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Evidence for reverse draping of magnetosheath field around the magnetosphere in IMP 8 observations for northward interplanetary magnetic field

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Abstract. Fedder and Lyon [1995] recently showed the results from a global three-dimensional magnetohydrodynamic (MHD) model of the solar wind interaction with the Earth's magnetic field for northward interplanetary magnetic field (IMF) that exhibited a "tadpole"-shaped closed magnetosphere. One consequence of this configuration is that the inner magnetosheath or boundary layer fields exhibit reverse draping at the flanks compared to what is expected from the classical gas dynamic picture. This reverse draping, which occurs as a result of near-cusp merging in the MHD model, appears to be present in the statistical field pattern observed on IMP 8 at $x \approx$ -25-31 R_E. The implication is that boundary layer field configurations for northward IMF produce very different **J**×**B** forces on the local boundary layer plasma than would be inferred from classical draping and thus may be responsible for some of the observed IMF dependence of the low-latitude boundary layer properties.

Introduction

It has long been appreciated (since *Dungey* [1961]) that the magnetosphere would have a "closed" configuration for northward interplanetary magnetic field (IMF), with magnetic merging occurring, if at all, downstream from the polar cusps. However, only recently have numerical simulations provided a picture of the full three-dimensional (3-D) configuration of the magnetic field under such circumstances. Figure 1, from *Fedder and Lyon* [1995], shows how the magnetosphere takes on a "tadpole" shape and how the magnetic field lines in a global magnetohydrodynamic (MHD) model of the solar wind-magnetosphere interaction look near the magnetopause for a perfectly northward IMF (also *Usadi et al.* [1993]). This configuration is basically the 3-D counterpart of a classic Dungey-like configuration for northward IMF [*Dungey*, 1961]. The field lines of Figure 1 are seen projected onto the noon-midnight meridional plane on the dawn magnetosphere. The gray lines show topologically closed field lines, i.e., geomagnetic field lines, the white lines are IMF in the magnetosheath close to the magnetopause. Between the gray lines and the white lines, there are open field lines which interconnect the polar ionosphere and solar wind, either between the north polar cap and the south magnetosheath or vice versa filling the boundary layer. Due to the cusp reconnection, the field lines of the northward magnetosheath (white) adjacent to the boundary layer are seen reverse draped beyond the cusp point [*Fedder and Lyon*, 1995]. This picture is to be compared with that in Figure 2, from *Luhmann et al.* [1984], which shows magnetosheath field lines for northward IMF from the gas dynamic magnetosheath model of *Spreiter and Stahara* [1980]. In Figure 2, the magnetosheath field lines (fine lines) are seen projected onto the *xz* plane. The darker lines in Figure 2 are the projected views of the field lines passing within ~1 R_E of the magnetopause that are antiparallel to and thus may reconnect with the magnetosphere field poleward of the cusps inside [*Luhmann et al.*, 1984]. The main difference between the field geometries in Figures 1 and 2 is that the draping of the magnetosheath field lines adjacent to the boundary is opposite along the flanks beyond the cusps. The gas dynamic (GD) model has no magnetosphere interconnection. It describes only the distorted IMF in the region between the bow shock and an "impenetrable" magnetopause under the frozen-in field assumption. The effect that cusp merging has on the magnetopause boundary layer field lines on the magnetosheath side is clearly apparent in Figure 1. While the field draping geometry in both pictures is the same in the outer magnetosheath, the fields on the dawn and dusk flanks of the MHD model magnetopause are "reverse-draped" compared to what is expected from the more traditional GD picture. This reverse draping has implications for the low-latitude boundary layer (LLBL), for example, because the associated **J**×**B** forces are opposite those expected. An observation of this signature would also confirm the existence of cusp merging for northward IMF.

Fairfield [1993] recently reported evidence for the finite tail length in ISEE 3 data obtained in the deep tail during periods of northward IMF consistent with the tadpole-shaped magnetosphere of *Fedder and Lyon* [1995]. In this study, we describe a search for further experimental verification of the field configuration in Figure 1 using a large statistical data base

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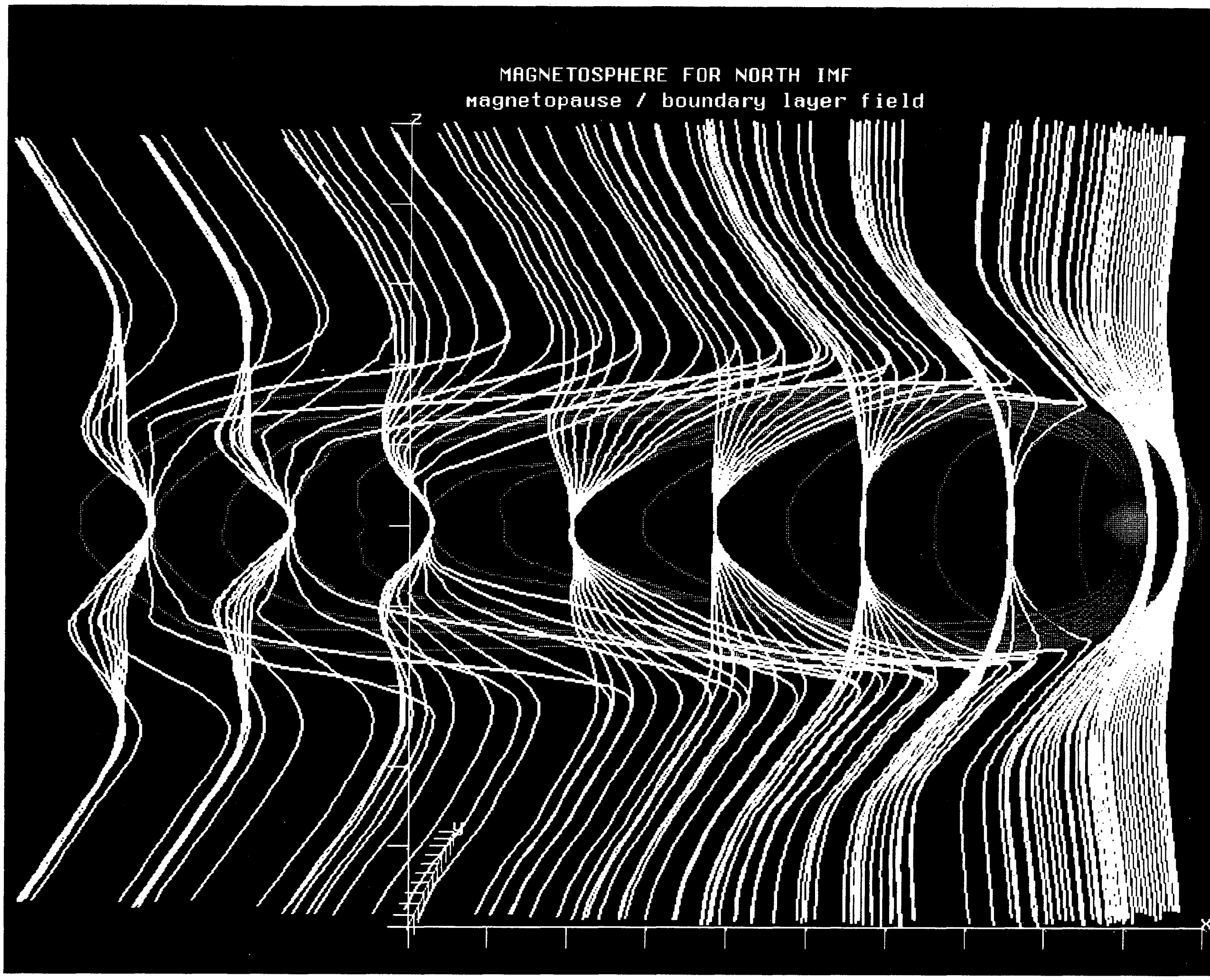

Figure 1. Global magnetohydrodynamic simulation results of *Fedder and Lyon* [1995] for northward IMFs. The axes are solar geomagnetic coordinates, each 100 R_E long. The gray ball-like object is the inner boundary of the model. The figure shows a snapshot of the northward magnetosphere at one instant; the field lines are the projections on the noon-midnight meridional plane, and the origin is at (-100,-50,-50). The view is given from the dawnside at ~300 R_E. The gray field lines are topologically closed, i.e., the magnetospheric field lines. The white field lines are IMF in the magnetosheath closer to the boundary. There are a few field lines which interconnect the polar ionosphere and the solar wind, either between the north polar cap and the south magnetosheath or vice versa which are given in the figure for clarity. The separation between the gray magnetospheric and white IMF field lines is 0.5 R_E in the *y* direction, while the separations of the gray closed field lines are 10 R_E in the *x* direction, downstream from the Earth. The reverse draping shape of the white field lines arises because of the cusp reconnection occurring at the high latitudes in the MHD model. In other words, they were previously gray, closed field lines.

for the tail magnetosheath from IMP 8. We find evidence that in the *xz* plane, the MHD model picture describes the magnetosheath field for northward IMF close to the magnetopause.

Data Description

The data sets used in this study are subsets of those used by *Kaymaz et al.* [1992]. The archived 5-min-averaged IMP 8 magnetometer data obtained between August 1978 and October 1982 at downtail (GSM *x*) distances beyond -25 R_E and the IMP 8 orbital sampling limit of ~-31 R_E were first examined to separate magnetosheath from upstream and tail data. IMF data from ISEE 3 were then used both to constrain the IMP 8 data set to intervals when the advected IMF was within 30° of GSM north (*z*) and to rotate the magnetosheath data by the angle between the *z* axis (north) and the measured IMF direction. This latter step "corrects" the data for departures from true north. The effects associated with the small IMF east-west (*y*) components are negligible in the statistics. The data were smoothed by averaging the data within a 4-R_E circle of each observation point as described by *Kaymaz et al.* [1992]. They were then separated into outer magnetosheath ($R = \sqrt{(y^2 + z^2)} >$ 25 R_E) and inner magnetosheath ($R < 25\ R_E$) regions in order to search for differences in the draping sense in the two regions. Here and elsewhere, field vectors were normalized to their upstream values to allow comparisons.

Figures 3a and 4a show the vectors obtained from the smoothed IMP 8 data for nearly northward IMFs. Figure 3a shows vector projections for the outer region from both the viewpoint of the Sun (top panel) and in the meridian (*xz*) plane (bottom panel) where the draping signature should be clearest.

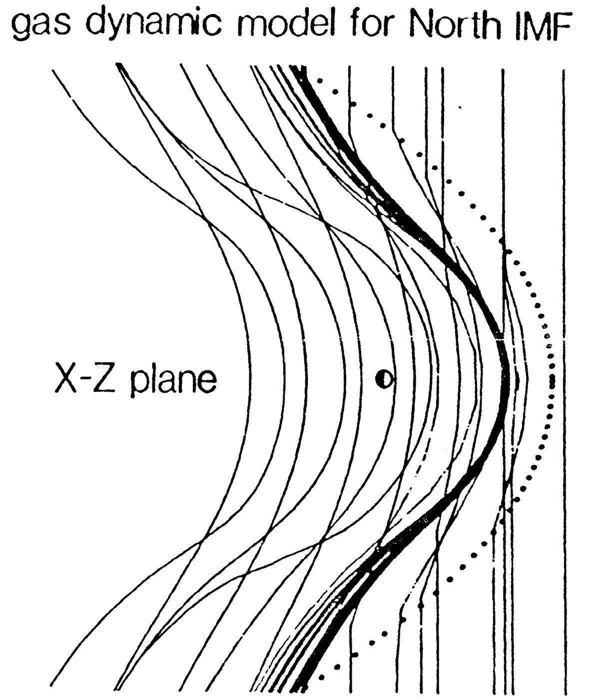

Figure 2. Gas dynamic magnetosheath simulation results of *Spreiter and Stahara* [1980] for northward IMFs [from *Luhmann et al.* 1984]. The figure shows the draping of the magnetosheath field lines close to the magnetopause during northward IMFs and gives the field line draping projection in the *xz* plane. The fine lines are the magnetosheath field lines, and the heavy lines are the projected views of field lines which pass within ~1 R_E of the magnetopause and are likely to be reconnecting poleward of the cusps of the magnetosphere inside. The draping geometry in this figure is to be compared with that in Figure 1. The difference is that beyond the cusps, Figure 1 shows reverse draped field lines owing to the cusp reconnection processes.

Figure 4a shows the same views for the inner region of the magnetosheath. There is a suggestion in the *xz* views that the draping senses in the inner and outer regions differ. Comparisons with the models help to elucidate this result.

Model Descriptions

The gas dynamic magnetosheath model of *Spreiter and Stahara* [1980] provides a picture of the geometry of advected fields in a supersonic flow past a blunt obstacle. This classic description of the magnetosheath and flow interaction has been used with considerable success to understand the bow shock shape and location and its control by the solar wind density, velocity, and temperature. While the GD model lacks the effects of magnetic pressure and curvature forces on the deflected flow dynamics (so that it does not produce a depletion layer, for example [e.g., *Zwan and Wolf*, 1976]), as well as any effects due to magnetic merging with the Earth's field at the magnetopause, it still gives the baseline picture of magnetosheath flows and fields from which such departures can be determined. Recent work of Stahara and Spreiter (see description by *Zhang et al.* [1996]) involving data comparisons have demonstrated impressive accuracy in predicting observed magnetosheath field and flow variations from measured upstream solar wind conditions.

To compare the IMP 8 observations with the GD model, we used a Mach 4.5 flow with a ratio of specific heats of 5/3 incident on a magnetopause shaped obstacle with model shape factor H/R_O = 0.25. The H/R_O parameter in the GD model determines the extent of the magnetopause flaring. Here, H is a scale height, and R_O is the magnetopause distance from the origin to the subsolar point (see *Spreiter and Stahara* [1980] for further explanation of this factor). The GD model field was then computed at the points of the observations assuming a prevailing northward IMF. For exact comparison, model field vectors at the IMP 8 data positions were averaged within a 4-R_E circle as was done with the IMP 8 field vectors. Figures 3b and 4b show the results in the same projections as were used for the IMP 8 data. While the outer gas dynamic magnetosheath model, Figure 3b, agrees well with the data in Figure 3a, the inner region comparisons in Figures 4a and 4b suggest that a reverse draping of inner magnetosheath fields occurs in the IMP 8 data, again using vectors normalized to the upstream field values.

The 3-D MHD simulation for northward IMF of *Fedder and Lyon* [1995] can be used in a similar way to compare with the observations. In this case we interpolate on the computational grid in order to obtain model field vectors at points corresponding to the data. Since the MHD model magnetopause radius appears to be slightly smaller than the observed magnetopause radius for the data set used, we applied a scaling factor of 0.85 to the position points of the observations when obtaining MHD model vectors. This adjustment can be attributed in part to the fact that the magnetopause in the MHD model is not highly resolved and in part to the fact that the upstream parameters in the model were not tailored to our observations. MHD model vectors also, for consistency with the IMP 8 data analysis procedure, were averaged within a 4-R_E circle. The results are shown in Figures 3c and 4c. It is apparent from Figure 3 that for the outer magnetosheath the IMP 8 data and both GD and MHD models look very much the same. However, for the inner magnetosheath (Figure 4) only the MHD model shows the reverse draping that appears to be present in the observations.

Conclusions

The sensitivity of the magnetosphere-solar wind interaction to the IMF orientation has long been recognized. That sensitivity ultimately relates to the merging configuration at the magnetopause and its effect on both the internal structure of the magnetosphere and the manner in which energy and momentum are transferred from the interplanetary plasma. The 3-D MHD simulations have the potential to allow us to envision the complicated topology of the magnetosphere and its immediate interplanetary environment but we first need to verify that these models are accurate. The results of *Kaymaz et al.* [1992] suggested that IMP 8 observations of the magnetosheath field at $x \approx -30$ R_E are consistent with the general IMF control seen in the *Fedder et al.* [1995] model. Here we have shown that at least one other special aspect of the northward IMF model configuration, namely, the reverse draping at the dawn and dusk flanks of the inner magnetosheath, is seen in the same data.

Hones et al. [1982] discussed the reverse-draped LLBL field lines in terms of an open magnetic field topology. One of his LLBL crossings showed the reverse-draped field line geometry very clearly. He also observed particle entry around the cusps. As a result, he suggested the reverse draping might occur due to the reconnection with the magnetospheric field lines at high latitudes. Here, we see that the reverse draped field lines may

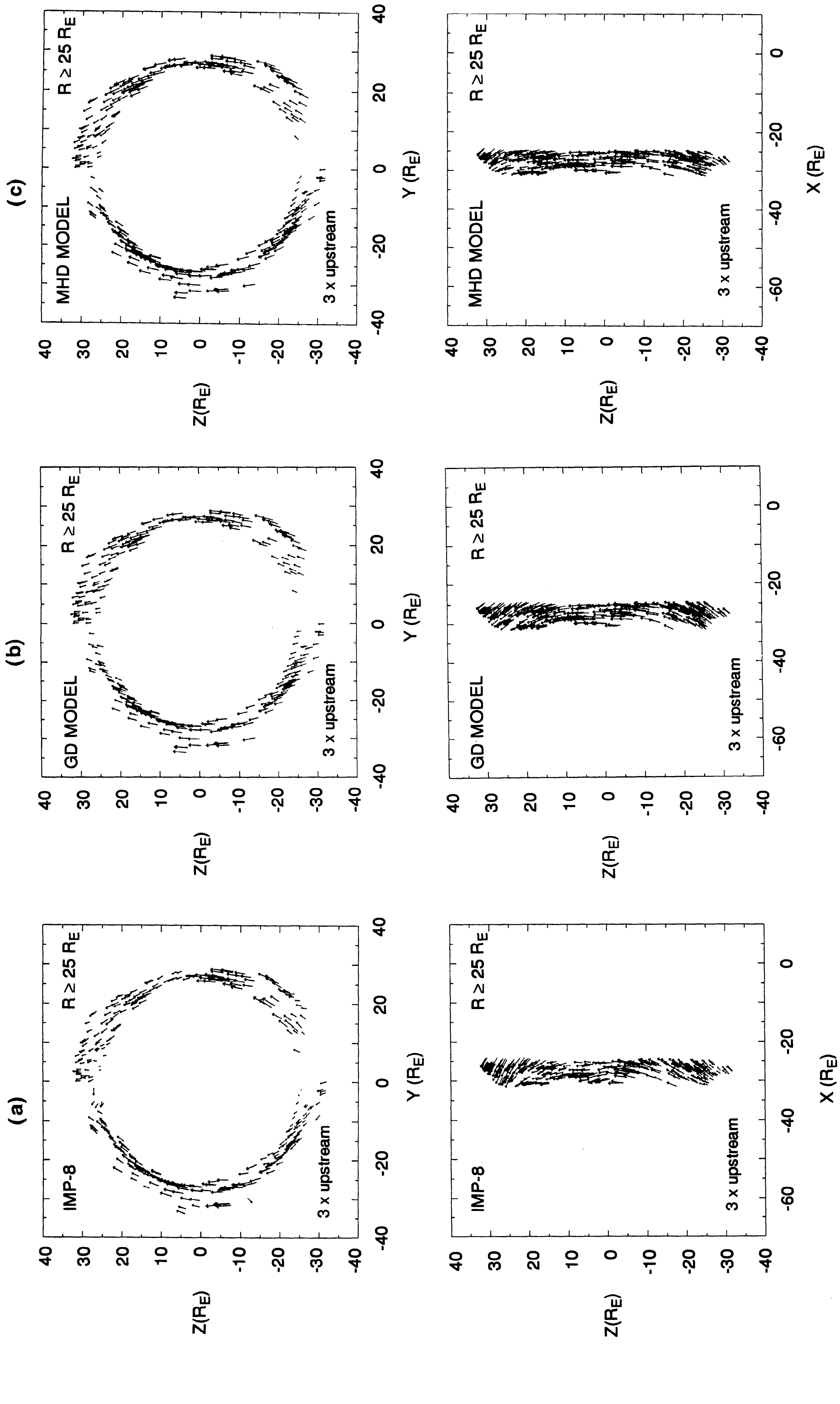

Figure 3. (a) IMP 8 magnetic field vectors for northward IMFs for outer magnetosheath, $R \geq 25\ R_E$, where $R = \sqrt{y^2 + z^2}$ and (b) Gas dynamic (GD) and (c) magnetohydrodynamic (MHD) model results at the positions of IMP 8 data seen in Figure 3a for northward IMFs. The top panels give the view from the Sun (*yz* plane), while the bottom panels are the views in the noon-midnight meridian (*xz* plane). Both models show draping patterns similar to the IMP 8 data. The vectors are normalized to the upstream field values.

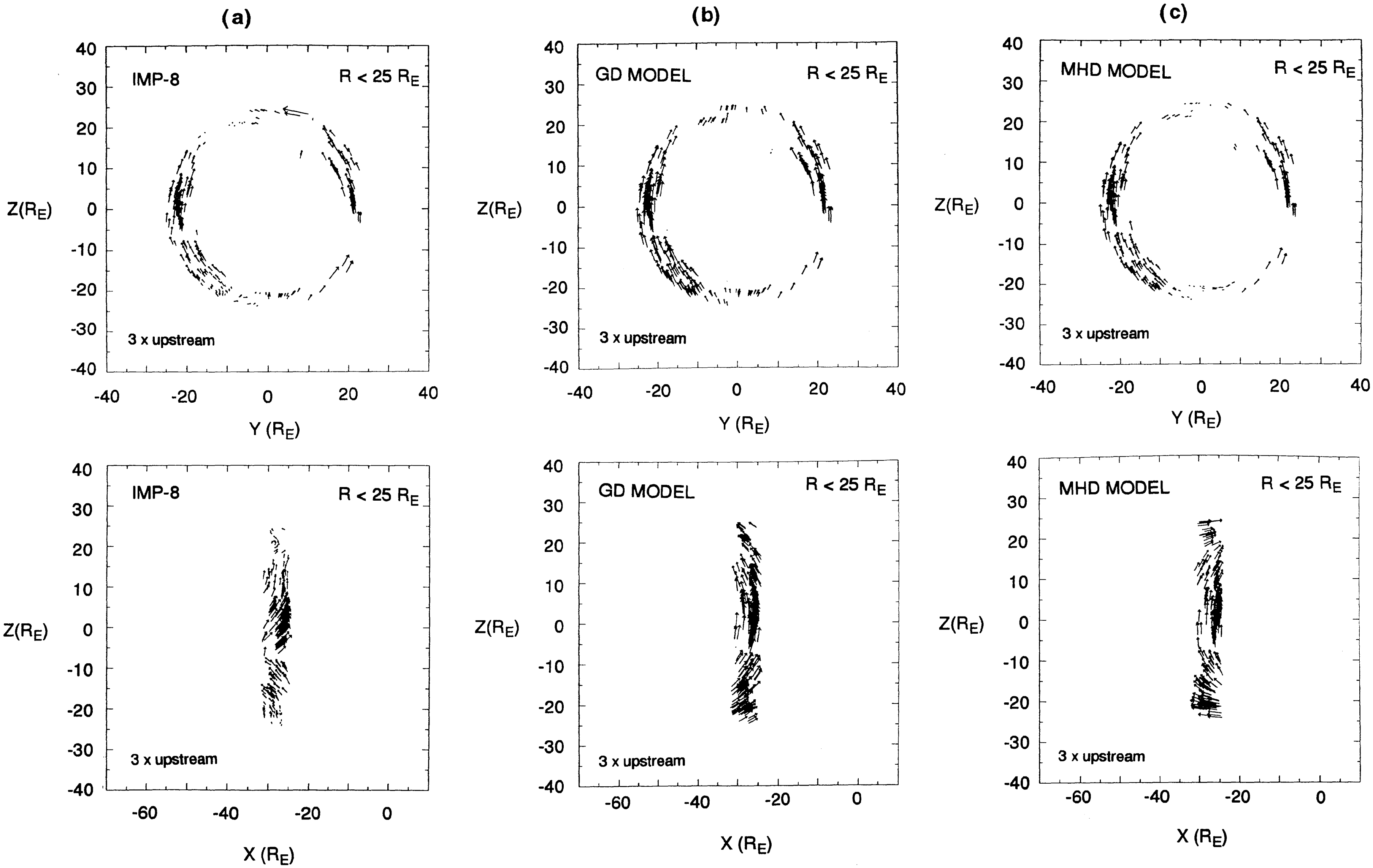

Figure 4. The same as Figure 3 but for the inner magnetosheath defined by $R < 25\ R_E$ where $R = \sqrt{y^2 + z^2}$. The difference between the gas dynamic and the MHD model draping is apparent in this figure. IMP 8 data taken closer to the boundary (Figure 3a, bottom panel) show a draping pattern reverse from that in the gas dynamic draping pattern but consistent with the MHD model draping pattern. The vectors are normalized to the upstream field values.

also be visible in the statistics of the IMP 8 data for northward IMF at $x \approx -30\ R_E$.

In another study, *Mitchell et al.* [1987] analyzed the dependence of the thickness of the low-latitude boundary layer on the IMF direction. They found the LLBL to be significantly thicker for northward IMF. The finding presented here has implications for studies of the LLBL which seek to explain this observation. **J×B** forces resulting from the reversed draped field line topology could account for some distinctive features. In particular, the field aligned currents and plasma acceleration related to reverse draping may play a dominant role in determining the appearance of the northward IMF LLBL.

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