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THE MAGNETOSPHERE TIME RESPONSE TO THE IMF BZ TURNING

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Abstract. We analyzed the time response of the polar cap electric field to the IMF Bz turning. Using the magnetic and plasma data from Wind, ACE, Geotail, Themis B and Themis C spacecraft 39 solar wind directional discontinuities (DD) were examined: 20 events with N-S Bz turning and 19 events with S-N Bz turning. Three methods were used to estimate the propagation time of the DD fronts. The reference time for the electric field response is the moment of DD arrival to the bow shock nose. The uncertainty of the arrival time estimate does not exceed 2 min. PC-index was used as an instrument to observe the polar cap electric field variations. The average time response value 13.6±6.4 min for all events was obtained. This value is close to one obtained by other authors. It is also in agreement with theoretical estimate of Erkaev (2003) ~ 10 min. for typical solar wind parameters.

Introduction

Investigation of the magnetosphere time response to the impact of direction discontinuity (DD) in the solar wind is important for establishing causal relationships of phenomena caused by this discontinuity. Besides this time delay value can be use for theoretical modeling of the interaction process. It is known that most geoeffective parameters are the Bz-component of the interplanetary magnetic field (IMF) and the dynamic pressure. When the DD with Bz southward turning arrives the magnetosphere the reconnection on the frontal region begins, and the global magnetospheric electric field (Em) is growing. The potential difference is transferred to the polar cap and DP2-current system become stronger. It can be seen in variations of PC-index.

Em time response in the polar caps was studied in [1].The time delay was determined between the DD arrival time to the point with coordinates (10, 0, 0) Re and the start time variation of the convection. The network consisting of 115 ground magnetometers was used for this study. They found 8.4 (± 8.2) minutes for the time delay. Note that DD front orientation in [1] was calculated with small accuracy. Estimated error in determining the DD arrival time to the reference point (10, 0, 0) is about 10 minutes. Strictly speaking, DD interacts firstly with a bow shock at the subsolar region which position depends on many internal and external parameters. Moreover, using the ground magnetic data we face a problem of the determination reference level. It is the source of additional errors.

The response of the transpolar electric field to influence of the southward IMF Bz turning was studied in [2]. The normals to the DD's fronts were determined based on two spacecraft data (GEOTAIL and WIND). The electric field above the polar cap was measured by the POLAR spacecraft. Delay of the electric field increase start time averaged over 30 events is about 10 minutes (as follows from Fig.10 a, b of [2]). This value is agreed with result [1]. At the same time there is rather large scattering between different events (Fig. 10 c of [2]).

So, approximately the same averaged values of time delays (about 10 minutes) were obtained in the papers mentioned above. Let us note that the dispersion was found practically equal to the average delay in majority of the studies. By our opinion, the uncertainties of the arrival time of the discontinuity front to the magnetosphere are the main source of the above scatter. Obviously, more accurate estimates of the time delay can be obtained by using data of satellites placed more closely to the magnetosphere and to the Sun-Earth line. On the other hand, the above large scatter may be result of the time delay dependence on some interplanetary or/and internal parameters of the Earth magnetosphere.

Thus, the goals of the present paper are the following. Firstly, to determine time delays between turning of the Bz IMF and response of the large-scale convection electric field with maximal possible accuracy using the data of THEMIS satellites. Secondly, to study possible interrelationships between the delays and the solar wind parameters.

Data and Analysis

In our work we investigated the DD with IMF Bz turning at the front both southward and northward. We used three methods for normal calculation: three-spacecraft method [4], tangential discontinuity method and MVA [5]. Data from satellites THEMIS B, THEMIS C (September-November 2007; August-September 2008), GEOTAIL (Jul. 28, 1999 October 29, 2001 December 26, 2002, 26 October, and November 2007), WIND (July 28, 1999, October 29 2001, December 26, 2002, 21 and 26 August 2007) with a 3-second resolution are used. For 9 events we use 16-second data from ACE (July 28, 1999 October 29, 2001, December 26, 2002, 21, 25 and 26 August 2007)

The normal calculation accuracy depends on the satellites position. For events when spacecraft is far from the Sun-Earth line, slight inaccuracy in normal determination can lead to large error of DD reference time. On the other hand, when spacecraft position is close to the Sun-Earth line but on large distance from the magnetosphere then significant deformation of the DD front is often observed.

The launch of the THEMIS spacecraft system allows us to enlarge the list of events. Due to the spacecraft position near the Earth and Sun-Earth line the normal calculation error and the front deformation are minimized (see Fig. 1).

The arrival time to bow shock nose was determined based on the equation (see Fig. 2)

$$(\Delta\vec{R}\cdot\vec{n}) = \Delta t(\vec{V}\cdot\vec{n}).$$

The desired quantity Δt is:

$$\Delta t = \frac{(\Delta\vec{R}\cdot\vec{n})}{(\vec{V}\cdot\vec{n})}$$

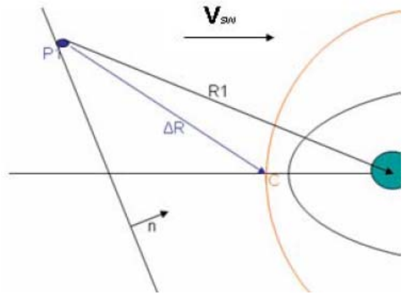

Fig.1. Scheme used for calculation of the DD front time propagation from satellite (point P) till bow shock (point C). R1 – is the satellite radial vector, ΔR – distance to reference point, n – vector normal to the DD front.

The bow shock nose coordinates for all events were taken from the site http://cdaweb.gsfc.nasa.gov/cgi-bin/eval1. cgi. Start time of the convection electric field increase (decrease) in the polar cap was determined as start of the decrease (increase) of PC-index. The latter is known linearly depending on strength of the convection electric field [6]. The accuracy of PC start time definition is about 1 minute (see Fig.2.).

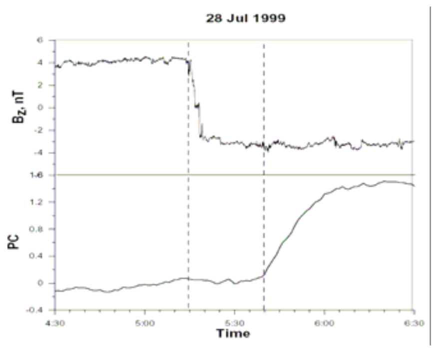

Fig. 2. An example of the IMF Bz (top) and PC-index (bottom) records.

Different methods used to determine vectors normal to the DD front not always give the same result. That's why the angles between normal vectors obtained by different methods are calculated for each event. The divergence angle less then 12 degrees is found in 80% events (Fig. 3). Only these events are taken into consideration.

Usage of the THEMIS data allows us to diminish inaccuracy of the reference time up to 1 min if the divergence of the normal angle does not exceed 10 degrees. So, we estimate the inaccuracy of the response time delay as 1-2 min.

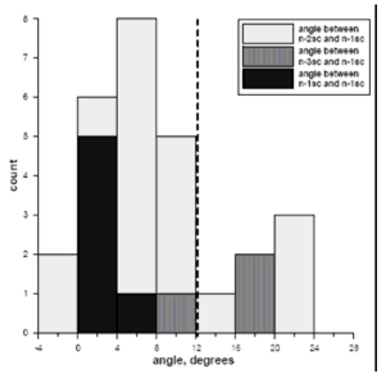

Fig. 3 The histogram of the divergence angle between normals calculated by different methods.

Thus, we have a list of 39 events: in 9 events a normal was defined by the three satellites method, in 23 - by the two satellites method. In 7 events we use the tangential discontinuity method based on only one spacecraft data.

Results

According to our analysis orientation of the DD front normal vectors varies in rather large limits. As can be seen from Fig. 4, directions of the normal vectors are almost homogeneously distributed among all sectors of the YZ plane. Angles between the DD front and the Sun- Earth line cover 20^o-90^o range. It means that the real orientation of DDs should be taken into account for appropriate calculation of the DD front-magnetosphere contact time. It is often believed that DDs are oriented along the Parker's spirals. Such supposition can lead to large errors.

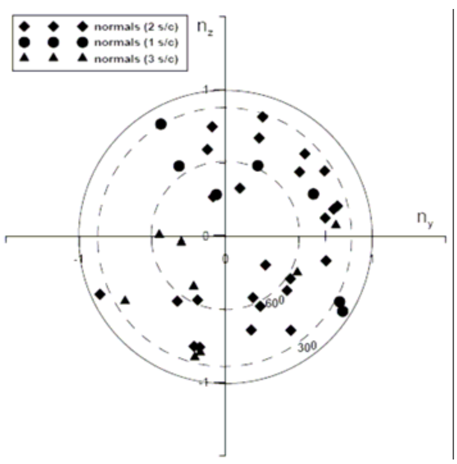

Fig. 4. Normal orientations in YZ plane.

Both the 2-spacecraft and the tangential discontinuity methods are based on the supposition that DD velocity is negligibly small relatively to the solar wind velocity. This supposition is exactly valid for the tangential discontinuity and approximately fits for any other type discontinuities having relatively small normal component of the magnetic field (Bn). All events studied are presented in our Fig. 5 in the Bn/B – ΔB/B coordinates. Here Bn/B is the relative value of the normal component of the magnetic field and ΔB/B is the relative value of the jump of the magnetic field. According to known methodic the discontinuities can be accepted as tangential ones if their ratios belong to the following ranges: Bn/B≤0.4, and ΔB/B≥0.2. In our collection there are 11 events corresponding to the above criteria. However, as can be seen from our Fig.5 other events also have Bn small enough to allow us to use the above mentioned methods.

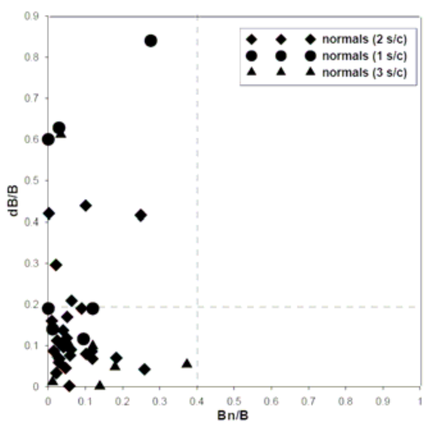

Fig. 5 See explanation in the text.

In 9 events we calculated the normal orientation by 3-spacecraft method. It allowed us to determine the DD's velocity relative to the solar wind. We found out average value as ~ 20 km / s that is negligible small relatively to average solar wind velocity (~ 400 km/s).

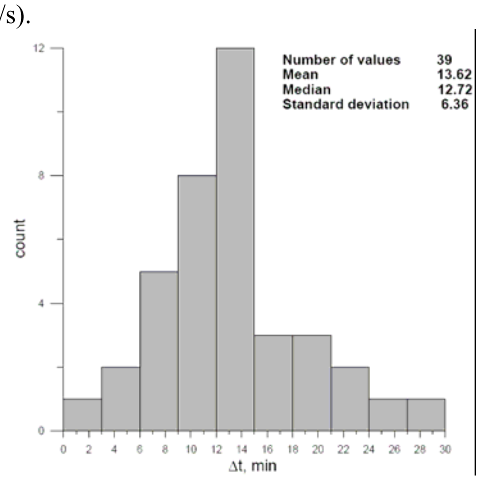

Fig. 6 Histogram of the response time delay of the transpolar electric field (as PC-index shows) relative to the contact of the DD with bow shock nose.

Fig. 6 shows the response time delay of the magnetosphere electric field (as PC-index shows) on DDs effect. The average Δt value is 13.6(± 6.4) minutes.

There is some difference between events with southward and northward IMF Bz turning. For events with southward Bz turning average Δt value is 15.1 ± 6.7 min, and it is 12.2 ± 5.8 min for events with northward Bz turning.

Discussion

Maximum accuracy determination of the response time of the magnetospheric electric field to a sudden IMF turning is the main goal of the present paper. Moreover, it's an attempt to understand possible physical reasons which are behind of the large scattering of the response time values corresponding to different events. Due to usage of the THEMIS data as well as especially accurate calculations of the DD front orientations we managed to minimize the total error of the time delay (Δt) up to 1-2 minutes. We found out average Δt as 13.6 minutes. This value is close to the result obtained in [1] and [2]. However, the scattering of the Δt value (± 6.4 minutes) considerably exceeds the accuracy of response time delay determination. This discrepancy allows us to conclude that any function dependence between time response values and the solar wind parameters exists.

In this connection, on the first step we tested the dependence of the response time on the following parameters: the solar wind dynamic pressure, the Mach-Alfven number, the DD front orientation, the value of IMF Bz jump and Bz background value. The response time is found slightly dependent only on the front orientation.

On the next step we carried out an attempt to find out a dependence of the response time on the physically reasonable function of any solar wind parameters. We have found an appropriate example of such function in [7] where the process of the magnetopause magnetic barrier formation was theoretically considered. Using analytical and numerical methods the authors solved non-steady problem related to variations of the magnetic barrier caused by the IMF southward turning. They obtained a simple formula for the estimation of the characteristic time of magnetic barrier formation:

$$\tau = 2.5\frac{L}{V_{sw}} \quad (1),$$

where L - the radius of curvature of the magnetosphere at the subsolar point.

This value is close to the subsolar point distance, which calculated as (Shue, 1997):

$$R_{mp} = (11.4 + K \cdot B_z)P^{-\frac{1}{6.6}},$$

where Rmp - the magnetosphere radius , P - the solar wind dynamic pressure, K = 0.013 for Bz> 0 and K = 0.14 for Bz <0.

Omitting the weak dependence of Bz, we obtain for τ:

$$\tau \approx \frac{c}{V^{1.3} n^{1/6.6}} \quad .$$

As a next step we calculated the value $V^{1.3}n^{1/6.6}$ for each of our events. The superposition of this calculated value with our experimental values Δt is shown in Fig. 7.

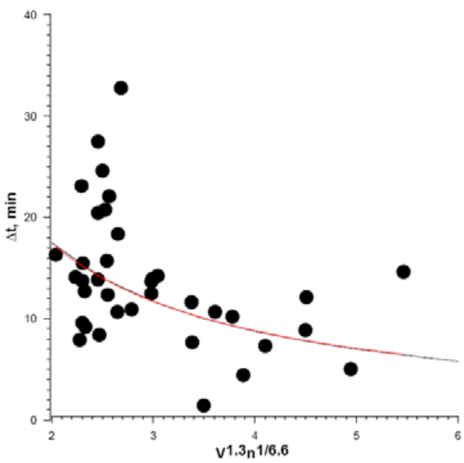

Fig. 7. See explanation in the text.

An inverse relationship between Δt and the value $V^{1.3}n^{1/6.6}$ is evident despite considerable scatter. The curve in the figure corresponds to this dependence; the constant C is defined for the midpoint. Thus, our results qualitatively confirm the conclusion of [7].

One of the reasons of the large scatter of points in Fig.7 may be unknown time of DD's spread from the bow shock nose to the magnetopause. Indeed the value (τ) is time of the magnetic barrier forming after the DD's arrival to the magnetopause. Our Δt value is the time delay between the DD's arrival to the bow shock nose and the PC-index reaction start. We can not determine the time of DD's spread from the bow shock to the magnetopause. According to the MHD simulation, this time may be 1-3 minutes. It is also known [3] that the signal propagation time within the polar cap is not more than 2 minutes. So, we subtract these 3+2 minutes from our ~ 14 minutes and obtain 9 minutes that is very close to the theoretical estimation.

In 11 events from our set the dynamic pressure jumps were observed in conjunction with IMF Bz variations. The response to the dynamic pressure increasing can be seen in the form of sudden impulses in the SYM-index. Comparing the PC start time delay with the sudden impulse start time delay we found out that there is a systematic delay PC variation to SYM variation. We can estimate the lower limit for the response time value as a difference between these two delays. This difference averaged over 11 events studied is 6.2 minutes.

Conclusion

Thus, we examined 39 events of the IMF Bz turnings. It is found that the average magnetosphere response time is 13.6(± 6.4) minutes including the spread time inside the magnetosheath. The experimentally obtained the reference time dependence on the combination of solar wind parameters controlling the magnetic barrier formation time is in qualitative agreement with theoretical predictions [7].

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