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Flux transfer events: Motion and signatures

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ABSTRACT

We present results from a 2.5 dimensional hybrid code simulation for the evolution of flux transfer events (FTEs) during intervals of due southward interplanetary magnetic field (IMF) orientation. The structures invariably form between pairs of reconnection lines, often remaining nearly stationary on the subsolar magnetopause before their motion begins. Although a few structures move sunward, ultimately coalescing with others, most eventually accelerate antisunward, reaching velocities many times greater than the sound speed in the magnetosheath but only about one Alfvén speed greater than the ambient magnetosheath flow. At these velocities, slow mode wakes (but not shocks) marked by density enhancements and magnetic field strength decreases extend outward from the structures into the magnetosheath. Upon encountering the cusps, the structures decelerate, undergo reconnection, and are destroyed.

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1. Introduction

Transient (~1–2 min) events are common in the immediate vicinity of the Earth's dayside magnetopause. Those exhibiting magnetic field strength enhancements and symmetric bipolar magnetic field signatures normal to the nominal magnetopause are termed flux transfer events or FTEs (Russell and Elphic, 1978). However, FTEs can also display depressed or crater-like magnetic field strength variations (Labelle et al., 1987) and/or asymmetric bipolar magnetic field signatures normal to the nominal magnetopause (Fear et al., 2010). Because they tend to occur for southward interplanetary magnetic field orientations and strongly sheared magnetosheath and magnetospheric magnetic field configurations (Berchem and Russell, 1984; Rijnbeek et al., 1984) and frequently exhibit accelerated mixtures of streaming magnetosheath and magnetospheric plasmas with densities intermediate between those of either region (Paschmann et al., 1982; Daly et al., 1984), FTEs observed near local noon are generally interpreted in terms of bursty reconnection. If FTEs contribute significantly to (Lockwood et al., 1990) or dominate (Lockwood et al., 1995) the overall solar wind–magnetosphere interaction, then studies of FTEs may tell us much about when, where, and how reconnection occurs as a function of solar wind conditions.

For example, case and statistical studies of observed (Korotova et al., 2009), calculated (Dunlop et al., 2005), or inferred (Rijnbeek et al., 1984; Berchem and Russell, 1984) structure velocities can reveal the location(s) of the reconnection line. In the absence of readily available high spatial and temporal resolution results from global numerical simulations, several researchers have used the analytical Cooling et al. (2001) model for the motion of reconnected magnetosheath and magnetospheric magnetic field lines to demonstrate that the locations where FTEs are observed are consistent with their formation along postulated subsolar reconnection lines (e.g., Dunlop et al., 2005; Fear et al., 2005; Wild et al., 2005, 2007). In this model, FTEs move at the sum of the local magnetosheath plasma and Alfvén velocities throughout their existence, i.e. they always move at the Alfvén velocity through the ambient magnetosheath flow. The model predicts structure speeds within a factor of 2 and directions to within 30° of those inferred from multispacecraft timing in 78% of cases in which structure dimensions exceed 5000 km (Fear et al., 2007).

The speed at which structures move through the ambient media is also an important factor in determining the signatures that they produce. Farrugia et al. (1988) showed that an extended cylinder moving through an incompressible magnetohydrodynamic plasma generates transient magnetic field strength enhancements and bipolar magnetic field signatures normal to the nominal magnetopause, as frequently observed. However, when Mach numbers approach or exceed unity compressible solutions must be employed. Fig. 1 illustrates the solution regimes predicted for a cylindrical structure moving through a compressible plasma when the ambient magnetic field lies perpendicular to the structure axis (Sonnerup et al., 1992). Supersonic and superAlfvénic structures generate fast mode shocks marked by magnetic field strength and density enhancements, while subsonic and subAlfvénic structures

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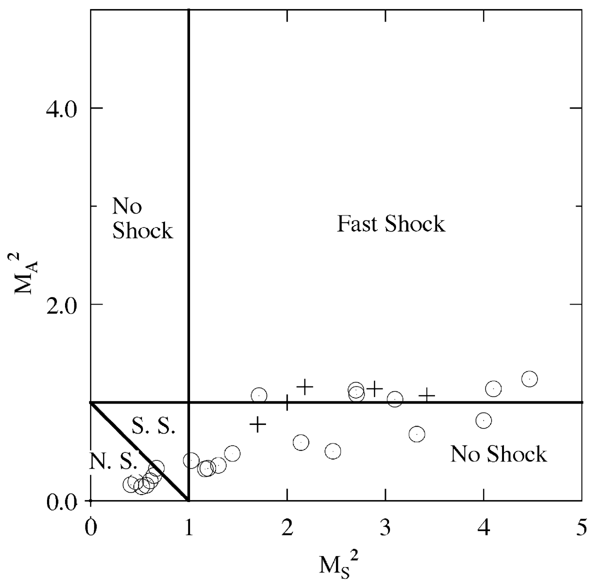

Fig. 1. Shock regimes predicted for single-adiabatic field-aligned flows as a function of the Alfvénic and sonic Mach numbers (Sonnerup et al., 1992). N. S. indicates no shock, while S. S. indicates slow shock. Circles indicate Mach numbers for the relative motion of the largest FTE in the simulation through the ambient magnetosheath plasma. Crosses indicate Mach numbers at the times when other structures generated notable density enhancements in the magnetosheath. As predicted by the Cooling et al. (2001) model, the structures eventually move through the magnetosheath at the Alfvén velocity ($M_A^2 \sim 1$).

moving faster than the slow mode speed generate slow mode shocks marked by density enhancements but magnetic field strength decreases. Structures moving at velocities much slower than the slow mode velocity, superAlfvénic but subsonic velocities, or supersonic but subAlfvénic velocities generate magnetic field strength and density perturbations, but no shocks.

When the sum of the pressure gradient and magnetic curvature forces acting upon structures is finite, they accelerate. With the advent of multispacecraft missions, it has become possible to calculate this rate of acceleration. Fear et al. (2009) demonstrated that the rate of acceleration was negligible in a case study of multipoint THEMIS observations near the flanks of the magnetosphere.

As space plasma physics transitions towards an environment in which results from global simulations based on first-principle physics become increasingly available, there is a need to compare the predictions of numerical simulations with those of the analytical models. Omidi and Sibeck (2007) presented results from a 2.5 dimensional global hybrid code simulation for the interaction of the solar wind with the magnetosphere indicating the frequent occurrence of FTEs on the dayside magnetopause. They identified one large structure that generated a slow mode bow wave as it accelerated towards the northern cusp and reached a speed approaching one Alfvén velocity faster than the ambient magnetosheath flow. This paper presents more detailed observations of the same structure and examines the predictions of the hybrid code model for more structures in the same run, addressing the locations where they are generated, their velocity and acceleration, and the slow mode bow waves that they generate. It places the new simulation results within the context of previously reported observations, simulations, and theoretical models.

2. Model

We examine output from the model originally presented by Omidi and Sibeck (2007). Solar wind plasmas and electromagnetic fields enter the noon–midnight meridional plane domain of the model through its dayside boundary and exit freely through the three remaining boundaries. As noted by Omidi and Sibeck (2007), the ratio of the standoff distance of the magnetopause to the proton skin depth in the solar wind is $\sim$85, resulting in a magnetosphere 7.5 times smaller than that of the Earth. Nevertheless, the resulting magnetosphere has characteristics similar to that of Earth's. The simulation retains all three components of the electromagnetic fields and plasma flows, the solar wind Mach number is set to 5, ion and electron betas are set to 0.5, resistivity is spatially uniform, and the IMF points due southward. Given the 2.5D nature of the model, simulation results are appropriate to studies of flux transfer events with the large dawn/dusk extents expected during intervals of strongly southward IMF orientation moving northward or southward along the noon meridian in response to combined pressure gradient and magnetic curvature forces (e.g., Fedder et al., 2002; Pinnock et al., 2003; Raeder, 2006).

Results from the simulation are presented in the *X*–*Y* coordinate system, where *X* points antisunward and *Y* points northward. The Earth lies at $(X, Y)=(450, 500)$. Distances are measured in units of ion skin depth or c/ω_{pi}, where ω_{pi} is the ion plasma frequency. For a solar wind density of 6 cm^{-3}, 1 $c/\omega_{pi}=93$ km. Time is measured in units of Ω_i^{-1}, where Ω_i is the ion gyrofrequency. For an IMF strength of 5 nT, Ω_i^{-1} is $\sim$2 s. We set $\Omega_i^{-1}=0$ at the time when the first FTE appears, which corresponds to $\Omega_i^{-1}=122.25$ in the paper of Omidi and Sibeck (2007). Velocities are measured in units of the solar wind Alfvén speed, V_A. For a southward-pointing IMF strength of 5 nT, $V_A=41$ km s^{-1}. Cell sizes in the simulation are 1 c/ω_{pi}, resistive scale lengths are 0.3 c/ω_{pi}. Densities and magnetic field strengths presented in this paper are normalized to solar wind values.

3. Simulation results

Figs. 2 and 3 present snapshots of densities, magnetic field strengths, and magnetic field directions at three times late in the simulation run: $\Omega_i^{-1}=67.95$, 72.6, and 79.35. The dayside magnetosphere is readily identifiable as a region of extremely low (0.05) normalized densities and high (>12) normalized magnetic field strengths. Dayside magnetospheric magnetic fields point northward ($+Y$). By comparison, magnetosheath densities are much higher ($\sim$3) and magnetic field strengths are much lower ($\sim$4). Dayside magnetosheath magnetic fields point southward. Mantle and lobe densities lie between those in the magnetosheath and dayside magnetosphere, ranging from 0.5 to 3. Mantle and lobe magnetic field strengths are also intermediate, ranging from 4 to 16. Mantle and lobe magnetic fields have strong southward components.

As noted by Omidi and Sibeck (2007), the most prominent transient feature in the simulation is the large FTE that moves northward along the magnetopause from a position near $(X, Y)=(375, 544)$ at $\Omega_i^{-1}=67.95$ to $(X, Y)=(407, 574)$ at $\Omega_i^{-1}=79.35$. Depressed ($\sim$2) densities, enhanced ($\sim$8) magnetic field strengths, and a closed loop structure bound the enhanced ($\sim$6) densities and depressed ($\sim$1) magnetic field strengths within the core region of this crater FTE. As the FTE moves away from its point of origin near the subsolar magnetopause, it generates a slow mode bow wave marked by enhanced densities and depressed magnetic field strengths. By $\Omega_i^{-1}=67.95$, a region of enhanced densities (and slightly depressed magnetic field strengths) stretches outward from the magnetopause and preceeds the arrival of the FTE. The density enhancement increases with time, becoming more prominent at $\Omega_i^{-1}=72.6$, and stretching outward into the magnetosheath from (rather than preceding)