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IMF ROTATIONS FOLLOWING INTERPLANETARY SHOCKS: THEIR INFLUENCE ON THE INTERACTION WITH MAGNETOSPHERE

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IP shocks are often accompanied with a rotation of the interplanetary magnetic field (IMF) over a large angle and this rotation can modify interaction process. The study discuses the interaction of the IP shock followed by an IMF rotation with the Earth magnetosphere with motivation to separate their effects. The results are based on the global MHD modeling of such interaction and are compared with observations.

1. Introduction

Moving toward Earth, an IP shock undergoes an interaction with the Earth's bow shock, magnetosheath, and magnetopause, and modification inside the magnetosphere. This train of interactions have been studied by several authors using magnetohydrodynamic (MHD) modeling or using the Rankine-Hugoniot (R-H) conditions. *Spreiter et al.* [1994], *Zhuang et al.* [1981], *Ivanov* [1964], *Dryer et al.* [1967], *Dryer* [1973], *Shen et al.* [1972], *Grib et al.* [1979] have shown that the interaction of an IP shock with the bow shock (a fast reverse shock) creates three discontinuities – the fast reverse shock, a fast forward shock, and a contact discontinuity between them.

Later, *Grib* [1982], *Pushkar et al.* [1991], *Grib and Pushkar* [2006] found that the interaction of the IP and bow shocks results in a train of different discontinuities and that the number of these discontinuities changes with the distance from the Sun-Earth line. The authors investigated an oblique interaction between the solar wind fast

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shock wave and the bow shock front and concluded that the discontinuity interaction depends on the IMF orientation.

MHD simulations [e.g., *Yan et al.*, 1996, *Samsonov et al.*, 2006] predict that an IP shock-bow shock interaction generates a following sequence of discontinuities: a fast shock propagating into the magnetosheath with a speed lower than that in the solar wind [*Samsonov et al.*, 2006], and three new discontinuities – a forward slow expansion wave, a contact discontinuity and a reverse slow shock.

On the other hand, the interaction between a fast shock and the magnetopause results according to the R-H conditions [*Grib*, 1972, *Grib et al.*, 1979] in a rarefaction wave propagating toward the bow shock; similar results were obtained by the 2-D MHD simulation of *Wu et al.* [2003]. Moreover, *Grib et al.* [1979] predicted that the interaction of this rarefaction wave with the bow shock leads to another reflected rarefaction wave which moves toward the magnetopause. From this prediction, one can assume that the chain of wave transformations can repeat many times.

In this paper, we try to find a method to classify the different discontinuities that are created as a sequence of the interaction of an IP shock and the following IMF rotation with the bow shock. Such study is actual and important because a statistical analysis of IP shocks during the last six years shows that 70% of shocks is followed by the IMF rotation and in 68% of these cases, the rotation of the IMF B_z component was observed within first 20 minutes after the shock arrival. For demonstration of an influence of the IMF rotation on the interaction, we have selected a representative example with favorable positions of the spacecraft in the solar wind (WIND) and in the magnetosheath (Geotail). In this example, data measured by WIND are used as an input to a global BATS-R-US (a Block Adaptive-Tree Solar-wind Roe-type Upwind Scheme) MHD model. Since discontinuities reflected from the magnetopause and/or from some internal magnetospheric boundary or even from the ionosphere can play an important role in the interaction process, we use three BATS-R-US runs. The comparison of results with the Geotail observations shows a good qualitative agreement but we conclude that an identification of different discontinuities is possible only with the MHD model support.

2. Observation

On July 28, 1996 at 1214:35 UT, the WIND spacecraft located far in the solar wind at $(179; 13; -10)_{\mathrm{GSE}}\ R_{\mathrm{E}}$ registered a fast forward shock. About 50 minutes later, at 1306:57 UT, the same shock was registered by Geotail located in the magnetosheath at $(4; 13; -5)_{\mathrm{GSE}}\ R_{\mathrm{E}}$. Unfortunately, no other spacecraft was in the solar wind, thus the shock parameter determination was based on the R-H relations and the WIND data. Parameters of the IP shock were: shock normal, $n = (0.92; -0.06; -0.39)$, shock speed, $V_{\mathrm{sh}} = 339$ km/s, and the Alfvénic Mach number, $M_{\mathrm{A}} = 2.06$. However, we note that the predicted time of the shock propagation from WIND to Geotail

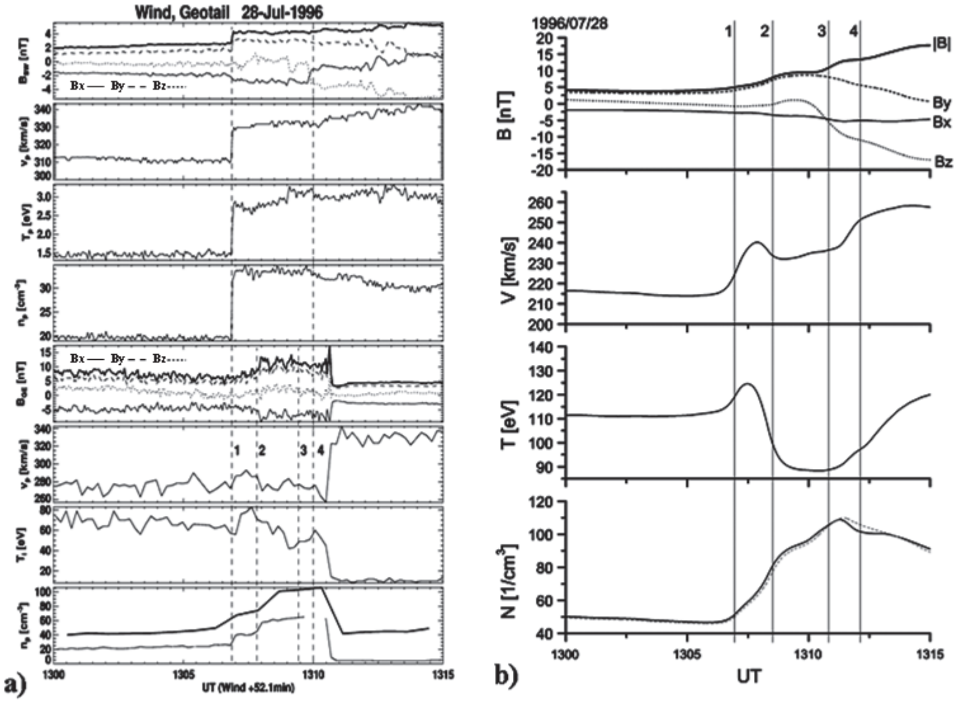

Figure 1. (a) Solar wind and magnetosheath observations of the IP shock through July 28, 1996. The first four panels correspond to WIND and the second four to Geotail measurements. (b) Temporal profiles of the IMF magnitude and three components; speed; temperature; and density as determined from the global MHD model.

based on these shock parameters was 50 minutes, whereas that observed time was ≈ 52 minutes. The good match of these two times suggests that the shock parameters were determined properly. Observations of both spacecraft are shown in Figure 1a. In Geotail panels, one can identify the following discontinuity: 1 – the transmitted IP shock; 2 – a combination of a forward slow expansion wave, a contact discontinuity and a reverse slow shock; 3 – non identified discontinuity; and 4 – a slow shock.

3. Structure of the IP shock front in the magnetosheath

Based on a comparison of observations with a local magnetosheath model, *Samsonov et al.* [2006] and *Safrankova et al.* [2007] suggested that the interaction of the IP shock with the bow shock would generate a new discontinuity that would follow the IP shock front in the magnetosheath. In their papers, this suggestion was supported by the modeled profiles of plasma parameters in the subsolar region but *Grib and Pushkar* [2006] have argued that the follow-up discontinuity (ies) would differ at different intersections of the interacting shocks. Since Geotail is located in the magnetosheath, we can test this prediction. We prepared MHD simulations of this IP shock using real measurements from WIND as an input data for a global BATS-R-US MHD model. The model solves fully conservative magnetohydrodynamic equations and uses a high-resolution finite-volume approximate Riemann solver scheme for calculation of ideal MHD equations [e.g., *Gombosi et al.*, 2002].

The results of simulations are shown in Figure 1b and one can seen similar discontinuities which can be identify as: (1) Expansions of the density, velocity, temperature, and magnetic field can be attributed to the decelerated front of the original IP shock because it has a character of the fast wave; (2) An increase of the magnetic field and density but the decrease of the speed and temperature can be probably attributed to a combination of the slow shock, rarefaction wave, and contact discontinuity; (3) An increase of the density and magnetic field and no change of the velocity and temperature can be distinguished by the magnetic field rotation and represents a tangential discontinuity or Alfvén wave; (4) A decrease of the density, and the increase of the temperature, velocity, and magnetic field are typical for a slow shock.

However, in both data and simulations, the IP shock was followed by the IMF rotation. Since an arrival of this rotation roughly coincides with the time of the best identified discontinuity, we performed new simulation runs with artificial timing of the follow-up IMF discontinuity in order to separate the effects of the IP shock and IMF rotation (Figure 2). For this task, the input data for the model were modified and new two runs of the model were requested:

(1) The simulation grid in the critical region of the dayside magnetosphere and magnetosheath was 0.06 R_E in order to identify accurately the discontinuities in the model results. The time step of the calculation was 3 s, in accord with the best WIND resolution of the plasma data;

(2) The input data were complemented with a five-minute interval with constant values of parameters that delayed the follow-up IMF discontinuity (Figure 2a).

(3) The input data with constant post-shock conditions (Figure 2b) were used.

Figure 3 presents the results of runs of global MHD simulations. The first run that is shown in the top panels basically repeats the run show in Figure 1 but it uses a significantly enhanced spatial resolution, especially in critical regions of the dayside bow shock and magnetopause. This procedure allowed us a more detailed analysis of the influence of the IMF rotation. The different discontinuities identified in the model data are distinguished with vertical lines and numbered. In all panels of the figure, 1 represents an arrival of the original IP shock. A compound discontinuity predicted by *Samsonov et al.* [2006] is denoted as 2. The further discontinuity induced by the IP shock–bow shock interaction identified in the first run (Figure 3) coincidences

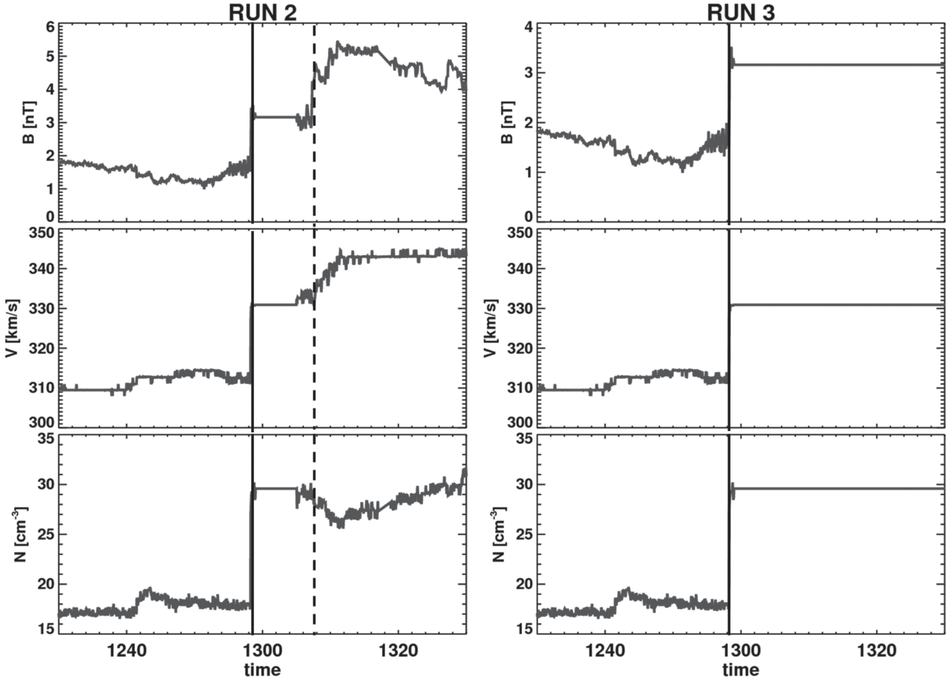

FIGURE 2. Two model runs with different timing of the follow-up IMF discontinuity (dashed line). (a) In the run 2, the IMF B_z rotation was shifted by 5 minutes; (b) in the run 3, the rotation was deleted.

with the upstream IMF discontinuity characterized by increases of the magnetic field, velocity, and density is 3. However, the second and third runs reveal that the increase of the magnetic field is a product of the arrival of the IMF rotation because we observe the magnetic field decrease when this arrival is delayed or absent, as it can be seen in the second and third panels of Figure 3.

The absence of the IMF rotation allows us to identify a set of new discontinuities generated by the IP shock – bow shock interaction: number 4 is characterized by the decrease of the magnetic field and density and following oscillations of both parameters (5 and 6). It is a question if their oscillations are connected with the scanning of the magnetosheath profile due to a oscillatory motion in this region *Nemecek et al.* [2011] or if it would be treated as a product of the IP shock interaction with the boundaries. However, the in-phase changes of the magnetic field and density suggest the latter as a more probable explanation.

In the second run, an arrival of the IMF rotation is shown as a line 7 and causes a large increase of the magnetic field. This increase propagates downstream but it is followed by a new tangential discontinuity which results for the upstream IMF rotation – bow shock interaction 8. The rise of the magnetic field magnitude is terminated

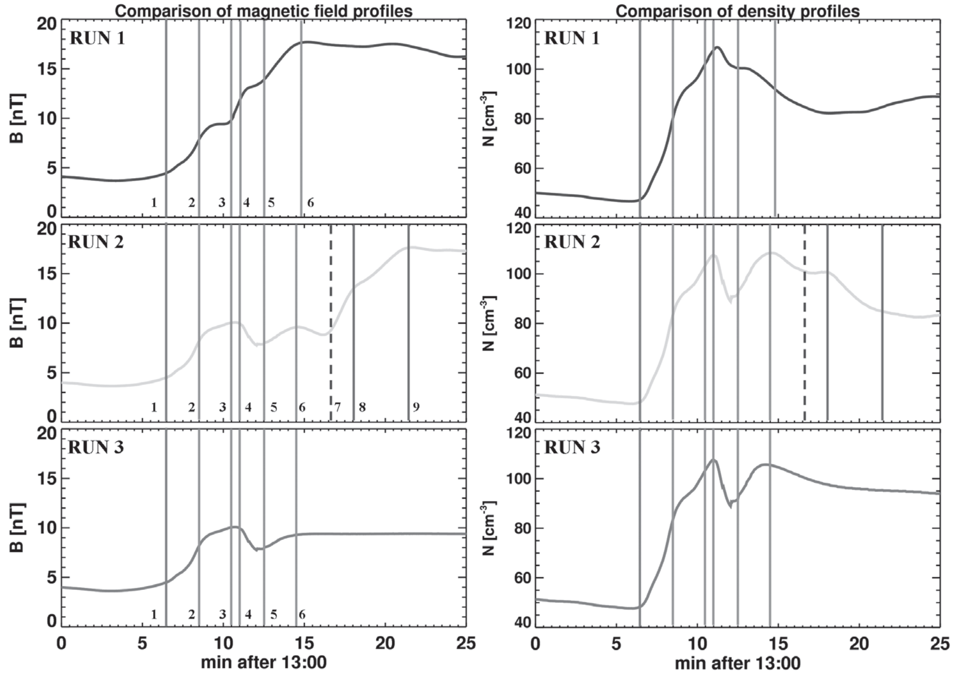

FIGURE 3. Changes of the magnetic field (a) and density (b) obtained as a result of three model runs; original data and two runs with the shifted IMF rotation after the IP shock.

by another discontinuity 9, after it, the magnetic field and density slowly decrease and eventually stay almost constant. These magnetic field discontinuities are similar to those observed in the first run, but the second run reveals that they are accomplished with simultaneous changes of the density. The system reaches a steady state in about 20 minutes after the IP shock arrival in the first and second runs, whereas about 10 minutes is enough in the third run where the IMF discontinuity is absent.

4. Conclusions

Based on these results and using an earlier study of the interaction IP shock/IMF discontinuity with bow shock we can draw several conclusions.

We have analyzed observations of an IP shock in the magnetosheath and compared data with the BATS-R-US global model. The attention was devoted to global features of the IP shock–bow shock–magnetopause interaction as well as to structure of the IP shock front in the magnetosheath. In simulation results, we see that (1) the IP shock creates a new discontinuity in the magnetosheath, (2) the interaction of the

IMF rotation with the bow shock results in a huge increase of the magnetosheath magnetic field, and (3) this increase propagates downstream but it is followed by a new discontinuity, and finally, (4) we identified three discontinuities that follow the IP shock front in the magnetosheath.

Classification of the discontinuities is difficult but we think that the discontinuity 2 in Figure 3a is the discontinuity reported by *Samsonov et al.* [2006] in the subsolar region and described as a combination of a forward slow expansion wave, a contact discontinuity, and a reverse slow shock. On the other hand, *Grib and Pushkar* [2006] reported a sequence of a fast shock, a rarefaction wave and a contact discontinuity moving downstream and followed by a new rarefaction wave also moving downstream according to our simulations. A more complicated set of a fast shock, a rotational discontinuity, a slow shock, and a contact discontinuity would move downstream. A similar set of discontinuities was found in the Geotail data. Identification of discontinuities in the data would be impossible without model results because they are masked by magnetosheath fluctuations of a similar amplitude and by a following rotation of IMF B_z.

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