THEMIS Observations of Boundary Layer Flows During a Storm: Evidence for the Quasi-Stable Storm Reconnection Region.

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Abstract

The Lyon-Feddar-Mobarry (LFM) global MHD code for the magnetosphere develops a quasi-steady reconnection region at about 35-45 R_E in the tail during storms. One of the features of this structure is that it produces a region of fast sunward flow just inside the magnetopause. In this paper we present evidence from THEMIS that such a flow layer does exist during the main phase of at least one storm. The implication is that the LFM solution to magnetospheric convection and magnetotail topology resulting from a strong, steady southward magnetic field in the solar wind may be physically realistic.

Introduction

The solar wind powers the magnetosphere primarily through magnetic reconnection [Dungey 1961]. In the most basic picture, the interplanetary magnetic field (IMF) merges with the Earth's dayside magnetic field, and the interconnected, open flux is transported to the magnetotail. Open flux reconnects at a distant X-line, which for relatively quiet conditions, is located about 100 R_E down the tail [e.g., Kivelson and Russell, 1995]. Newly reconnected closed flux is then transported earthward from the distant neutral line, completing the circulation pattern.

Erickson and Wolf [1980] noted that this picture was not sustainable as a time-independent description of the magnetosphere. Flux tubes that reconnect at the distant neutral line (which they placed at 60 R_E) would have very large flux tube volumes. As they convect earthward, the adiabatic compression of the plasma would produce physically unreasonable plasma pressures in the inner magnetosphere. This "pressure-balance inconsistency" means that steady convection from the distant neutral line is impossible and that some global magnetospheric instability would have to resolve the problem. Later, Hau [1991] showed that steady convection would produce a deep minimum in B_z in the plasma sheet that could produce a near-Earth reconnection region.

The development of a near-Earth reconnection region in response to enhanced convection driven by a southward IMF has long been postulated as an essential feature of substorms [e.g., Hones, 1984]. In the neutral line model of substorms, the near-Earth neutral line initially begins in the central plasma sheet, reconnecting closed field lines. It releases a plasmoid when it begins to reconnect lobe field lines, at which point the near-Earth substorm reconnection region retreats tailward, becoming the new distant neutral line [e.g., Hones, 1984; Baker et al., 1996]. One of the features of the substorm neutral line is that it generates bursts of flow, and these highly temporally limited flow bursts in the central plasma sheet are a major signature of substorm activity [Angelopoulos et al., 1992; Lopez et al., 1994]. From the point of view of global convection, the substorm is the global instability that solves the pressure-balance inconsistency by removing part of the earthward convecting flux tubes through reconnection.

While a substorm is a global response to a transient increase in dayside merging, a sustained southward IMF produces a different response known as a magnetic storm [e.g., Gonzalez et al., 1994]. The solar wind conditions that produce magnetic storms can include many hours of large southward IMF that produces strong magnetospheric convection. The same analysis regarding the pressure balance inconsistency applies for storms as well. Steady convection during a magnetic storm is impossible given a distant neutral line at 60 R_E or beyond. So how does the magnetosphere resolve the problem? Does it do it through a substorm process or by some other mechanism?

<u>MHD Storm and Substorm Simulations</u>

The Lyon-Fedder-Mobarry global MHD code [Lyon et al., 2004] has been used to simulate a number of storms [Goodrich et al., Lopez et al., 2000] and substorms [Lyon et al., 1998; Wiltberger et al., 2000]. These simulations have been shown to reproduce substorm observations quite well [Lopez et al., 2001], including features such as the bursty bulk flows [e.g., Wiltberger et al., 2000], and the loading and unloading of the polar cap flux [Lyon et al., 1998]. However, the storm simulations develop a particular and unexpected feature, as reported by Lopez et al. [2000]. After the initial substorm at the beginning of the main phase, the reconnection region in the tail does not retreat tailward as it does in the substorm simulations. Instead, it sits in the mid-tail, around 35 R_E to 45 R_E, reconnecting newly merged flux as it is transported to the tail. The polar cap flux does not change by very much, indicating that there is a rough balance between dayside merging and nightside reconnection and that there is quasi-steady convection in the magnetosphere. In fact, Lopez et al. [2004] pointed out that if in reality the sequence of loading and unloading of the polar cap flux disappears during the main phase of storms, the notion of a "storm-time substorm" is problematic if one views the storage and release of magnetotail energy to be a fundamental aspect of substorms.

So how does this behavior fit into the theoretical result of Erickson and Wolf [1980] that steady magnetospheric convection is impossible? That earlier result was predicated on convection beginning at a distant neutral line, but if the "distant" neutral line is not so distant, as occurs in the storm simulations, then the compression of earthward convecting flux tubes (and the plasma) will be much less, and quasi-steady steady convection might be able to occur. But is there any evidence that this state of affairs actually takes place during storms? Lopez et al. [2003] presented observations from IMP-8, Geotail, and Interball that suggested that during the main phase of storms there is a reconnection region in the 30 RE region that can sit there for a couple of hours at a time. However, the results were circumstantial since there were only magnetic field data available for the handful of cases found, so there are no direct observations of tailward flow at the same time as the negative B_z observations.

There is another feature of the storm-time reconnection region that can be tested with observations. Goodrich et al. [2007] noted that during storm times the LFM simulations develop a curious flow pattern, with the creation of high-speed sunward flow channels along the flanks of the magnetosphere. This flow transports newly closed flux from the storm-time reconnection region to the merging region on the dayside, establishing a quasi-steady magnetospheric circulation. These storm-time flows are distinct from the magnetotail flow bursts produced by LFM during substorm simulations [e.g., Wiltberger et al., 2000]. The substorm simulation flow channels are temporally limited and not confined to the flanks of the magnetosphere, and appear to have properties [Wiltberger et al., 2000] much like the flows observed during real substorms [Angelopoulos et al., 1992; Lopez et al., 1994].

An example of flows in the LFM simulation during storm-time driving (B_z=-10 nT, with V=400 km/s and n=5 cm^{-3}) is presented in Figure 1. One can clearly see the high-speed sunward flow channels along the inner boundary of the magnetopause, which is marked by the black line. Such a structure should be observable during the main phase of a storm if a satellite spends time in the region just inside the flank magnetopause. It is precisely the existence of such flows during one storm that we document in the following section.

Observations of the Storm of November 20, 2007.

On the morning of November 20, 2007, a moderate storm began, as can be seen in Figure 2. The main phase began just after 0900 UT, and the buildup of the ring current (as indicated by Dst) was at its most intense until 1400 UT. This is the period that we would expect to be characterized by a strong, steady southward IMF. At this time the THEMIS spacecraft [Angelopoulos, 2008] were outbound, with apogee near the dawn terminator. Unfortunately, the regular suite of solar wind monitors did not provide data during this interval, however THEMIS B was in the solar wind about 30 R_E away from Earth on the dawn flank. From 0930 UT until 1230 UT, THEMIS B (data not shown) observed a fairly steady B_z (in GSM coordinates) of about -15 nT, consistent with the development of the storm. Unfortunately, only magnetometer data [Auster et al., 2008] from THEMIS B are available because THEMIS B was deploying a boom at the time and the plasma instruments were turned off.

Figure 3 shows plasma data [McFadden et al., 2008] from the THEMIS E satellite, which was outbound near the dawn terminator at (-3.9, 9.7, -3.5) R_E in GSE coordinates at 1000 UT. The data show an encounter with large fluxes of low energy (magnetosheath) ions and electrons from 1030 UT to 1215 UT. However, except for a brief period right around 1100 UT, there was not a complete dropout of the high-energy (magnetospheric) component of the plasma. Instead there was a mix of high energy and low energy plasma on magnetospheric (northward) field lines, which is characteristic of the low latitude boundary layer (LLBL). Also, the magnetic field became very noisy, turning southward right around 1100 UT until about 1120 UT. This indicates that THEMIS E was just inside the magnetopause in the LLBL for much of the time from 1030 UT to 1130 UT, except from 1100 UT to 1120 UT, when it was in the magnetosheath. This places THEMIS E in the right place at the right time to test the predictions of the LFM storm simulations.

When THEMIS E was in the magnetosheath the flow was strongly antisunward, as one would expect. However, on the earthward side of magnetopause, in the LBLL, there were significant episodes of fast (≥200 km/s) sunward flow. We see these flows just before 1100 UT, and just after 1130 UT, when THEMIS E reentered the magnetosphere. Moreover, these flows were long-lived (10-15 min) compared to substorm flows (about 2 min), therefore they are not likely to be substorm-related. Later in the day, just before 1300 UT, there was a sharp and extended transition to magnetosheath plasma, suggesting a sudden earthward motion of the magnetopause, with THEMIS E spending very little time in the LLBL. In this case, there was only a very brief episode of sunward flow as THEMIS E rapidly passed through the LLBL. Later at 1600 UT, and again at 1630 UT, there were fast sunward flows coincident with the appearance of plasma and magnetic field characteristic of the LLBL. THEMIS D (data not shown) recorded a similar pattern. When the plasma data indicated the satellite was in the LLBL, fast sunward flows, some lasting much longer than typical substorm bursty bulk flows, were generally observed.

Conclusion

The LFM global MHD code produces a quasi-steady, mid-tail (35-45 R_E) magnetotail reconnection region during the main phase of a magnetic storm that roughly balances the rate of dayside merging. This reconnection region exists close enough to the Earth to allow a quasi-steady convection pattern to be established. However, observational confirmation of this structure in the magnetotail has been difficult. A distinctive feature of this state of the magnetotail is the existence of a thin region of sunward flow just inside the magnetosphere. Observations from THEMIS support the existence of this feature. We therefore conclude that LFM simulation results might well be representing reality during storms and that it is likely that a quasi-steady storm-time neutral line does exist in the magnetotail.

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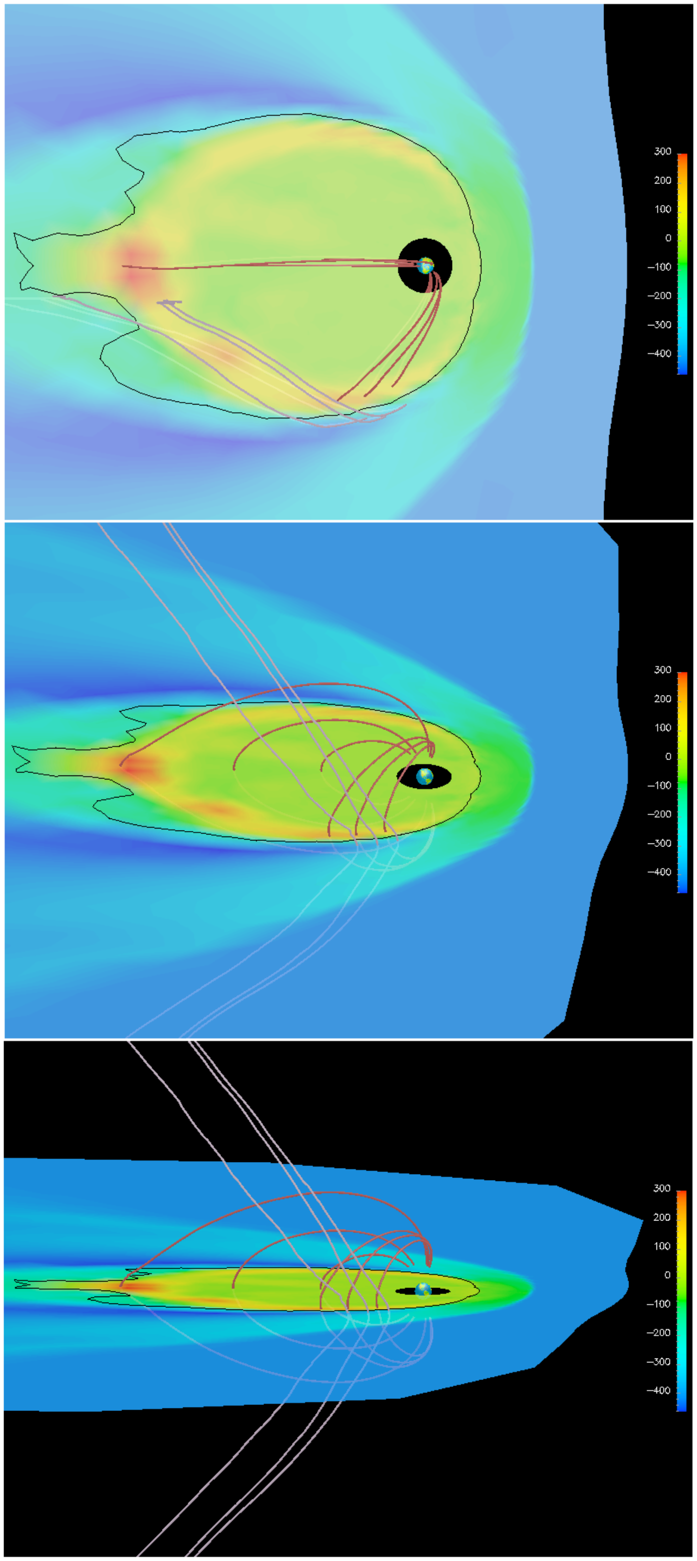

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Figure 1. LFM simulation results under steady driving. The color-coded velocity in the equatorial plane is presented from three perspectives with the B_z=0 contour in black. The red field lines are magnetospheric, while the white ones are magnetosheath field lines.

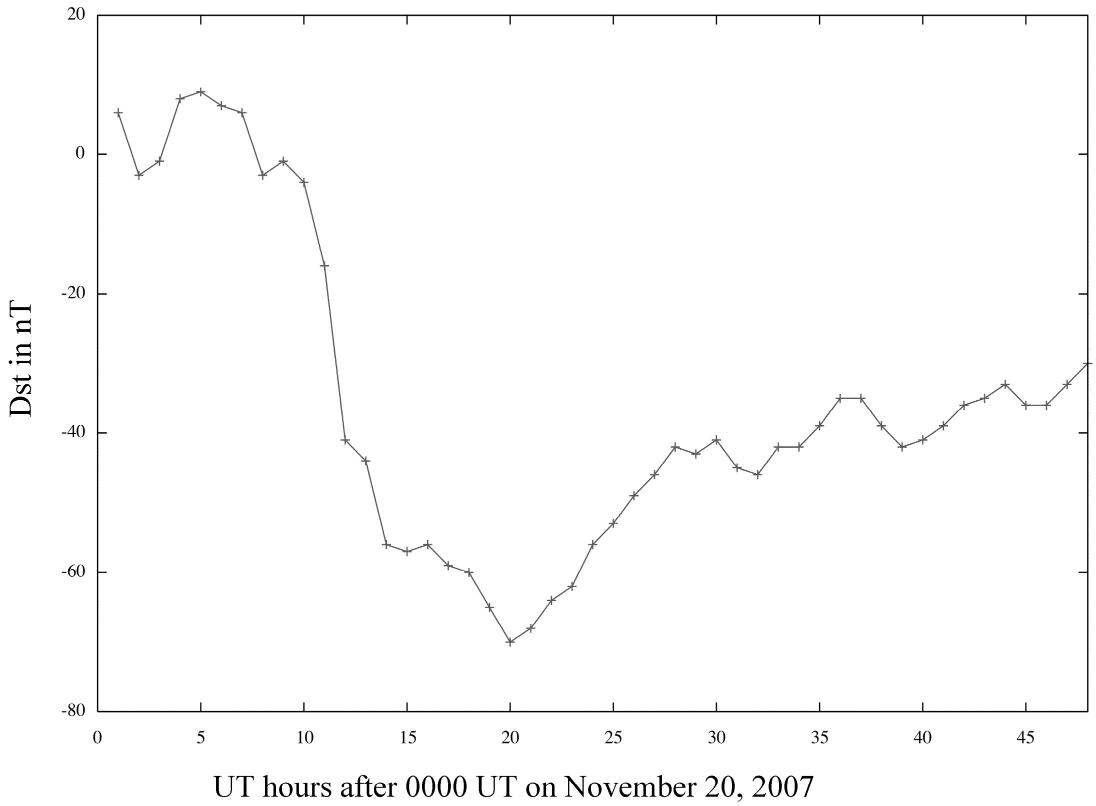

Figure 2. Provisional Dst for the storm of November 20, 2007

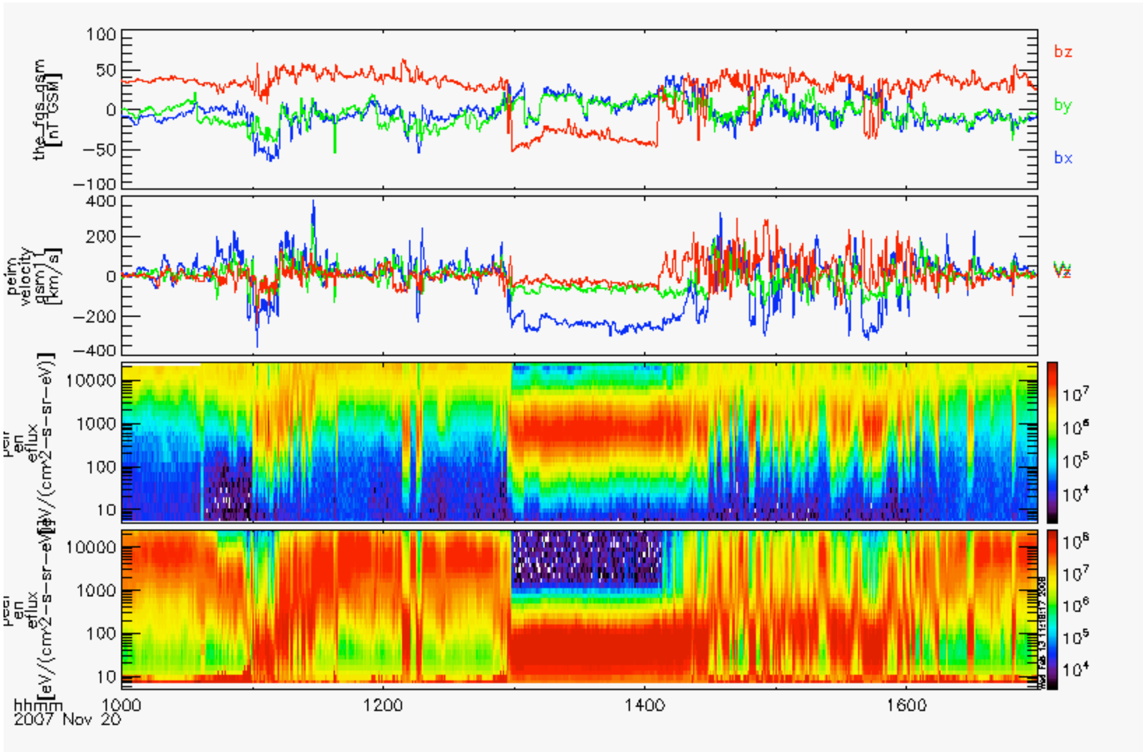

Figure 3. Magnetometer and plasma data from THEMIS E from 1000 UT to 1700 UT on November 20, 2007. Electron flux is on the bottom panel and ion flux is on the panel above. The V_x is in blue in the second panel from the top, and sunward flow is positive.