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Effect of change in large and fast solar wind dynamic pressure on geosynchronous magnetic field*

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We present a comparison of changes in large and sharp solar wind dynamic pressure, observed by several spacecraft, with fast disturbances in the magnetospheric magnetic field, measured by the geosynchronous satellites. More than 260 changes in solar wind pressure during the period 1996–2003 are selected for this study. Large statistics show that an increase (a decrease) in dynamic pressure always results in an increase (a decrease) in the magnitude of geosynchronous magnetic field. The amplitude of response to the geomagnetic field strongly depends on the location of observer relative to the noon meridian, the value of pressure before disturbance, and the change in amplitude of pressure.

Keywords: solar wind dynamic pressure changes, geosynchronous magnetic field

PACC: 9410, 9420, 9430

1. Introduction

An increase or a decrease in the solar wind dynamic pressure ($P_{\rm d}$) can compress or expand the magnetosphere and result in various types of disturbances in the magnetosphere–ionosphere system. One of those disturbances is the disturbance to the geosynchronous magnetic field, which has been studied by several authors. For example, Rufenach *et al* found that the average values of quiet magnetospheric magnetic field measured by geostationary operational environmental satellites (GOES) spacecraft generally increased when the hourly-averaged solar wind pressure increased.[1] Borodkova *et al* and Sibeck *et al* have shown a direct correspondence between dayside magnetospheric magnetic field variations and step function decreases or increases in solar wind pressure.[2,3] Using hourly-averaged data, Wing *et al* have shown that changes in the solar wind and the geosynchronous magnetic field near noon are correlated with each other, but on the nightside are anti-correlated.[4] In a recent paper by Lee *et al*,[5] the response of geosynchronous magnetic field to the enhancement in the solar wind $P_{\rm d}$ was investigated separately for cases of northward and southward interplanetary magnetic fields (IMFs). It was found that for $P_{\rm d}$ enhancement with southward IMF the geosynchronous response on the dayside was mostly compressional, while on the nightside it was dipolarization-like response.

The response of the geosynchronous magnetic field strength around local noon to solar wind parameters was studied by Sanny *et al*.[6] It was found that the variation in the geosynchronous magnetic field strength was strongly affected by the change in the solar wind $P_{\rm d}$ but seemingly independent of the northward or southward direction of IMF.

Another study by Borodkova *et al* [7] has demonstrated that a sharp increase (decrease) in the solar wind $P_{\rm d}$ always results in an increase (a decrease) in geosynchronous magnetic field strength with a maximum amplitude near noon. Some similar and additional results using the different database were obtained in the work by Wang *et al*.

Thus, the variation in a magnetospheric magnetic field must be related to a corresponding change in a magnetospheric current system on a large scale,

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i.e. the Chapman–Ferraro, ring, cross-tail and Birkeland currents. The amplitude and time delay of the response of each current system to the change in solar wind should be different and vary with local time. But fast response of the geosynchronous magnetic field to the change in sharp solar wind $P_{\rm d}$ is mostly a manifestation of Chapman–Ferraro current reconstruction.[2,7]

In this paper we present the detailed study of the dependence of the amplitude of response to geosynchronous magnetic field on the amplitude of change in dynamic pressure, the position of observation relative to local time sectors, and the values of the solar wind $P_{\rm d}$ before disturbance as well. We choose some changes in strong and sharp solar wind pressure for this study, so as to be able to reliably separate the effect of $P_{\rm d}$ change on the magnetosphere from the effects of other disturbances in the solar wind. Observations performed by GOES satellites are used for this study because they provide a large database of nearly continuous geosynchronous magnetospheric magnetic field measurements.

It should be noted that, according to both our data and results from Wing and Sibeck [4] and Lukianova,[8] the magnetospheric response to the sudden change in solar wind $P_{\rm d}$ strongly depends on whether the magnetosphere is quiet or disturbed. In this work we mainly consider the events only observed under quiet magnetospheric condition with a geomagnetic $D_{\rm st}$ index not exceeding 40 nT.

2. Data

To conduct our study we need simultaneous solar wind and geosynchronous observations. As a solar wind plasma monitor we use two sets of data:

a) high time (1 s) resolution solar wind ion flux measurements from the omnidirectional plasma sensor (VDP) experiment[9] onboard the INTERBALL-1 satellite located near the Earth's magnetosphere[10] for the period 1996–2000;

b) key physical plasma parameters from the Solar Wind Experiment (SWE) onboard the WIND spacecraft (http://cdaweb.gsfc.nasa.gov), Solar Wind Electron, Proton, and Alpha Monitor (SWEPAM) instrument onboard the Advanced Composition Explorer (ACE) (http://www.srl.caltech.edu/ACE/) and Interplanetary Monitoring Platforms (IMP) 8 Massachusetts Institute of Technology (MIT) plasma investigations (ftp://space.mit.edu/pub/plasma/imp/www/imp.html) during 1996–2003.

On the basis of these data sets we choose large (more than 2 nPa for most cases) and sharp (duration less than 10 min) changes—increases or decreases (steps or pulses) in solar wind $P_{\rm d}$—and compare them with variation in the geosynchronous magnetic field. Each change in the solar wind $P_{\rm d}$ chosen for this study is confirmed by simultaneous observations on more than one spacecraft.

Geosynchronous observations are provided by the GOES spacecraft.[11] We use magnetospheric magnetic field measurements with a time resolution of 1 minute (http://goes.ngdc.noaa.gov).

3. Response of geosynchronous magnetic field to solar wind $P_{\rm d}$ change

We begin with taking for example the response of the geosynchronous magnetic field response to sudden change in the solar wind $P_{\rm d}$. Because the geomagnetic magnetic field is dipolar, the z-component is the main component of the dayside field at geosynchronous orbit. We use the change of the B_Z component in Geocentric Solar Magnetospheric (GSM) coordinate system to determine the response of geosynchronous magnetic field.

Figure 1 presents an example of such observations. The left-side panels in this figure, from top to bottom show simultaneous measurements of geosynchronous B_Z-component at GOES-8 and GOES-10 and solar wind $P_{\rm d}$ and magnetic field at INTERBALL-1, WIND and IMP 8 on June 6, 2000. The right-side panel presents the positions of all spacecrafts and projection of the calculated leading pressure front at the $(X-Y)$ Geocentric Solar Ecliptic (GSE) plane (the method of such calculation was presented in Ref.[12]). Due to the pressure front inclination, a strong decrease in solar wind $P_{\rm d}$ from $\sim 6-8$ to $\sim$1 nPa first encountered IMP 8 at 16.14 Universal Time(UT), 10 minutes later reached INTERBALL-1 and after 2 minutes was observed at WIND. Consequently, geosynchronous magnetic field B_Z at GOES-8 located near 11.30 LT (where LT stands for local time) decreased by 35 nT from 16.28 to 16.35 UT. GOES-10 located near 7.30 LT also observed a decrease of 11.6 nT in B_Z that occurred from 16.33 to 16.37 UT.

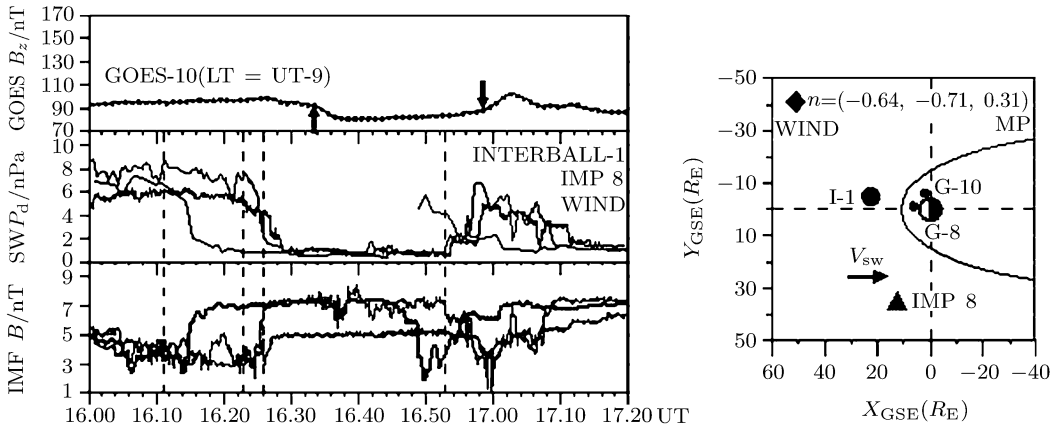


Fig.1. The response of geosynchronous magnetic field to the change in solar wind pressure. Left panels show simultaneous measurements of geosynchronous B_z component at GOES-8 and GOES-10 and solar wind plasma and magnetic field at INTERBALL-1, WIND and IMP 8 spacecrafts on June 6, 2000. The vertical dashed lines mark the start of change in the solar wind $P_{\rm d}$ and arrows mark the start of the corresponding changes at geosynchronous orbit. Right panel presents the positions of all satellites and projection of the calculated leading pressure front at the $(X-Y)$GSE plane. The components normal to the front are shown in this panel.

Half an hour later solar wind pressure increased (trailing front of this pulse), which was first observed again at IMP 8 (which had plasma data gap at this moment), then at 16.52 UT at INTERBALL-1 and 1 minute later at WIND. Both GOES-8 (at $\sim$ 12 LT) and GOES-10 (at $\sim$ 8 LT) observed the increase in $B_{\rm Z}$ near 16.53 – 54 UT.

It should be noted that during this event the magnitude of IMF (indicated in bottom panel of Fig.1) is oppositely changed in sign. Such a behaviour of IMF value is typical of large and sharp change in solar wind dynamic pressure. So, most of their values are tangentially discontinuous.

Thus, the evident similarity between the change in solar wind $P_{\rm d}$ and the response of magnetospheric magnetic field, demonstrated in this example, suggests that the change in solar wind $P_{\rm d}$ can result in the transient compression or decompression in the magnetospheric magnetic field.

4. Statistical survey

For statistical study we have selected 261 events of changes in solar wind $P_{\rm d}$ from two data sets that met our criteria. These data were observed by two or more spacecrafts and had a clear response of geosynchronous B_Z at one or two GOES satellites.

4.1. Comparison of the amplitudes of disturbances

Figure 2 presents the relationship between the amplitudes of changes in solar wind dynamic pressure d$P_{\rm d}$ and the corresponding changes in geosynchronous B_Z magnitude dB_Z for all events under consideration. Positive values of dB_Z indicate $P_{\rm d}$-increasing events while negative values are related to $P_{\rm d}$-decreasing events. The solid lines show the best fit to the pressure-increasing and decreasing events, correspondingly.

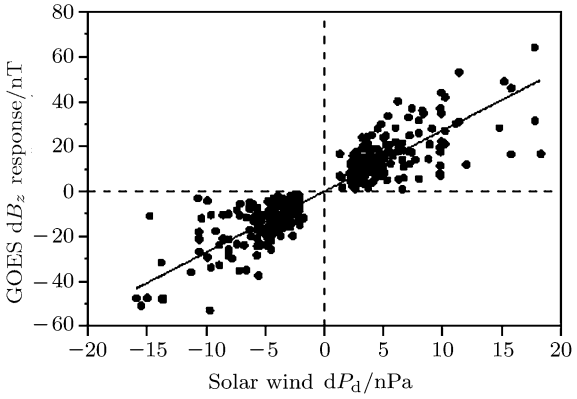


Fig.2. The relationship between d$P_{\rm d}$ of change in solar wind $P_{\rm d}$, and dB_z of corresponding change in geosynchronous B_z magnitude. Black points indicate events from the both data sets mentioned above. Solid line represents the best fit to all data.

The solar wind d$P_{\rm d}$ varies in a wide interval ranging from -16 to 18 nPa while dB_Z varies from -55 to 62 nT. One can see that the scattering of points is rather

large. The same solar wind d$P_{\rm d}$ causes different responses of geosynchronous B_Z and vice versa; similar responses of geosynchronous B_Z correspond to various amplitudes of changes in solar wind $P_{\rm d}$. Although the scattering of the dB_Z values is very large, on average the response amplitude of B_Z is proportional to the pressure change d$P_{\rm d}$. Definitely, in each case the increase of $P_{\rm d}$ resulted in an increase in geosynchronous B_Z and the decrease of $P_{\rm d}$ resulted in a decrease in geosynchronous B_Z for all LTs.

4.2. The local time dependence of the amplitude of geosynchronous response

Previous studies[4,5,7] revealed that the amplitude of response of the geosynchronous B_Z to the change in solar wind $P_{\rm d}$ strongly depended on the spacecraft position in local time. Such a dependence of response amplitude dB_Z of geosynchronous magnetic field on local time for our case is shown in Fig.3 by crosses.

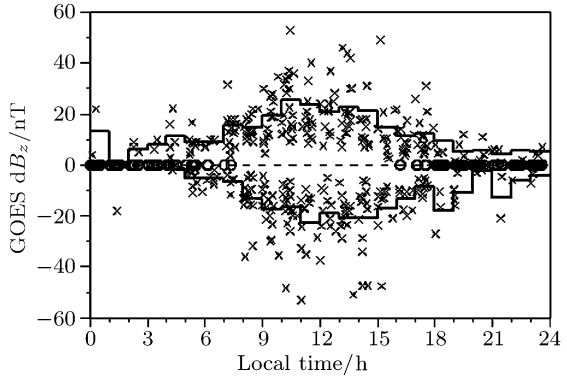


Fig.3. The dependence of response of geosynchronous B_z to the change in solar wind pressure in the local time (denoted by crosses). Circles denote solar wind events without obvious response of geosynchronous B_z. Solid lines show histograms of average dB_z responses in each one-hour local time bin for pressure-increasing and decreasing events.

Positive values of dB_Z are related to pressure-increasing events, while negative values of dB_Z indicate pressure-decreasing events. The histogram of average dB_Z responses in each one-hour local time bin is also shown in Fig.3 separately for the pressure-increasing and decreasing events. We can see again a large scattering of the points, especially around noon. However, in spite of the large data scattering the averaged dB_Z value obviously increases near noon and decreases toward dawn and dusk, which is similar to the results from previous studies. Circles in Fig.3 denote the events of solar wind $P_{\rm d}$ change without geosynchronous B_Z response, i.e. GOES satellites located at some LT indicated in Fig.3 observed zero amplitude of response to change in solar wind pressure. One can see that all events without magnetospheric response took place either on the dawn/night side before 7.30 LT or on the dusk/night side after 16.30 LT.

With two GOES satellites operating simultaneously it is possible to determine the difference of the amplitudes of response of the geosynchronous B_Z to the same event in the solar wind. Data selected in this way (shown in Ref.[7]) indicates that in each case the response amplitude of geosynchronous B_Z is higher at the satellite located more closely to the noon meridian. So, the decrease in the amplitude of the response to the sharp change in $P_{\rm d}$ with local time passing from noon agrees qualitatively with the results of previous studies for hourly averaged values.[4]

We determined the relative change in geosynchronous B_Z by the ratio between the response dB_Z and the geosynchronous magnetic field B_Z before the disturbance for our case. Figure 4 presents the dependence of relative B_Z responses (dB_Z/B_Z) on local time, separately for pressure- increasing events (positive values) and pressure-decreasing events (negative values). Solid lines represent the averaged value of dB_Z/B_Z in each local time bin. The dependence of dB_Z/B_Z on local time is much weaker than the dependance of dB_Z on local time shown in Fig. 3, and the averaged value of dB_Z/B_Z is only slightly larger at the position where GOES satellite was located nearer to the noon meridian. In other words, the relative B_Z response (dB_Z/B_Z) is weakly dependent on local time. It means that for smaller B_Z (far from noon) the response dB_Z is also smaller.

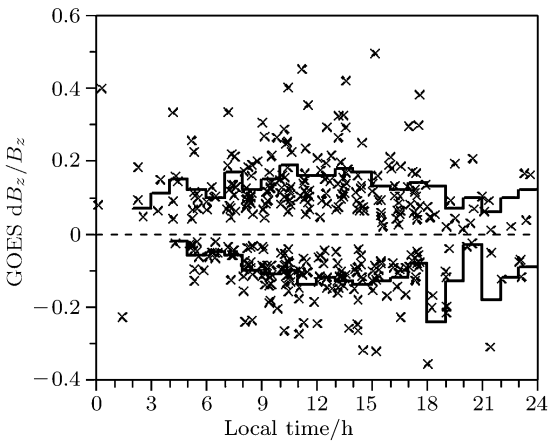


Fig.4. The dependence of relative B_Z responses (dB_Z/B_Z) on local time, for pressure-increasing (positive values) and decreasing events (negative values). Solid lines represent the averaged value of dB_Z/B_Z in each local time bin.

4.3. The dependence of the amplitude of disturbance (dB_z) on several parameters

From Fig.2 we can see the large scattering of values of geosynchronous responses dB_Z for the same amplitude of change in dynamic pressure, d$P_{\rm d}$. Figure 3 displays a large dispersion of dB_Z in the 9–15 hour local time range. We try to investigate what may be responsible for such a large scattering.

There are several possible sources affecting the response amplitude of geosynchronous B_Z. Here they are the amplitude of change in solar wind pressure, value of pressure before the change, value of geosynchronous B_Z, the local time (LT) of observer, the strong inclination of pressure front and some other sources. From the factors listed above we can exclude the value of geosynchronous B_Z component, because in the first approximation it depends mainly on solar wind pressure; a higher solar wind pressure results in a stronger geosynchronous magnetic field. Geosynchronous magnetic field depends also on local time, reaching a maximum value near noon and decreasing at midnight.

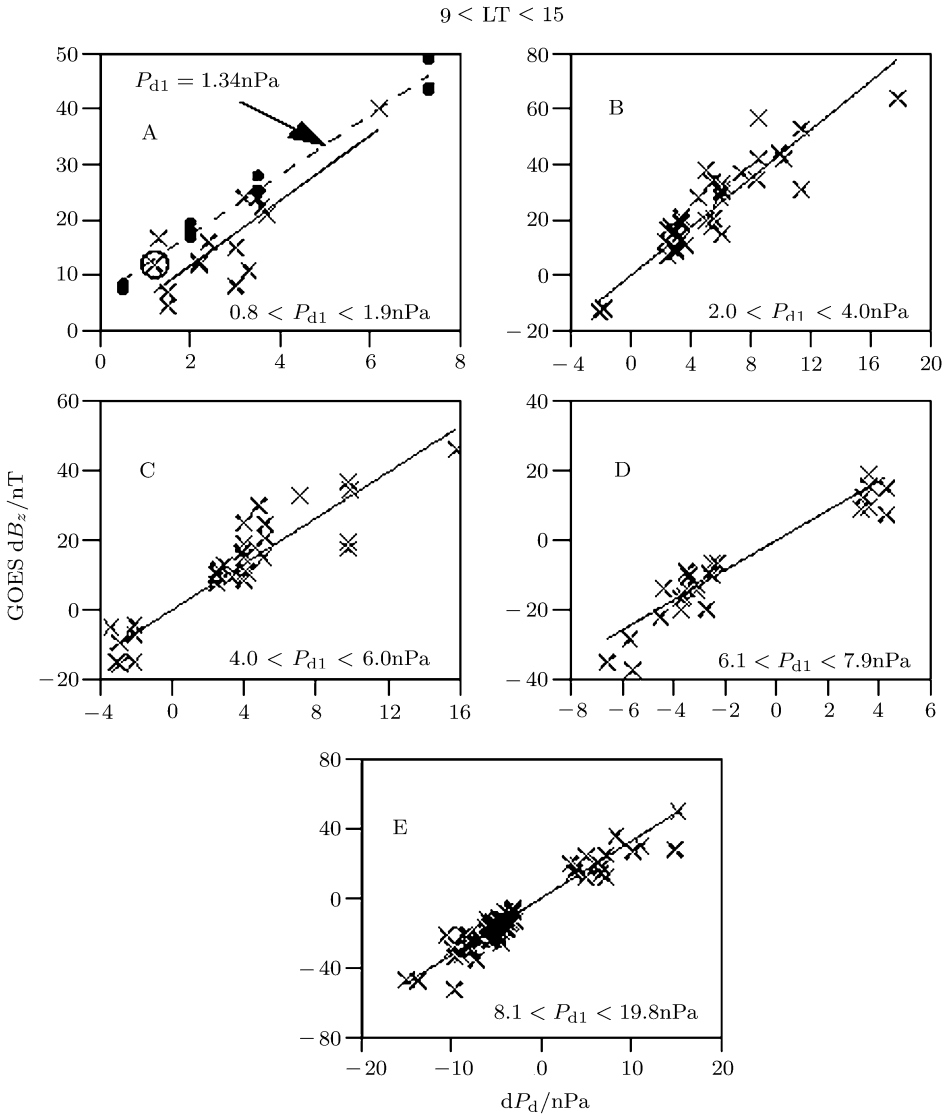


Fig.5. Relationship between the amplitude of response of geosynchronous B_Z, dB_Z, and the amplitude of change in solar wind pressure, d$P_{\rm d}$ (denoted by crosses) for events in the 9 – 15 LT range. Each panel presents the data related to different narrow ranges of upstream pressure $P_{\rm d1}$ indicated on the panel. Solid lines represent best fits to the data. Black points and dashed line on panel A represent results of numerical simulation. A small circle marks the event with the same initial pressure $P_{\rm d1}$ = 1.34 nPa as the value used in numerical simulation.

We decide to investigate the dependence of magnetospheric response in the 9–15-h local time range (of large scattering) on the amplitude of change in solar wind $\mathrm{d}P_\mathrm{d}$ for different initial states of magnetosphere, i.e. whether or not the magnetosphere is compressed before the arrival of pressure change. To verify it, we divide our events into five categories in accordance with the values of initial solar wind P_d that compresses the magnetosphere. The relations between the amplitude of change in the solar wind $\mathrm{d}P_\mathrm{d}$ and $\mathrm{d}B_Z$ at the geosynchronous orbit for different values of initial/upstream solar wind dynamic pressure $P_{\mathrm{d}1}$ are marked by crosses in Fig.5. Each panel shows the dependence of $\mathrm{d}B_Z$ on $\mathrm{d}P_\mathrm{d}$ in a rather narrow range of $P_{\mathrm{d}1}$ indicated on the panel. Positive values correspond to pressure-increasing events, negative values are related to pressure-decreasing events. Solid lines on panels in Fig.5 indicate linear fits to selected categories of the events drawn through the origin. We can see that such a selection allows us to obtain a better proportionality between B_Z and $\mathrm{d}P_\mathrm{d}$ values. The slope of the linear fit changes and has a clear tendency to decrease with the initial solar wind pressure increasing from 5.9 for $0.8< P_\mathrm{d}1 < 1.9$ nPa to 3.3 for a high range $8.1< P_\mathrm{d}1 < 19.8$ nPa. It means that, on average, under the same amplitude of change in solar wind P_d the geosynchronous B_Z response is higher for the case in which the magnetosphere is less precompressed.

4.4. MHD simulation

In order to interpret the observations, we use our recently developed three-dimensional MHD code PPMLR-MHD[13] to simulate the response of geosynchronous magnetic field to the change in solar wind P_d. This code has been extended to its parallel version and used to study the interaction of the interplanetary shocks with the magnetosphere.[14]

The initial interplanetary magnetic field is assumed to be the Parker field (-3, 3, 0) nT. After the magnetosphere has reached a steady state, we introduce the solar wind disturbances from the upstream direction and mimic the change in solar wind P_d by changing the solar wind density only. In the simulating of the main features presented in Fig.5, we choose a solar wind P_d as $P_{\mathrm{d}1} = 1.34$ nPa, which corresponds to the middle of upstream pressure interval, presented in panel A of Fig.5, to simulate the response of geosynchronous B_Z to the change in pressure in the 9–15 LT range. The result is shown in panel A of Fig.5 by black points. Dashed line indicates the linear fit to our simulation. It is seen that MHD calculations are fairly close to experimental results though there exists a little bit large discrepancy in between. A small circle marks the event with the same initial pressure $P_{\mathrm{d}1} = 1.34$ nPa as the value used in the numerical simulation. This event coincides very well with the simulation result.

So, we can conclude that for a range of low $P_{\mathrm{d}1}$ the numerical and measured results qualitatively and even quantitatively match each other, i.e. the amplitude of response of geosynchronous magnetic field is proportional to the amplitude of change in solar wind pressure under a constant upstream solar wind $P_{\mathrm{d}1}$.

It should be noted that our MHD simulation result also gives the qualitative dependence of amplitude of response of the geosynchronous magnetic field on the local time, which is similar to the experimental result.

5. Conclusions

1. The sharp and large changes in solar wind dynamic pressure ($\mathrm{d}P_\mathrm{d}$) always correspondingly produce some disturbances to a geosynchronous magnetic field ($\mathrm{d}B_Z$) in response.

2. These responses are clearly seen on the day side of magnetosphere but may be very small on the nightside.

3. The amplitude of response is a complicated function of the value of dynamic pressure before change $P_{\mathrm{d}1}$ (decreasing as the latter increases), amplitude of the change in pressure, the value of geosynchronous magnetic field (increasing as the latter increases) and the value of local time of observations (having a maximum near the local noon).

4. When we select a rather narrow range of the dynamic pressure before it changes and local time around noon, we obtain a clear relationship between amplitudes of change in sharp dynamic pressure and amplitudes of geosynchronous response.

5. The recently developed 3D MHD code can be used to simulate fairly well for low $P_{\mathrm{d}1}$ values the experimental response of B_Z to $\mathrm{d}P_\mathrm{d}$.

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