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Geospace magnetic field responses to interplanetary shocks

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[1] We perform a statistical survey of geospace magnetic field responses, including the geosynchronous magnetic field and the sudden impulses on the ground, to interplanetary shocks (IP shocks) between 1998 and 2005. The magnitude of the geosynchronous magnetic field (dB_z) responses to IP shocks depends strongly on local time, which peaks near the noon meridian; however, the relative magnitude of the responses depends only weakly on local time. These results are similar to those obtained from the statical study of the responses to solar wind dynamic pressure pulses. However, negative responses (where dB_z is negative) were sometimes observed in the nightside of the magnetosphere even though the IP shocks always caused increases in the solar wind dynamic pressure, a new phenomenon not widely reported in the literature. Our analysis shows that ~75% of negative responses in the midnight sector are associated with southward interplanetary magnetic field. For a moderately compressed magnetosphere, the amplitude of the geosynchronous response dB_z could be determined by the average value of the background local magnetic field. As the magnitude of the upstream solar wind dynamic pressure increases, the rate of response increases correspondingly. The dB_z at the geosynchronous orbit near local noon and the amplitude of sudden impulses (dSYM-H) on the ground are highly correlated.

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1. Introduction

[2] Changes in solar wind dynamic pressure (P_d) affect the magnetosphere and perturb the magnetosphere-ionosphere system. The manifestations of those disturbances include changes in the magnetic field at the geosynchronous orbit and sudden impulse (SI) observed by ground-based magnetometers. The SIs include positive sudden impulse (SI^+), negative sudden impulse (SI^-) and SI^+-SI^-.

[3] The response of the geosynchronous magnetic field to the interplanetary disturbances has been studied by several authors. *Rufenach et al.* [1992] showed that for quiet conditions, the average value of the magnetic field measured by the GOES satellites at geosynchronous orbit increases when the hourly averaged solar wind dynamic pressures increases. *Borodkova et al.* [1995] and *Sibeck et al.* [1996] found a direct correspondence between dayside magnetospheric magnetic field changes and step function decreases and increases in the solar wind P_d. Using hourly averaged data, *Wing and Sibeck* [1997] investigated the effects of interplanetary magnetic field (IMF) z component and the solar wind dynamic pressure P_d on the geosynchronous magnetic field. *Sanny et al.* [2002] showed that the variability of the geosynchronous magnetic field strength near local noon was strongly affected by changes in the P_d but independent of the IMF B_z. *Lee and Lyons* [2004] indicated that the geosynchronous response to solar wind P_d enhancement is mostly compressional on the dayside, while when the IMF is southward the response is similar to dipolarization on the nightside. *Moldwin et al.* [2001] found that pressure pulses associated with IMF Bz southward are either absent or give rise to smaller compressions in the study of the magnetotail responses to solar wind pressure pulses. *Borodkova et al.* [2005] demonstrated that sharp increases (decreases) in the solar wind P_d always result in increases (decreases) in the geosynchronous magnetic field strength with the maximum amplitude near noon. Further study by *Borodkova et al.* [2006] indicated that the amplitude of magnetic field response in geosynchronous orbit strongly depends on the location of observer, the value of pressure before disturbance and the change in the amplitude of the pressure. *Wang et al.* [2007] studied the magnetic field response at geosynchronous orbit to solar wind P_d pulses, and showed that the magnitudes of the responses peak near the noon meridian, consistent with previous work focusing on the responses to the sharp and large solar wind dynamic pressure changes. However, the relative magnitudes of the responses of the geosynchronous magnetic field depend weakly on local time. The most frequently observed interplanetary shocks at 1 AU are fast forward shocks [e.g., *Richter et al.*, 1985], which can cause significant solar wind P_d changes in a short time scale. However, the response of magnetic field at geosynchronous

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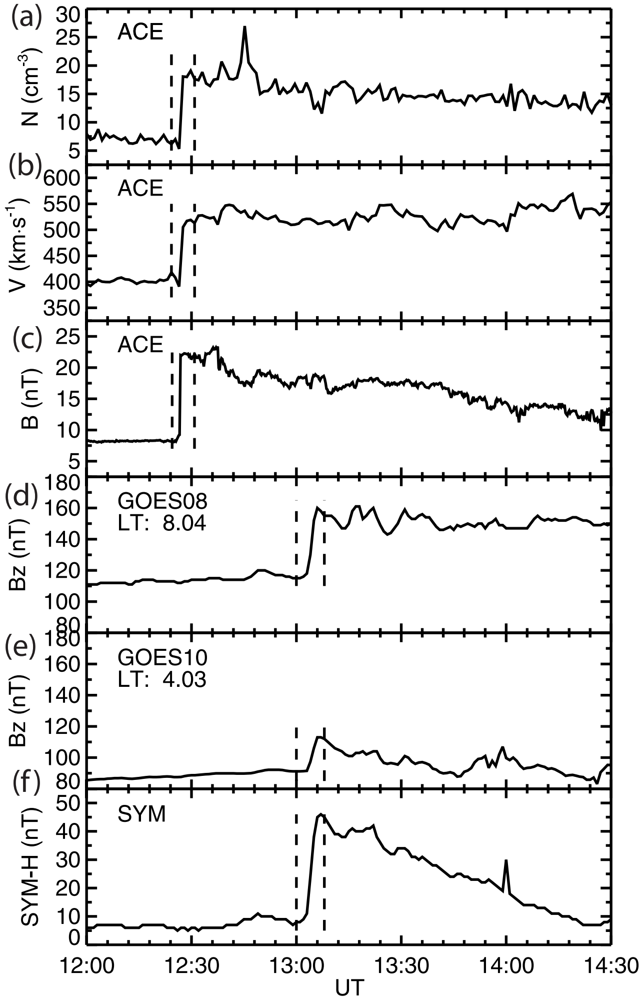

Figure 1. The response of the geosynchronous magnetic field and the sudden impulse caused by an interplanetary shock on 23 June 2000. (a) The solar wind number density, (b) speed, (c) magnetic field observed by the ACE spacecraft, the geosynchronous magnetic field z component B_z observed at the (d) GOES 8 and (e) GOES 10 spacecraft, and (f) SYM-H.

orbit to interplanetary shocks has not been specifically investigated.

[4] Interplanetary shocks cause sudden impulses (SIs) on the ground. The term sudden storm commencement (SSC) indicates the sudden rise in magnetic field strength at the beginning of the initial phase of a geomagnetic storm, whereas sudden impulses can also occur during the main phase of a storm or even outside the interval of a storm period. Quantitative studies reveal a good correlation between the SI amplitude at the low latitudes stations at noon and the change in the square root of the solar wind dynamic pressure across the shock/discontinuitiy [*Russell et al.*, 1992, 1994a, 1994b]. The response varies with local time [*Russell et al.*, 1992] and the direction of the interplanetary magnetic field (IMF) [*Russell et al.*, 1994a, 1994b]. *Wang et al.* [2006] surveyed interplanetary (IP) shocks and storm sudden commencements (SSCs) observed between 1995 and 2004, and found that about 75% of SSCs are associated with shocks, and the orientation of the IP shock (i.e., the angle between the shock normal and the Sun-Earth line) affects the SSC rise time. Since the sudden impulses and the response of the geosynchronous magnetic field are both caused by IP shocks, it is of interest to investigate the association between the sudden impulses on the ground and the geosynchronous magnetic field responses. The data sources and methodology are introduced in section 2. The statistical results are presented in section 3, and the summary is given in section 4.

2. Data Sets and Methodology

[5] Since launch in 1998, the ACE satellite has orbited the Earth-Sun L1 point and provided continuous upstream solar wind data. IP shocks were identified in the ACE 64 s time resolution solar wind data for the period 1998.02–2005.04, which can be obtained from http://www.srl.caltech.edu. We use geosynchronous observations with 1-min resolution magnetic field data from GOES 8, GOES 10, and GOES 12 http://goes.ngdc.noaa.gov) which cover the same time range. Then we associated these IP shocks with disturbances in the geosynchronous magnetic field. As shown later, the geosynchronous magnetic field responses are usually observed by two or more GOES satellites.

[6] The geomagnetic indices SYM-H [*Iyemori*, 1990] are derived by averaging the H (south-north direction) component of the magnetic field observations from 6 ground stations, which is randomly selected from a station group of 10 low- to middle-latitude stations. The SYM-H index is essentially the same as the hourly *Dst* index except that the SYM-H index provides 1-min time resolution. We use the indices SYM-H (available at http://swdcwww.kugi.kyoto-u.ac.jp) to determine the amplitudes and rise times of SIs and their association with IP shocks.

[7] Figure 1 presents a typical example of the geosynchronous magnetic field response and a sudden impulse caused by the interplanetary shock on 23 June 2000. Since the z component in the GSM coordinate system of the magnetic field at geosynchronous orbit dominates, we choose this component only to describe the geosynchronous magnetic field response. Figures 1a–1c show the solar wind number density, speed, and interplanetary magnetic field (IMF) $|B|$, respectively, observed by ACE on 23 June 2000. Figures 1d and 1e show the geosynchronous magnetic field Bz component from the GOES 8 and GOES 10 spacecraft, and Figure 1f shows the geomagnetic indices SYM-H index. At 1227 UT, ACE (at (219.5,8.6,−27.5)Re GSM) observes an interplanetary shock with a density ratio of about 2.6 and a speed of 634 km s^{-1}. About 36 min later, GOES 8 (at ~0800 LT) and GOES 10 (at ~0400 LT) simultaneously detect the geosynchronous B_z response, with 41.8 nT and 21.5 nT increases in magnitude. The sudden impulse is also clearly indicated by the SYM-H increase in 1304 UT. With the solar wind conditions priori to the shock, the distance to the magnetopause is estimated to be about 10 Re. Assuming the shock propagated with a constant speed of 634 km s^{-1}, it took about 35 min for the shock to travel from ACE to the magnetopause, in agreement with

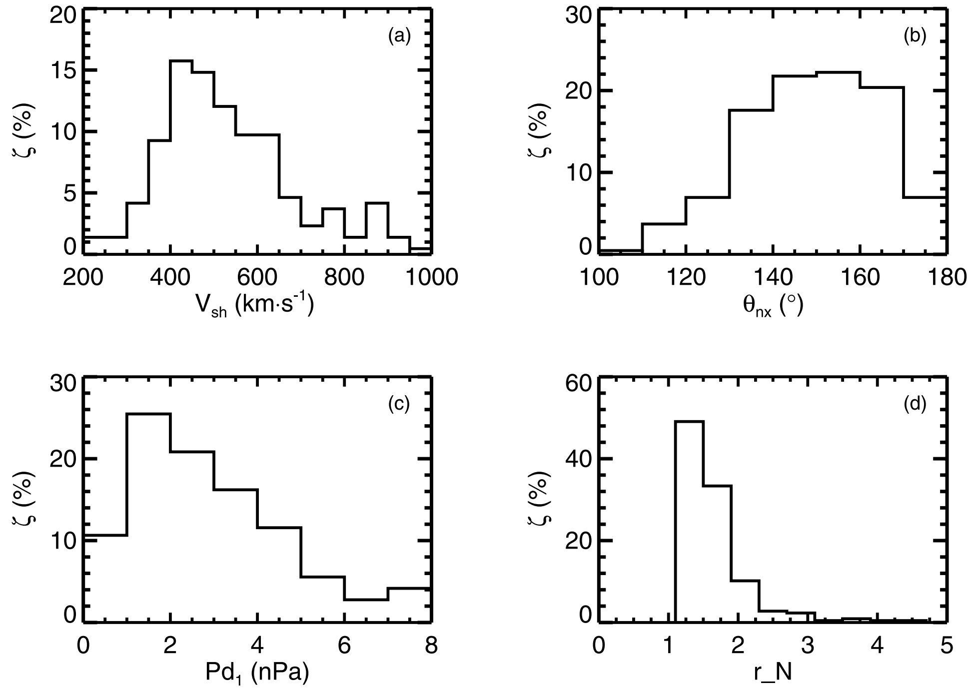

Figure 2. Statistical properties of the selected 216 IP shocks. The percentages of these IP shocks are plotted as a function of (a) the shock speed V_{sh}; (b) the shock orientation, i.e., the angle between the shock normal and the GSE *x* axis (θ_{nx}); (c) the upstream solar wind dynamic pressure (Pd_1); and (d) the density ratio (r_N).

the delay time of the geospace response to the IP shock at ACE.

3. Statistical Survey

[8] The same IP shock list as in our previous work [*Wang et al.*, 2006] is used in this study. The approach to find IP shocks and calculate shock parameters is summarized here. First, we applied an autosearch computer program to find potential shock and shock-like solar wind structures in the ACE data sets, and then visually inspected each event. We identified 250 fast forward IP shocks in the solar wind data between 1998.02 and 2005.04. For each shock case, Magnetic Coplanarity (MC), Velocity Coplanarity (VC), three Mixed methods (MX1, MX2, MX3) [*Schwartz*, 1998], and the Rankine-Hugoniot method were used to determine the shock normal, shock speed, and Mach number [*Berdichevsky et al.*, 2000]. We selected the IP shocks which had corresponding responses of the geosynchronous magnetic field observed by at least one of the GOES series satellites. We required changes in the geosynchronous magnetic field of at least 3 nT to include an event in this study. Using this criterion, 216 out of all the 250 IP shocks or ~88% of shock events during this time period had corresponding response of the geosynchronous magnetic field observed by GOES satellites. Furthermore, all of the 216 IP shocks also had corresponding effects in the SYM-H index. Figure 2 shows the statistical properties of the selected 216 IP shocks. The percentages of these IP shocks are plotted as a function of the shock speed V_{sh} (Figure 2a); the shock orientation, i.e., the angle between the shock normal and the GSE *x* axis (θ_{nx}) (Figure 2b); the upstream solar wind dynamic pressure (Pd_1) (assuming 100% protons) (Figure 2c); and the density ratio (r_N) (Figure 2d). Most of these IP shocks have speeds of 350–650 km s^{-1} with the average speed near 500 km s^{-1}, upstream solar wind dynamic pressures of 1–6 nPa, and a density ratio of 1–2.5 nPa. Most of the shock orientations are in the range 130–170°; an angle of 180° indicates the shock is antiparallel to the Sun-Earth line and thus hits the magnetosphere head-on. In the following sections, we will perform a statistical survey on the geosynchronous magnetic field responses and sudden impulses on the ground associated with these IP shocks.

3.1. Geosynchronous Magnetic Field Responses to IP Shocks

[9] The GOES spacecraft observed geosynchronous magnetic field responses associated with the 216 IP shocks with different amplitudes at different local times. Previous work shows that the magnetospheric response to sudden changes in solar wind P_d strongly depends on whether the magnetosphere is quite or disturbed [*Wing and Sibeck*, 1997; *Borodkova et al.*, 2005]. We chose only those cases when magnetosphere is quiet ($Dst > -30$), the total number of which is 173, to perform a statistical study of the dependence of the geosynchronous magnetic field response versus local time. Figure 3 gives the local time dependence of the amplitude of the geosynchronous B_z responses dB_z (Figure 3, left), and the relative amplitude dB_z/AV-B_z (Figure 3, right), where AV-B_z is the time-averaged B_z value during the response period. Each point in Figure 3 denotes one geosynchronous B_z response observed by one of the GOES spacecraft. More responses were observed in the dayside regions than in the nightside regions. The amplitude of the data

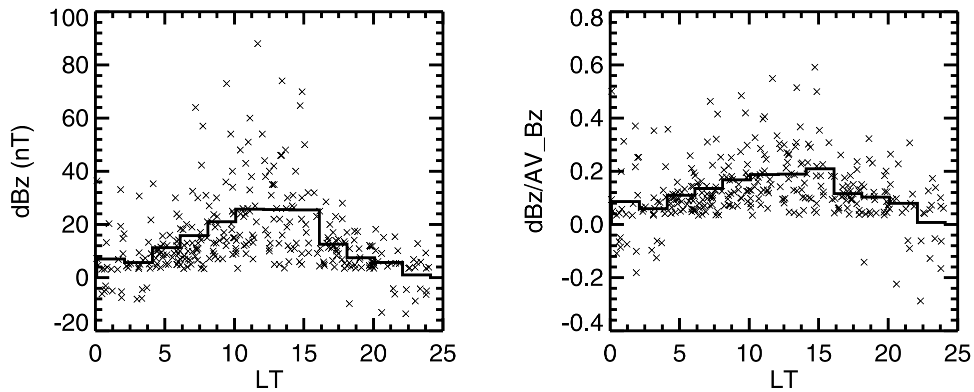

Figure 3. Dependence of (left) the amplitude dB_z and (right) the relative amplitude dB_z/AV-B_z of geosynchronous magnetic field response on local time.

scatter is largest at the noon meridian and decreases toward the nightside. The solid lines in the histograms in Figure 3 shows the average dB_z and dBz/AV-B_z values in each 1-h local time bin. While the dependence of B_z on local time is relatively strong with a peak near the noon meridian, the dependence of the relative amplitude dB_z/AV-B_z is much weaker, similar to the responses to the fast and large solar wind dynamic pressure P_d [e.g., *Borodkova et al.*, 2005] and solar wind dynamic pressure pulses [*Wang et al.*, 2007]. However, there are 21 negative responses (where dB_z is negative) in the nightside of the magnetosphere even though the IP shocks always cause increases in the solar wind dynamic pressure, a new phenomenon which has not been widely reported in the literature. For each "negative dBz" interval, we find that there is a decrease in the total field. Figure 4 gives an example of an event which occurred on 7 November 2004. The ACE satellite observed an IP shock with solar wind dynamic pressure increase at the L1 point around 1000 UT, and the IMF B_z is northward. About 50 min later, the geosynchronous magnetic fields observed by the GOES 10 and GOES 12 satellites, and SYM-H index all showed responses. During this events, GOES 10 was in the midnight region while GOES 12 was in the dawn region. Although the response of the geosynchronous magnetic field observed by GOES 12 increases as expected, the response observed by GOES 10 shows a very sharp decrease of B_z in the midnight region. Of the magnetospheric current system, an increase of the tail current could probably result in such a decrease. A negative response to the IP shock at synchronous orbit in the midnight sector indicates enhancement of cross-tail current in the near-Earth plasma sheet (within ~20 Re), which can be reproduced by an global MHD simulation regardless of IMF orientations [*Wang et al.*, 2005]. For IMF southward cases, enhancement of the plasma sheet current is driven by enhanced reconnection at the dayside magnetopause [*Kan*, 1990], making negative responses more likely to happen. Our analysis shows that ~75% of negative responses (16 out of 21 cases) in the midnight sector are associated with southward IMF.

[10] Figure 5 shows the dependence of the magnitude of the geosynchronous magnetic field responses (dB_z) to IP shocks on the time-averaged local magnetic field (dB_z/AV-B_z). In order to exclude the affects of the solar wind dynamic pressure P_d, we classified them into three groups on the basis of the upstream solar wind P_{d1}, (1) 0–1.5 nPa, (2) 1.5–2.5 nPa, and (3) 2.5–4.0 nPa, to account for the compression condition of the magnetosphere before the IP shock passage. The dashed lines in Figure 5 give linear fits to the observations. When the magnetosphere is moderately

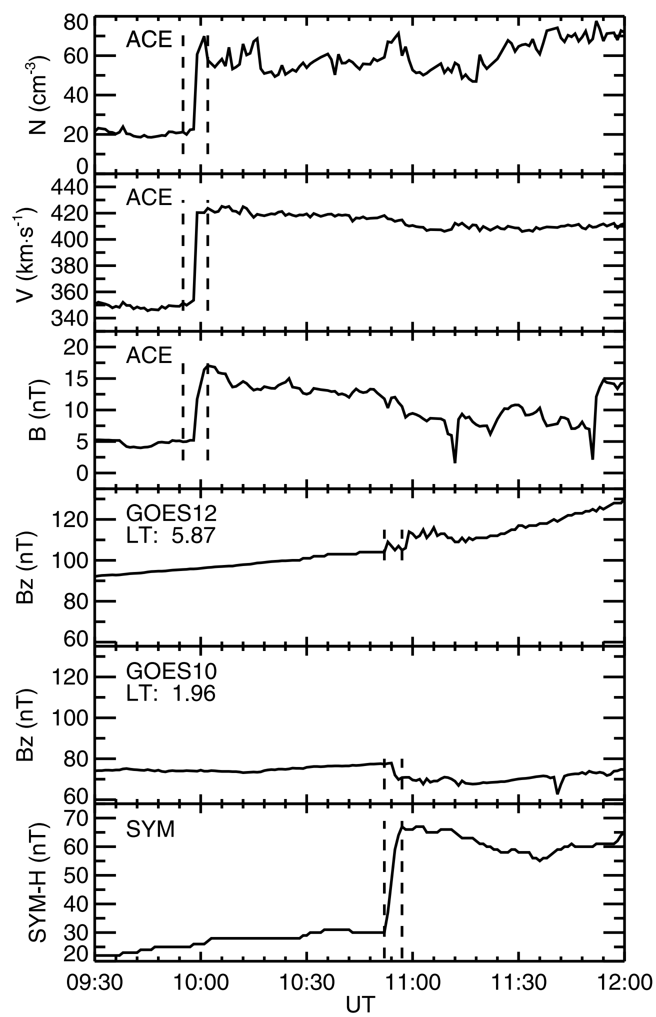

Figure 4. An example of the negative response of the geosynchronous magnetic field caused by the interplanetary shock on 7 November 2004. The format is the same as in Figure 1.

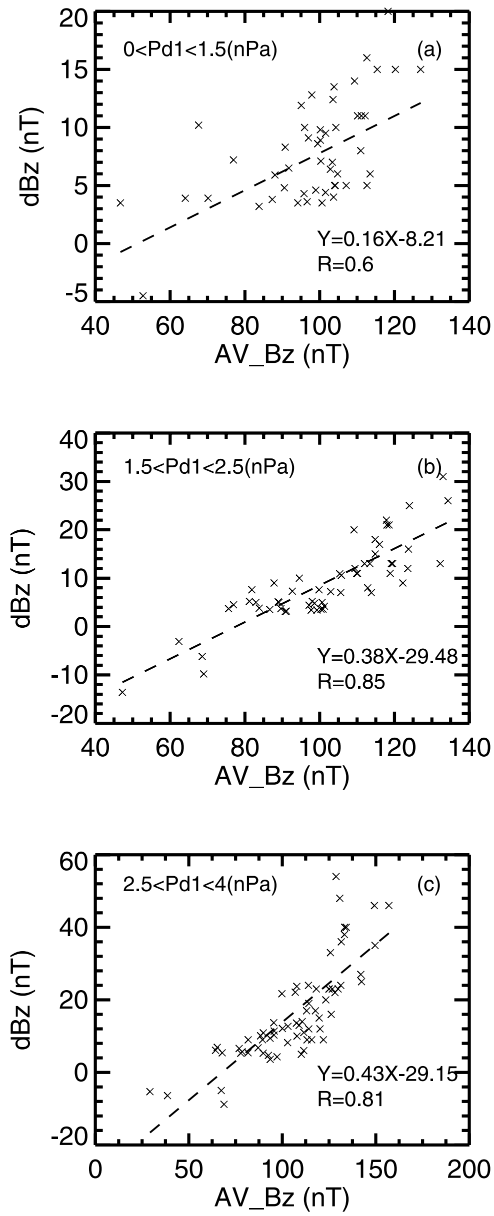

Figure 5. Relationship between the amplitude of the geosynchronous B_z response (dB_z) and the time-averaged geosynchronous B_z (AV-B_z).

compressed, i.e., the upstream solar wind dynamic pressure is in the range of [1.5, 2.5] nPa and [2.5, 4.0] nPa, the amplitude of dB_z is proportional to the value of AV-B_z, with correlation coefficients of more than 0.81. However when the solar wind upstream P_d is in the range of [0, 1.5] nPa, the linear fit is not as strong as the previous cases, with a correlation coefficient of only 0.6. As the magnitude of the upstream solar wind P_d increases, the slope of the linear fit line increases as well; that is, the rate of geosynchronous magnetic field change increases correspondingly. We do not discuss the cases when the magnetosphere is heavily compressed (i.e., P_{d1} > 4 nPa), since they are rare. We conclude that for a moderately compressed magnetosphere, the amplitude of the geosynchronous B_z response is mainly determined by the value of AV-B_z, while the upstream solar wind P_d affects the slope of this dependence.

[11] The change of geosynchronous magnetic field (dB_z) is affected by the Chapman-Ferraro current, especially around the subsolar region, which is very sensitive to the change of the square root of the solar wind dynamic pressure ($d\sqrt{P_d}$) [*Sanny et al.*, 2002]. Figure 6 shows the dependence of dB_z on $d\sqrt{P_d}$ when GOES satellite observed the magnetic field in the local time from 0900 to 1500 LT. The dashed line gives the linear fit of the data, with a correlation coefficient of 0.84. The change of geosynchronous magnetic field (dB_z) around the subsolar region is thus mainly determined by the change of the square root of the solar wind dynamic pressure across the corresponding IP shock.

3.2. Relationship Between the Amplitude of Sudden Impulses and IP Shocks

[12] Using the T89 model, *Russell et al.* [1994a] indicates for northward IMF B_z, there is 18.3 nT/1 (nPa)$^{1/2}$ magnetic field increase at noon at the Earth's surface and 14.9 nT/1 (nPa)$^{1/2}$ increase on the night side during the passage of the IP shocks, which were determined by their observation data. The SYM-H can be regarded as the average value of ground station magnetic field responses in the horizontal direction for all local times. We use the SYM-H index to estimate the amplitude of sudden impulses (dSYM-H) caused by the IP shocks. Figure 7 shows the dependence of dSYM-H on the change of square root of solar wind dynamic pressure. The dashed lines represent linear fits to the observations. For $Dst > -30$ nT, the correlation coefficient R is about 0.68 as plotted in Figure 7a. The events are then classified into 3 groups on the basis of the upstream solar wind P_d as in Figure 5: [0, 1.5], [1.5, 2.5], and [2.5, 4.0] nPa, the results are plotted in Figures 7b–7d. The correlation coefficients between dSYM-H and $Pd_2^{1/2} - Pd_1^{1/2}$ are 0.83, 0.69 and 0.69, respectively. The amplitude of sudden impulses correlates better with the change of square root of solar wind dynamic pressure when the magnetosphere is less compressed.

3.3. Relationship Between SYM-H Responses and the Geosynchronous Magnetic Field Responses

[13] IP shocks change the magnetospheric current system, thus causing the variation in the magnetic field both at

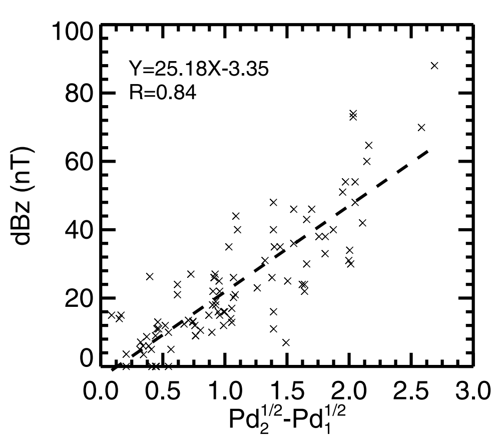

Figure 6. Dependence of the change of geosynchronous magnetic field (dB_z) in the local time from 0900 to 1500 LT on the change of the square root of the solar wind dynamic pressure, where the subscripts 1 and 2 denote the state upstream and downstream of a IP shock, respectively.

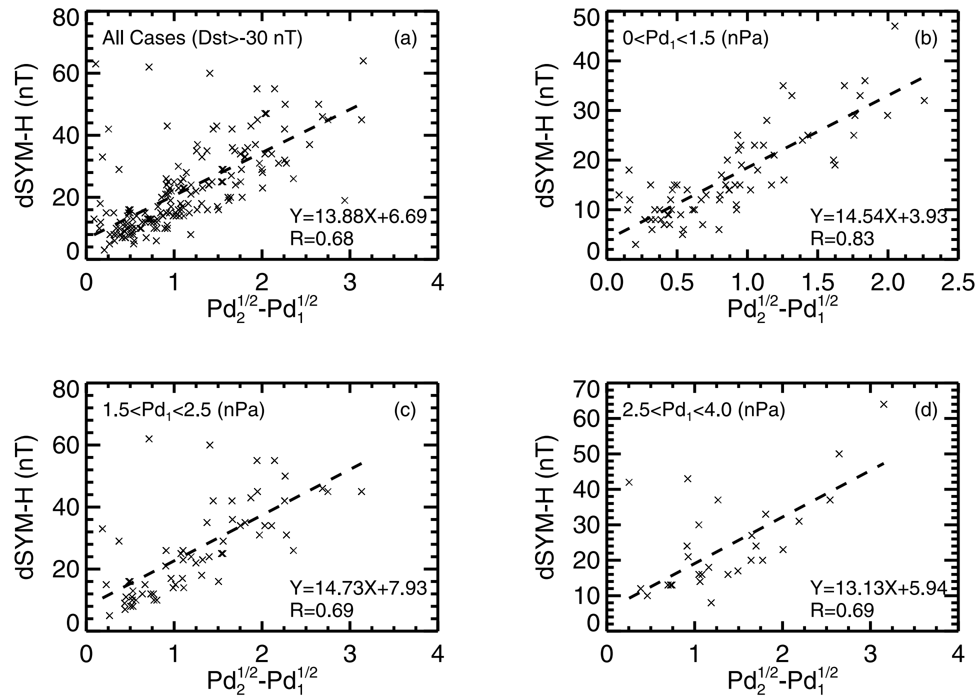

Figure 7. Dependence of the amplitude of sudden impulses dSYM-H on the change of the square root of the solar wind dynamic pressure for different upstream solar wind dynamic pressure Pd_1 in quiet time (Dst > -30 nT): (a) all cases, (b) $0 < Pd_1 < 1.5$ nPa, (c) $1.5 < Pd_1 < 2.5$ nPa, and (d) $2.5 < Pd_1 < 4.0$ nPa.

geosynchronous orbit and on the ground. The dominant magnetospheric current vary with local time at geosynchronous orbit. For example, the magnetopause current or Chapman-Ferraro current dominates in the subsolar region [*Borodkova et al.*, 2005, 2006] whereas in the midnight region the cross-tail current, the C-F current, and the substorm current wedge are all important [*Wing and Sibeck*, 1997]. The fast plasma sheet flow may have a significant effect [*Ohtani et al.*, 2006] and the Birkeland currents contribute in the dawn and dusk regions [*Wing and Sibeck*,

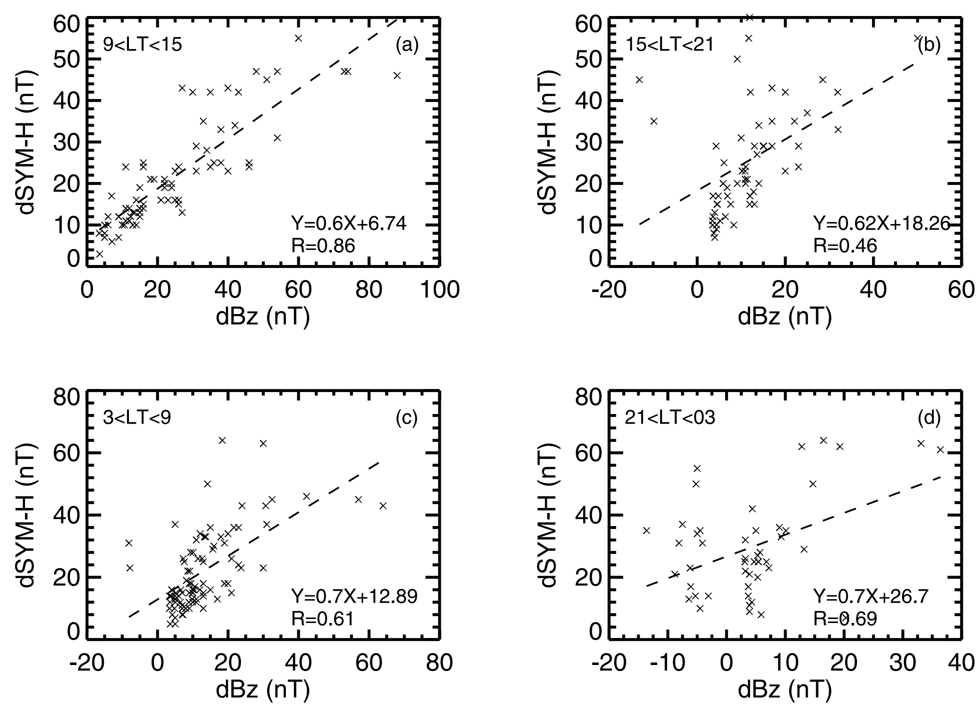

Figure 8. Relationship between the amplitude of sudden impulses dSYM-H and the geosynchronous magnetic field responses dB_z in the regions of (a) subsolar, (b) dusk, (c) dawn, and (d) midnight. The dashed lines denote linear fits to the observations.

1997]. Except for the Region 1 FACs, all current systems contribute to the SYM-H [*Kamide and Maltsev*, 2007]. In an attempt to relate the change of SYM-H on the ground to the magnetic field change at geosynchronous orbit, we group the geosynchronous magnetic field responses into 4 categories on the basis of the region they observed: (1) subsolar region (0900–1500 LT), (2) dusk region (1500–2100 LT), (3) dawn region (0300–0900 LT), and (4) midnight region (2100–0300 LT). Figure 8 shows the correlation between dSYM-H and dBz for these regions. The dashed lines show linear fits to the observations. The correlation coefficient R between the amplitude of sudden impulses dSYM-H and the geosynchronous magnetic field responses dB_z are 0.86, 0.46, 0.61 and 0.61 in the subsolar, dusk, dawn, and midnight regions, respectively. Probably because dBz at geosynchronous orbit and dSYM-H on the ground are mainly affected by the Chapman-Ferraro current in the subsolar region, they are highly correlated. Therefore, we can estimate the geosynchronous magnetic field responses dB_z around the subsolar region by measuring the amplitude of sudden impulses dSYM-H on the ground.

4. Discussion and Summary

[14] We perform a statistical survey of the geosynchronous magnetic field response and the sudden impulses on the ground to interplanetary shocks between 1998.02 and 2005.04. We find 216 out of all the 250 IP shocks produce geosynchronous magnetic field responses observed by GOES satellites and changes in the SYM-H index (sudden impulses). For the other 34 IP shocks, the GOES satellites happened to be located on the nightside and the dynamic pressures prior to the IP shock arrival were relatively smaller, therefore they did not detect significant changes of the geosynchronous magnetic field. We choose events in geomagnetic quiet times, with $Dst > -30$, for our statistical study. The main points of this study are:

[15] 1. The magnitude of the responses of the geosynchronous magnetic field (dB_z) to IP shocks peaks near the noon meridian, however the relative magnitude of the responses of the geosynchronous magnetic field (dB_z/AV-B_z) depends only weakly on local time. These statistical results are not sensitive to the choice of averaging time interval. These results are similar to previous work focusing on the geosynchronous response to sharp and large solar wind dynamic pressure changes and to dynamic pressure pulses. There are 21 negative responses (where dB_z is negative) in the nightside magnetosphere even though the IP shocks always cause increases in the solar wind dynamic pressure. Our analysis shows that $\sim$75% of negative responses in the midnight sector are associated with southward IMF.

[16] 2. For a moderately compressed magnetosphere, with the upstream solar wind dynamic pressure is in the range of [1.5, 2.5] nPa and [2.5, 4.0] nPa, the amplitude of the geosynchronous B_z response is mainly determined by the value of AV-B_z, while the upstream solar wind P_d affects the slope of this dependence.

[17] 3. The change of geosynchronous magnetic field (dB_z) around the subsolar region is mainly determined by the change of the square root of the solar wind dynamic pressure across the corresponding IP shock, while the amplitude of sudden impulses correlates better with the change of square root of solar wind dynamic pressure when the magnetosphere is less compressed.

[18] 4. The change of geosynchronous magnetic field (dB_z) at geosynchronous orbit near the subsolar region and the amplitude of sudden impulses dSYM-H on the ground are highly correlated.

[19] **Acknowledgments.** We acknowledge the use of data from ACE and GOES plasma and magnetic field experiments teams. This work was supported by grants NNSFC 40621003, 40674082, and 40831060 and in part by the Specialized Research Fund for State Key Laboratories of China. J.D.R also received support from NSF grant ATM-0207775.

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