconnected magnetic field component; the z direction (normal direction) is normal to the boundary/current layer; and the x direction (guide field direction) is perpendicular to the magnetic reconnection plane, which is determined by the right-hand rule. The LMN coordinate system is the result from the boundary normal analysis, in which the L, M, and N directions are, ideally, corresponding to the $y, -x$, and z directions, respectively. Fig. 1 (left) illustrates the local coordinate orientation for the basic configuration of the March 23, 2002 event where we have idealized the location of the event to be at the dusk terminator. In this paper, L is chosen positive along the reconnection magnetic field component on the cusp (lower density) side of the boundary and N is chosen to point outward into the magnetosheath (high density) region. The negative sign in the x direction is due to the right-hand rule.

Fig. 1 (right) presents the 4-s resolution data of plasma density, magnetic field, and plasma velocity from Cluster 1 (1133 UT to 1145 UT, 12 min). The X component of the magnetic field and plasma velocity have been reversed for an easier comparison with the M component from boundary normal analyses. Note that a magnetospheric plasma density of $6\,\mathrm{cm}^{-3}$ as well as negative X and Z magnetospheric magnetic field components imply that the satellite crossed from the dayside instead of the tail lobe. Magnetic reconnection is expected to operate mainly along the Y direction due to the large magnetic shear, in which the magnetic B_Y component varies from 0 nT in the cusp region to -30 nT in the magnetosheath. The plasma jet with $V_Y \approx 100\,\mathrm{km/s}$ in the current layer (from 1137 UT to 1140 UT) is likely caused by magnetic reconnection (Zhang et al., 2008), which implies a negative normal magnetic field component based on the reconnection configuration (see Fig. 1 (left)). However, the magnetic B_Z component significantly increases to about 30 nT in the current layer. Also, the magnetic B_Z component should monotonically increase up to the crossing of the magnetospheric boundary. Thus, this large B_Z perturbation is also inconsistent with the background model magnetic field, indicating a large boundary modulation. Ideally, the magnetopause motion speed is available from the Cluster satellites by fitting multiple crossing timings (Harvey, 1998). However, in this specific case, the separation of four satellites (≈ 100 km) is too small to deduce a reliable velocity of magnetopause motion. Therefore, alternatively, the magnetopause motion speed is estimated by the DeHoffmann–Teller frame speed $V_{\mathrm{HT}} = (-199, 51, 120)\,\mathrm{km/s}$ (de Hoffmann and Teller, 1950) from the least-squares analysis technique developed by Sonnerup et al. (1987) and the respective boundary normal directions.

It is instructive to examine different boundary analysis methods to find a reasonable local coordinate system for further study. The L, M, and N directions in GSE coordinates, and the velocity of the magnetopause motion along the N direction, $v_n = \hat{\mathbf{e}}_N \cdot \mathbf{V}_{\mathrm{HT}}$, are listed in Table 1, and the components of the magnetic field and plasma velocity along these directions are presented in Fig. 2. The MVA-B (Sonnerup and Cahill, 1967) and Siscoe (Siscoe et al., 1968) methods are two traditional boundary normal tools. The basic assumption is that the antiparallel (y) and normal (z) directions are corresponding to the largest and smallest magnetic field variance (MVA-B) or average field amplitude (Siscoe) directions. Zhang et al. (2008) found that the N direction from the MVA-B method is mainly along the $-X$ direction instead of the expected Z direction. Therefore, they believed the MVA-B method interchanges the N and M directions, which is likely due to the large perturbation of the magnetic normal (Z) component. However, even if we interchange the M and N directions; apparently, the large magnitude of the normal velocity (V_M) is also inconsistent with the reconnection configuration, which indicates the MVA method mixes the N and M components. The N direction from the Siscoe method is mainly in the positive Z direction. However, it also has a large component along the magnetosheath flow (X) direction, which leads to an even larger V_N. Besides, there is almost no antiparallel magnetic component in spite of a strong gradient in the magnetic L and M components. The constraint method defines the M direction through the average magnetic field direction and applies the