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Draping of strongly flow-aligned interplanetary magnetic field about the magnetopause

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Abstract

Many dynamic processes of the magnetosphere are directly driven by the solar wind and the occurrence of magnetic merging at the magnetopause. The location of magnetopause magnetic merging, or reconnection, is now fairly well understood when the interplanetary magnetic field (IMF) contains large B_y and B_z components in relation to the B_x component (in Geocentric Solar Magnetospheric (GSM) coordinates). However, when the IMF contains a large *X*-component (i.e., is closely flow-aligned), it is not yet well understood how the shocked IMF drapes about the magnetopause, and how this affects the occurrence and location of magnetic merging. In this initial study, we examine from observations how a nearly flow-aligned IMF drapes about the magnetopause. The results of this study are expected to be useful for comparisons with both analytic and global numerical models of the magnetosheath magnetic field.

Keywords: Magnetosheath; Magnetopause; IMF draping

1. Introduction

The location of magnetic reconnection at the dayside magnetopause is now fairly well understood when the interplanetary magnetic field (IMF) contains large B_y and B_z GSM-components in relation to the B_x component (e.g., Trattner et al., 2007, 2012; Trenchi et al., 2008; Fuselier et al., 2011). However, it is not well understood where reconnection occurs when a relatively large IMF B_x component exists (also described in the literature as a nearly radial IMF, as it is closely oriented along a direction that intersects the center of the Sun). This is because there is poor understanding of how the magnetic field drapes about the magnetosphere for an IMF with a dominant *x*-component. Therefore, in order to improve understanding of where magnetic reconnection at the magnetopause is likely to occur, it is important to understand IMF draping under all solar wind conditions. For example, for strongly solar wind flow-aligned IMF configurations, it is easy to envision that a draped IMF may be oriented in one direction over part of the magnetopause (e.g., southward, causing dayside magnetopause reconnection), while simultaneously oriented the opposite direction over other regions of the magnetopause (e.g., northward, leading to reconnection tailward of the cusp). This type of behavior has recently been noted in a numerical model by Tang et al. (2013) for an exactly flow-aligned IMF. The separation between, for example, northward and southward draped magnetosheath magnetic field in general is not yet well understood in the case of strongly radial IMF.

However, there are many challenges involved when studying strongly flow-aligned IMF conditions. The first involves the probability of finding such solar wind intervals. Using the solar wind flow velocity ($\boldsymbol{V}$) to define a 'polar' direction, the angle between the IMF ($\boldsymbol{B}$) and velocity is defined as $\cos^{-1}(\boldsymbol{V}{\cdot}\boldsymbol{B}/(VB_T))$ (also often described as a cone angle). The fraction of the unit sphere covered by cone

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angles close to the 'pole' is small, and so the number of intervals when the IMF lies close to flow velocity vector is also small (described more quantitatively below). For completeness, the 'azimuthal' angle (also called the IMF clock angle) is often described as $\tan^{-1}(B_z/B_y)$.

The second challenge involves the steadiness of the IMF, and hence the cone angle. When the cone angle is closer to 90°, small random variations in the IMF do not change these angles significantly. However, when the angle is close to 0° (or 180°), small random variations can significantly change both the cone and clock angles.

The third challenge is how to propagate the solar wind from its point of measurement (often close to the L_1 Lagrangian point) to the bow shock, and then through the magnetosheath. The simplest method is to calculate the propagation time using the distance of the solar wind monitor from a model bow shock and divide by the solar wind velocity; and then add another small time increment using the distance from the model bow shock to the spacecraft near the magnetopause, divided by a slowed solar wind speed (e.g., $V/4$). More advanced (and presumably more accurate) models account for the phase front using the IMF (Weimer et al., 2002, 2003; Bargatze et al., 2005; Haaland et al., 2006; Weimer and King, 2008). However, when the IMF is strongly flow-aligned, it can be very challenging to determine the most appropriate propagation time using these more involved models.

Finally, the IMF intersection with the normal to the bow shock can provide an additional challenge. The region immediately downstream of the quasi-parallel shock is known to be quite turbulent (e.g., Greenstadt and Fredricks, 1979; Kan and Swift, 1983; Scholer et al., 1993), due to shock reformation, convection of foreshock instabilities into the magnetosheath, and the *in situ* excitation of various wave modes. For nearly radial IMF, the quasi-parallel bow shock covers most of the dayside region, and strongly influences the magnetosheath flow downstream. However, it is also known that despite the turbulent magnetosheath field on the downstream side of the bow shock, the shocked IMF is aligned tangential to the magnetopause as the plasma flow approaches this surface. It is not clear whether the components tangential to the magnetopause are as turbulent as they are further upstream from the magnetopause, or if they retain some of the large-scale directionality of the IMF configuration.

There have been some observational studies which have examined the effects of nearly flow-aligned IMF on the magnetosphere. Merka et al. (2003) noted that under such conditions the magnetopause was located significantly further from the Earth than predicted by statistical models. However, the magnetosheath has also been found to be thinner under conditions of strongly flow-aligned IMF as compared to other IMF orientations (e.g., Jelínek et al., 2010; Suvorova et al., 2010). Shue et al. (2009) investigated a case with multiple THEMIS spacecraft wherein the magnetopause was found to rebound, with fast sunward flows confined to a relatively small region of the magnetopause. Farrugia et al. (2010) examined an interval when Wind was in the magnetosheath and ACE in the solar wind. The interplanetary flow was within 15° of the flow vector, and fair agreement was found with an analytic formulation of magnetic field components derived from perturbations to the Spreiter and Rizzi model (Spreiter and Rizzi, 1974). In addition, pulsed high-speed flows exceeding that of the solar wind were observed in the dawnside boundary layer, which were discussed in terms of the Kelvin–Helmholtz instability.

For this study, magnetosheath magnetic fields draping the magnetopause are examined when the IMF cone angle ($\cos^{-1}(B_{x\text{-}aGSE}/B_T)$) lies between 5° and 15° or between 165° and 175° from the nominal aberrated solar wind direction (aberrated Geocentric Solar Ecliptic (GSE) coordinates). These ranges of IMF configurations are chosen so that a sufficient number of relatively strongly flow-aligned cases can be investigated, while the small asymmetry of the IMF from the flow direction is used to examine how the draped IMF differs on the two sides of the magnetosphere.

As mentioned above, the restrictions on the IMF cone angle exclude a large percentage of the possible IMF configurations. If the distribution of IMF orientations were completely isotropic, then one would expect that 3.03% of the intervals would lie within the cone angle ranges. However, the actual solar wind IMF configuration at 1 AU lies preferentially along a Parker-spiral angle of 45°, and favors the ecliptic plane. The influence of the Parker-spiral angle is shown using the 1-min resolution OMNI IMF data set for the interval April 1996–October 2005 in Fig. 1a, where peaks are observed at ~45° and ~135°. Folding the cone angles such that $\theta = \cos^{-1}(|B_{x\text{-}aGSE}|/B_T)$, the percentage of time that the IMF vector is between 5° and 15° from the flow direction is 3.38% (Fig. 1b).

It is noted that periods of nearly flow-aligned IMF of long-duration (a few to several hours) have been catalogued in various investigations (Neugebauer and Goldstein, 1997; Neugebauer et al., 1997; Watari et al., 2005; Pi et al., 2014), and the variation in occurrence frequency has been examined in terms of the solar cycle, with varying results. The focus of the present study, however, is not concerned with the distribution of IMF cone angles as a function of solar cycle phase.

Although there have been several studies of the consequences of perfectly flow-aligned IMF (e.g., Spreiter and Rizzi, 1974 (and references therein); Tang et al., 2013), there is relatively little knowledge as to how the IMF drapes about the magnetosphere when a relatively strong (but not perfectly flow-aligned) IMF $B_{x\text{-}aGSE}$ component exists. As mentioned above, the work of Farrugia et al. (2010) provides an excellent case study for an IMF orientation of ~15° deviation from the solar wind flow direction; tracked using Wind observations in the magnetosheath and ACE solar wind observations. Farrugia et al. also used perturbation techniques to derive magnetic field components, which compared favorably with the magnetosheath obser-