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Quiet time variability of the geosynchronous magnetic field and its response to the solar wind

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[1] We present a survey of the variability of the geosynchronous magnetic field strength on the dayside using observations by the GOES satellites over a period exceeding 4 years. Only intervals of reduced geomagnetic activity, as defined by $Dst > -20$ nT, were considered in this study. The magnetic field strength data were filtered with a passband of 1.7 mHz to 17 mHz (1–10 minutes), a process that eliminates the diurnal variation of the field strength and the effects of most of the higher frequency (>17 mHz) ultralow-frequency (ULF) waves. The geosynchronous field strength appears to exhibit the greatest variability in the prenoon sector for spiral interplanetary magnetic fields (IMF) and in the postnoon sector for orthospiral IMF, suggesting that pressure pulses generated in the foreshock/bow shock region may have a significant influence on the geosynchronous field. The seasonal dependence of the variability was determined to be positively correlated to the seasonal dependence of ground-based observations of magnetic impulse events. The response of the variability of the geosynchronous magnetic field strength around local noon to solar wind parameters was also studied. Here, we observed that the variability was strongly affected by changes in the solar wind dynamic pressure but was seemingly independent of the northward/southward direction of the interplanetary magnetic field. However, for high solar wind dynamic pressures, the variability was found to be greater for northward IMF than for southward IMF. *INDEX TERMS:* 2784 Magnetospheric Physics: Solar wind/magnetosphere interactions; 2740 Magnetospheric Physics: Magnetospheric configuration and dynamics; 2752 Magnetospheric Physics: MHD waves and instabilities; 7835 Space Plasma Physics: Magnetic reconnection; 2731 Magnetospheric Physics: Magnetosphere—outer; *KEYWORDS:* variability, solar wind, geosynchronous magnetic field, dynamic pressure, IMF

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1. Introduction

[2] The geosynchronous magnetic field in the dayside magnetosphere is responsive to interactions between the solar wind and Earth's magnetosphere. The strongest changes occur during geomagnetic storms. While there are large-scale distortions of the nightside magnetosphere, dayside currents are also modified during such intervals, and this commonly results in large fluctuations of the geosynchronous field. Dayside ultralow frequency (ULF) pulsations associated with storms have been observed in many past studies. For example, *Barfield and McPherron* [1972, 1978] reported the presence of Pc 5 pulsations during the main phase of geomagnetic storms. The peak in their occurrence rate was in the 1200–1900 LT sector, which corresponds to the region of storm-associated enhancements of the partial ring current.

[3] During geomagnetically quiet intervals, the effects of variations in the interplanetary magnetic field (IMF) and in the solar wind dynamic pressure (P_d) on the geosynchronous magnetic field become more evident. For example, *Sibeck* [1994] presented case studies in which the dayside geosynchronous magnetic field strength decreased during periods when the IMF was directed southward. *Rufenach et al.* [1992] investigated the dependence of the components of the quiet geomagnetic field on P_d but not the IMF direction, using ground-based geomagnetic index criteria $AE < 120$ nT and $|Dst| < 20$ nT. They found that the quiet H field

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component increased with P_d, with the strongest dependence occurring around local noon and midnight, suggesting a tail current dependence on pressure. *Wing and Sibeck* [1997] correlated the geosynchronous magnetic field with both the IMF B_z component and P_d and found similar results to those of *Rufenach et al.* [1992]. They interpreted the geosynchronous field perturbations not only in terms of magnetospheric current systems but equivalently to the launching of fast rarefaction waves by magnetic merging occurring in the equatorial region for IMF $B_z < 0$ and at higher latitudes for IMF $B_z > 0$.

[4] The solar wind-magnetosphere interaction often produces transient events in the dayside magnetosphere observed as short-lived (~1 min) variations in magnetic field, plasma, and energetic particle parameters. Events marked by bipolar fluctuations in the magnetic field component normal to the nominal magnetopause and enhanced total magnetic field strengths were termed flux transfer events (FTEs) by *Russell and Elphic* [1978], who interpreted them as flux ropes of interconnected magnetospheric and magnetosheath magnetic field lines resulting from patchy, sporadic merging at the magnetopause. Although southward IMF orientation favors merging, specific events may be triggered by variations in solar wind parameters such as southward IMF turnings [*Lockwood et al.*, 1989; *Lockwood and Wild*, 1993] or dynamic pressure increases [*Elphic*, 1990]. Alternately, the trigger may be related to intrinsic instabilities at the magnetopause and not the solar wind, as suggested by *Le et al.* [1993]. Other proposed causes for the events include impulsive penetration of solar wind plasma filaments [*Lemaire*, 1977], the Kelvin-Helmholtz instability [*Southwood*, 1979], and solar wind/foreshock pressure pulse driven magnetopause motion [*Sibeck et al.*, 1989].

[5] Statistical studies of transient events observed near the dayside magnetopause [for example, see *Rijnbeek et al.*, 1984; *Berchem and Russell*, 1984; *Southwood et al.*, 1986; *Kuo et al.*, 1995; *Sanny et al.*, 1998] have found that the events occur predominantly during periods of southward IMF, a basic tenet of the sporadic merging model. These studies provide compelling evidence that transient events observed near the dayside magnetopause are indeed FTEs.

[6] Statistical studies of transient events observed deep in the magnetosphere or at geosynchronous orbit [for example, see *Kawano et al.*, 1992; *Borodkova et al.*, 1995; *Sanny et al.*, 1996, 2001] found that the occurrence of transient events had little dependence on IMF orientation and that the motion of the majority of the events agreed with the predictions of the pressure pulse model. The geosynchronous events result from the propagation of fast mode waves traveling through the magnetosphere that are produced by pressure pulses impinging on the magnetopause [*Sibeck*, 1993]. The pressure pulses may be inherent in the solar wind [*Burlaga and Ogilvie*, 1969; *Roberts et al.*, 1987] or generated in the foreshock region [*Fairfield et al.*, 1990]. Simulations by *Thomas et al.* [1995] and *Lin et al.* [1996a, 1996b] indicate that pulses can be generated in the foreshock region by ions streaming away from the quasi-parallel bow shock, particularly when the IMF changes its direction. These upstream pulses are then carried by the solar wind into the shock where interactions may produce large-amplitude pulses propagating downstream and impinging upon the magnetopause. The majority of geosynchronous transient events are observed in the prenoon sector [*Sanny et al.*, 2001]. This suggests that many of the events may be produced by pressure pulses generated in the foreshock/bow region since the prenoon magnetopause lies generally behind the quasi-parallel bow shock where such pulses are thought to be produced.

[7] Magnetospheric transient events are also mapped into the ionosphere since the events launch Alfvén waves that carry currents and electric fields down magnetic field lines to the ionosphere. These signatures are observed in high-latitude ground magnetograms and are called magnetic impulse events (MIEs). MIEs are characterized by changes (typically $\sim 10^2$ nT) in the vertical component of the magnetic field lasting several minutes. They have been considered to be the ionospheric signature of bursty merging at the magnetopause [*Sandholt et al.*, 1986; *Fukunishi and Lanzerotti*, 1989; *Mende et al.*, 1990] as well as the signature of events due to solar wind/bow shock pressure variations [*Friis-Christensen et al.*, 1988; *Sibeck*, 1993; *Sibeck and Korotova*, 1996]. It has also been suggested that MIEs may be associated not with a single mechanism but various simultaneous effects at the magnetopause [*Lanzerotti et al.*, 1990].

[8] Several statistical studies of MIEs [*Lanzerotti et al.*, 1991; *Hughes et al.*, 1995; *Sibeck and Korotova*, 1996] found a double-peaked pattern in their distribution pattern, with a pronounced prenoon peak and a smaller, secondary postnoon peak. The secondary peak is not observed in similar studies by *Glassmeier et al.* [1989], *Vorobyev et al.* [1994], and *Lin et al.* [1995]. *Sanny et al.* [2001] compared their distribution of geosynchronous transient events with the distribution of MIEs collected by *Sibeck and Korotova* [1996]. While both distributions exhibited general similarities such as a majority of prenoon events, the double peak was not observed for the transient event pattern. The authors suggested that foreshock/bow shock pressure pulse induced events may represent a significant contribution to the production of MIEs.

[9] In this statistical study we investigate the variability of the dayside geosynchronous magnetic field strength as a function of local time, season, the northward/southward orientation of the IMF, and solar wind dynamic pressure during intervals of reduced geomagnetic activity. High-resolution magnetic field measurements made by the Geostationary Operational Environmental Satellites (GOES 5 and GOES 7) from late 1984 through 1988 are used in the analysis. The solar wind data that correspond to the GOES observations were collected by the Interplanetary Monitoring Platform (IMP) 8 satellite [*King*, 1982]. The primary objective of this project is to learn about the relative contributions of transient events (FTEs and pressure pulse events) to the fluctuations in the magnetic field strength at geosynchronous orbit. This is done using the local time distribution pattern as well as dependence on IMF B_z and the solar wind dynamic pressure P_d. In addition, we will examine the seasonal dependence of the geosynchronous field variability and determine if there is any correlation to the seasonal dependence of MIEs.

2. Data Sets

[10] All geosynchronous magnetic field data used were obtained by the GOES 5 and GOES 7 satellites [*Grubb*,

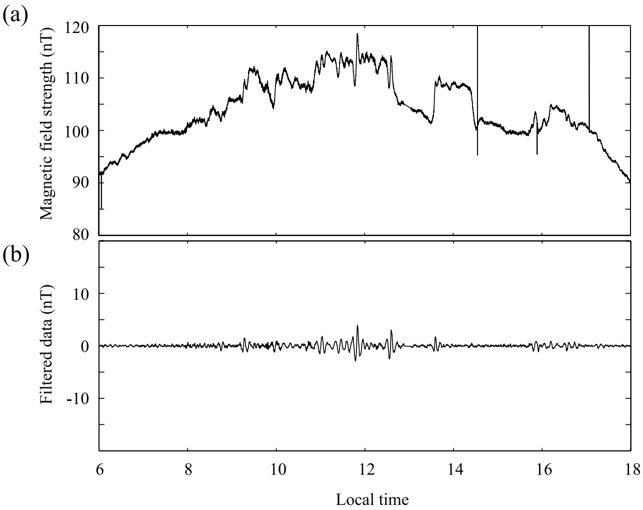

Figure 1. (a) Dayside magnetic field strength as observed by GOES 5 on 4 January 1985. (b) The data after being filtered to a passband of 1–10 min.

1975]. Twenty-four hour data files from GOES 5, GOES 6, and GOES 7, all with a time resolution of 3 s, make up a collection available from day 229, 1984 to day 366, 1988 from http://sd-www.jhuapl.edu, the Web site of the Johns Hopkins University Applied Physics Laboratory. In order to cover the entire interval, we used observations by GOES 5 from day 229, 1984 to day 84, 1987, and by GOES 7 from day 85, 1987 to day 366, 1988. Throughout the entire period, the local time (LT) position of the two spacecraft were related to universal time (UT) by approximately LT = UT − 5.

[11] Since we are interested in examining the contributions of transient events to the variability of the geosynchronous field strength, we considered only days with reduced geomagnetic activity, using a criterion of $Dst > -20$ nT. For each day in this subset we parsed the magnetic data file to include only the dayside hours and removed any noise spikes that were present. We then filtered the data with a passband of 1.7 mHz to 17 mHz (1–10 min), a process that retained the transient event fluctuations but eliminated the diurnal variation of the field strength and the effects of most of the higher frequency (>17 mHz) ultra-low-frequency (ULF) waves. Figure 1 shows an example of this procedure for 4 January 1985. The magnetic field strength measured on the dayside by GOES 5 is shown in the upper panel. The diurnal variation of the field strength is evident, and there are several prominent noise spikes. The bottom panel shows the filtered data over the same period. Hourly averages of the standard deviation of these results, or B_{var}, were calculated and tabulated in our database.

[12] Solar wind conditions for the events were obtained from the OMNIWeb site of the National Space Science Data Center, http://nssdc.gsfc.nasa.gov/omniweb. Hourly averages of the solar wind properties downloaded for this study were IMF B_z (in GSM coordinates), N, the proton number density, and V, the flow speed. For each hourly interval the standard deviations of N and V, which we denote as N_{var} and V_{var}, were also obtained.

3. Statistical Survey

3.1. Local Time and Seasonal Distribution

[13] We begin by considering the local time distribution of the variability of the geosynchronous magnetic field strength B_{var}. During the period from day 229, 1984 to day 366, 1988, there were 695 days that met our criterion of $Dst > -20$ nT. Of these, 44 days occurred in 1984, 147 days in 1985, 178 days in 1986, 194 days in 1987, and 132 days in 1988. Some days had hourly intervals with no data. The maximum number (13) of these missing intervals occurred at 0800 and 1000 LT; the minimum number (6) occurred at 1700 LT. Hence the number of hourly averages of B_{var} available for each hourly bin over the dayside range from 682 to 689.

[14] The plot of the hourly averages of B_{var} as a function of local time is shown in Figure 2a. We estimate the

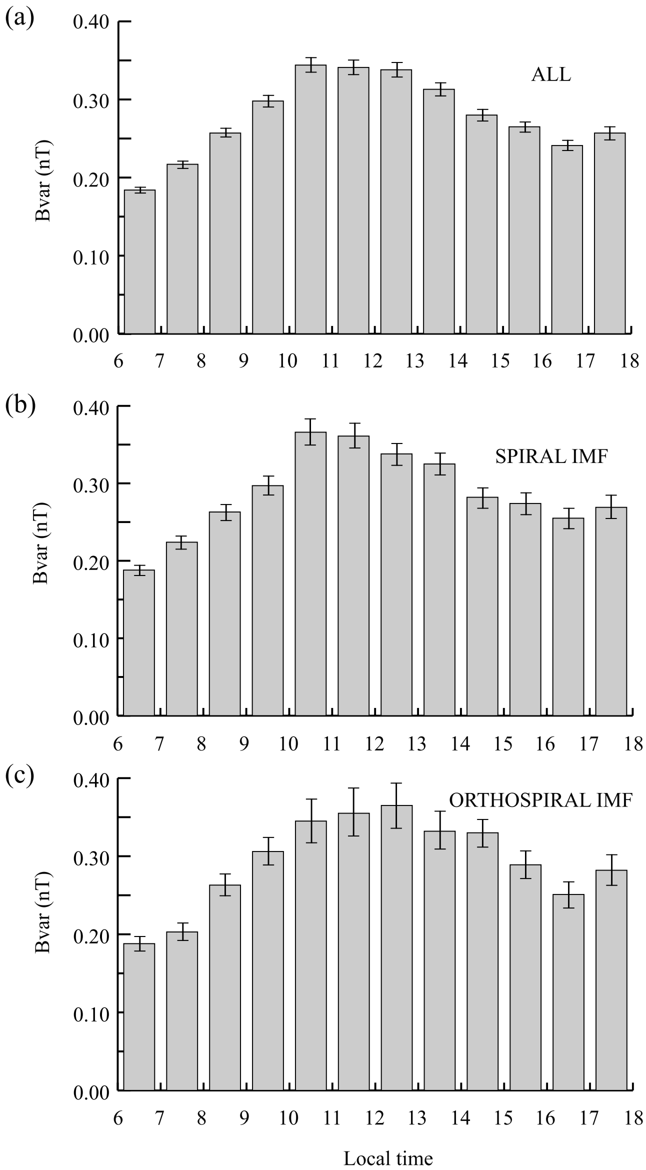

Figure 2. The local time distribution of the variability of the geosynchronous magnetic field strength for (a) all days, regardless of solar wind conditions, (b) periods of spiral IMF, and (c) periods of orthospiral IMF.

uncertainty in the average value of B_{var} within each bin by $\pm\sqrt{\sigma}/N$, where σ is the standard deviation of the population of values of B_{var} and N is the number of values of B_{var} in that bin. The uncertainties, which range from a minimum of $\pm 3.9 \times 10^{-3}$ nT (0600–0700 LT) to a maximum of $\pm 8.8 \times 10^{-3}$ nT (1300–1400 LT), are indicated here as well as in subsequent figures.

[15] The variation of B_{var} over the dayside is smooth and has a peak centered at about 1100–1200 LT as shown in Figure 2a. A comparison of the values of B_{var} for hourly intervals located correspondingly before and after this peak indicate that in general, the fluctuations in the geosynchronous magnetic field strength are greater on the duskward side of the peak than on the dawnward side. The only exception is at 1000–1100 LT and 1200–1300 LT, where B_{var} is greater in the former interval.

[16] As noted by *Anderson et al.* [1990], the afternoon hours are characterized by a great variety of pulsation activity, with noise periods, compressional and radially polarized waves, and toroidal resonances occurring there with regularity. It is likely that such activity made a significant contribution to the variability in the postnoon sector. For example, our passband of 1–10 min filtered out some but not all of the Pc 4 pulsations and none of the Pc 5 pulsations. We found that on the dayside these pulsations occurred generally in the postnoon sector near dusk (this is especially noticeable at 1700–1800 LT in Figure 2a). This is in agreement with previous work on ULF waves based on data at geosynchronous orbit. For example, *Arthur and McPherron* [1981] and *Kokubun et al.* [1989] observed an afternoon population of Pc 4 waves. Using particle data, *Su et al.* [1977] discovered that Pc 5 pulsations had a primary occurrence maximum in the afternoon and a secondary predawn maximum near 0400 LT. The Pc 5 distribution reported by *Kokubun* [1985] peaked in the afternoon before dusk and contained few events after dusk. From two years of GOES 2 and GOES 3 data, *Higuchi and Kokubun* [1988] discovered the peak occurrence region of Pc 5 waves to be around 15 00–1700 LT. Figure 3 shows three examples of ULF pulsations that we observed in the postnoon sector.

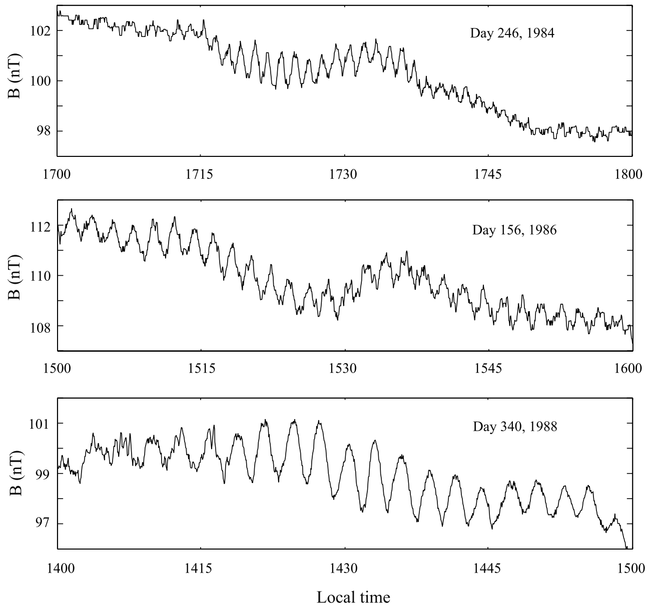

Figure 3. Examples of ULF pulsations observed in the postnoon sector.

[17] It is not clear whether the prenoon peak of the distribution of B_{var} shown in Figure 2a is a result of the solar wind impinging on the magnetopause, Earth's motion about the Sun, or a combination of both effects. Since Earth moves at about 30 km/s around the Sun, the effective solar wind flow direction is shifted some 4–6 degrees away from the Sun-Earth line toward dawn and may contribute to the fact that the distribution is centered at 1100–1200 LT. In order to test the influence of the solar wind on the local time distribution of B_{var}, we examine if the distribution has any correlation to the orientation of the IMF. Simultaneous IMF measurements were available for nearly 50% of the hourly intervals of Figure 2a. Of this number, the hourly intervals for the more common spiral IMF orientation ($B_x \cdot B_y < 0$) outnumbered the hourly intervals for orthospiral IMF orientation ($B_x \cdot B_y > 0$) by nearly a 3 to 1 ratio. Figure 2b shows the local time distribution of B_{var} for intervals of spiral IMF. The number of hourly averages of B_{var} within each bin is around 240. Figure 2c shows the corresponding local time distribution for intervals of orthospiral IMF. Here, the number of hourly averages of B_{var} within each bin is around 85. A comparison of these two figures suggests that there is a shift between the peaks of the distributions. The peak of the distribution for spiral IMF is in the prenoon sector at around 1100 LT while the distribution for orthospiral IMF has a broad peak centered at 1200–1300 LT in the postnoon sector. Hence the orientation of the IMF appears to have a discernible effect on the variability of the magnetic field strength at geosynchronous orbit.

[18] In a study by *Sanny et al.* [2001], the distribution of 174 transient events observed at geosynchronous orbit also exhibited a prenoon peak similar to that for the normal IMF spiral orientation shown in Figure 2b. The motion of these events and their dependence on solar wind properties indicated that they were primarily generated by variations in the solar wind dynamic pressure. Furthermore, in a study of the occurrence patterns of MIEs by *Sibeck and Korotova* [1996], the distribution of these events also exhibited a prominent prenoon peak along with a secondary postnoon peak. MIEs occur on magnetic field lines that map to the outer dayside magnetosphere and have been shown to be directly related to fluctuations at geosynchronous orbit [*Sibeck*, 1993].

[19] *Sibeck and Korotova* [1996] surveyed the seasonal dependence of MIEs by considering the number of events observed each month. Like other studies [*Glassmeier et al.*, 1989; *Sibeck et al.*, 1996] they reported a summer minimum in the distribution. Figure 4a shows the seasonal distribution we found for the variability of the geosynchronous field strength. The data used for each month all come from hourly averages within the 4-hour sector 1000–1400 LT around local noon, which also surrounds the peak in the distribution of B_{var} of Figure 2a. We choose this sector for several reasons. First, the contributions of Pc 4 and Pc 5 pulsations, whose distributions peak in the late afternoon, are greatly diminished. This is true as well for events due to the Kelvin-Helmholtz instability, which generally appear on

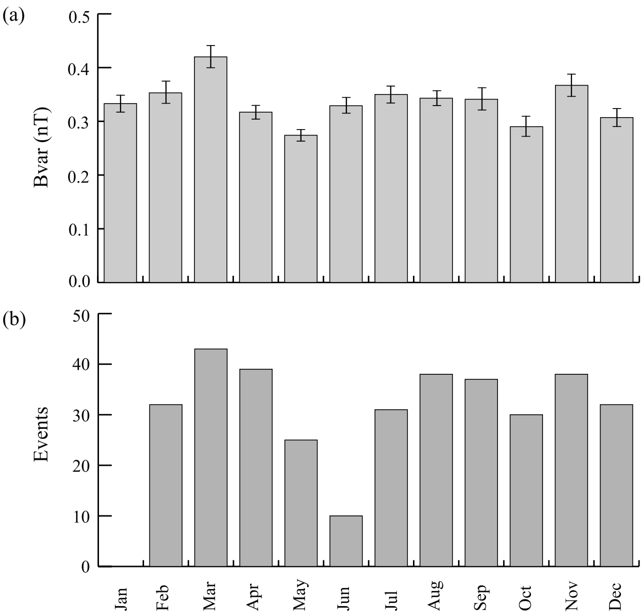

Figure 4. A comparison of the seasonal distributions of (a) the geosynchronous field variability with (b) observations of MIEs (reproduced from *Sibeck and Korotova* [1996]).

the flanks of the magnetosphere and accelerate tailward with the magnetosheath flow [*Southwood*, 1979]. Finally, the sector around local noon is most sensitive to solar wind parameters, whose influence will be considered shortly. Figure 4b is reproduced from *Sibeck and Korotova* [1996]. It shows the monthly distribution of MIEs, except for January, when no data were available. Both distributions exhibit a summer minimum and similar variations in the other months. The summer minimum is less pronounced in B_{var} since it is not a measure of individual events but a variability of the total field. Furthermore, the minimum in B_{var} occurs in May whereas the minimum in the number of MIEs occurs in June. As a measure of their similarity/difference, we calculated the correlation coefficient of the distributions. This was found to be +0.48. Hence while there is a positive correlation between the two distributions, it is not a strong one.

3.2. Dependence on IMF B_z and on Solar Wind Dynamic Pressure P_d

[20] We now survey the dependence of the variability of the geosynchronous field strength on the solar wind. As before, all values of B_{var} used in the plots will be hourly averages within the 4-hour sector 1000–1400 LT.

[21] Figure 5 shows B_{var} binned within 1.0-nT intervals of IMF B_z from −5 nT to +7 nT. The rightmost bin contains all data points where IMF $B_z > +7$ nT in order to accumulate a representative number of points in that bin. The number of data points within each bin ranges from a minimum of 14 (-5 nT $< B_z < -4$ nT and 6 nT $< B_z <$ 7 nT) to a maximum of 299 ($0 < B_z < 1$ nT). The uncertainties range from a minimum of ±0.015 nT (-1 nT $< B_z < 0$) to a maximum of ±0.044 nT (5 nT $< B_z <$ 6 nT), as indicated in the figure.

[22] Figure 6 is a plot of B_{var} versus solar wind dynamic pressure P_d. The number of data points within each bin ranges from a minimum of 26 (6 nPa $< P_d <$ 7.5 nPa) to a maximum of 614 (1.5 nPa $< P_d <$ 3.0 nPa). The uncertainties range from a minimum of ±0.007 nPa (1.5 nPa $< P_d <$ 3.0 nPa) to a maximum of ±0.093 nPa (6 nPa $< P_d <$ 7.5 nPa) as shown.

[23] These two figures indicate that fluctuations in the geosynchronous field strength appear to be much more sensitive to the solar wind dynamic pressure than to IMF B_z. In order to examine the combined effects of IMF B_z and P_d on the geosynchronous field strength, we separate the data into two groups based on P_d. The "high pressure" group consists of data when P_d is greater than its median value, and the "low pressure" group consists of data when P_d is less than its median value. We then plot these two groups versus IMF B_z. The result is shown in Figure 7. Like Figure 5, the variability of the geosynchronous field strength does not appear to have any discernible dependence on IMF B_z, in this case, regardless of the solar wind dynamic pressure.

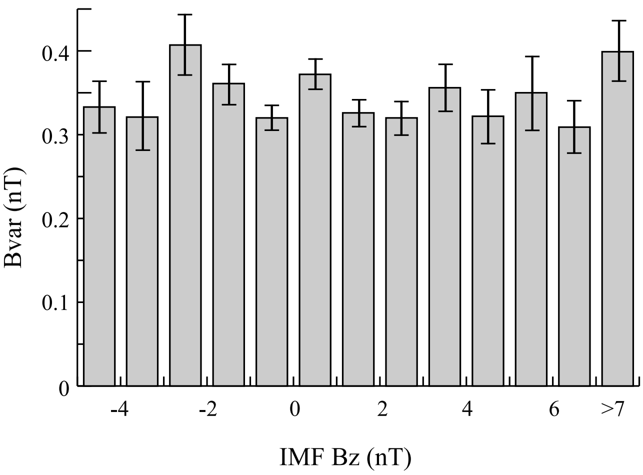

Figure 5. The variability of the geosynchronous magnetic field strength as a function of IMF B_z. The rightmost bin is made up of points where IMF $B_z > 7.0$ nT.

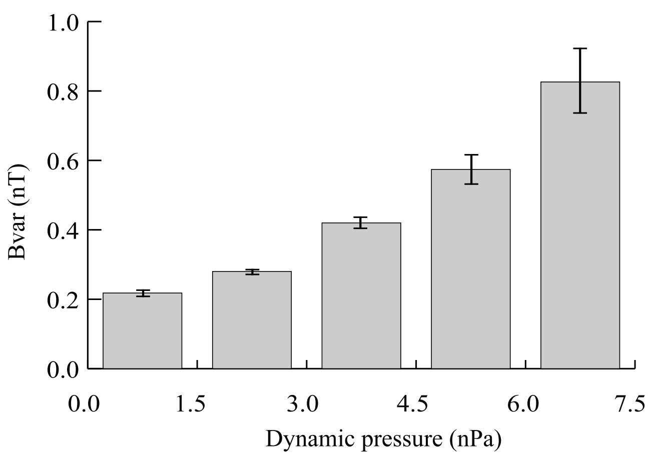

Figure 6. The variability of the geosynchronous magnetic field strength as a function of the solar wind dynamic pressure.

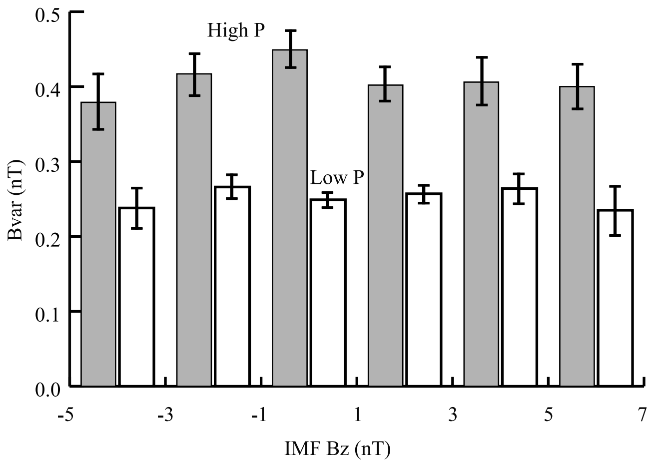

Figure 7. The dependence of B_{var} on IMF B_z for (a) solar wind dynamic pressures greater than the median value and (b) solar wind dynamic pressures less than the median value.

[24] An alternative way to examine the combined effects of IMF B_z and P_d on B_{var} is shown in Figure 8. The data are grouped according to the direction of IMF B_z and then binned versus P_d. At lower pressures there is little difference in the variability of the geosynchronous field for northward or southward IMF. As the pressure increases, the difference is more pronounced as the geosynchronous field appears to become significantly more disturbed for northward IMF than for southward IMF. The large uncertainties associated with the values of B_{var} in the highest-pressure bin result from the small number of hourly averages available for this range of solar wind dynamic pressure. For IMF $B_z > 0$, there were 17 hourly averages of B_{var}, and for IMF $B_z < 0$, there were 8 hourly averages of B_{var}. Within the other bins, the hourly averages of B_{var} for either northward or southward IMF ranged from 33 to 382.

3.3. Dependence on Variations in the Solar Wind Dynamic Pressure

[25] We conclude our statistical survey by considering the dependence of B_{var} on variations in the solar wind dynamic pressure, or P_{var}. This parameter can be determined from knowledge of N, N_{var}, V, V_{var}, P_d, and σ_{NV}^2, the covariance between N and V. For a quantity $x = f(u, v)$, the error propagation equation [*Bevington and Robinson*, 1992] yields

$$\sigma_x^2 \approx \sigma_u^2 \left(\frac{\partial x}{\partial u}\right)^2 + \sigma_v^2 \left(\frac{\partial x}{\partial v}\right)^2 + 2\sigma_{uv}^2 \left(\frac{\partial x}{\partial u}\right)\left(\frac{\partial x}{\partial v}\right), \quad (1)$$

where σ_x, σ_u, and σ_v are the standard deviations of the quantities x, u, and v, respectively, and σ_{uv}^2 is the covariance between u and v. Applying equation (1) to the solar wind dynamic pressure $P_d = mNV^2$, where m is the proton mass, we obtain for the variability of P_d

$$P_{var} = mV\sqrt{V^2N_{var}^2 + 4N^2V_{var}^2 + 4NV\sigma_{NV}^2}. \quad (2)$$

[26] For typical values of N and V the first term within the square root provides the greatest contribution to P_{var}. The second term has a contribution of about 10% or less, and the covariance term has a contribution of 5% or less. In order to determine hourly averages for σ_{NV}^2, we used the original IMP 8 measurements of N and V. These are available at ftp://space.mit.edu/pub/plasma/imp/fine_res/, the ftp Web site for IMP 8 at the MIT Center for Space Research.

[27] It is generally accepted that as the solar wind dynamic pressure increases, so does its variability. To investigate this, we make a scatterplot of P_{var} versus P_d using the window 0.0 nPa < P_{var} < 2.0 nPa and 0.0 nPa < P_d < 8.0 nPa, where over 99% of the points lie. The results are shown in Figure 9. The trendline is a linear least squares fit to the data. Its positive slope indicates that P_{var} does indeed increase with P_d.

[28] We now bin the variability of the geosynchronous field strength with respect to our calculated values of P_{var} using a width of 0.15 nPa for the bins. As shown in Figure 10, the variability of the geosynchronous magnetic field strength increases with the variability of the solar wind dynamic pressure. This increase appears to be somewhat

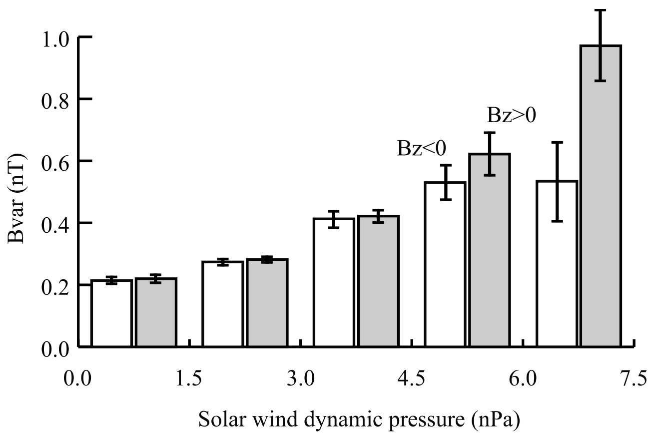

Figure 8. The dependence of B_{var} on P_d for (a) IMF $B_z < 0$ and (b) IMF $B_z > 0$.

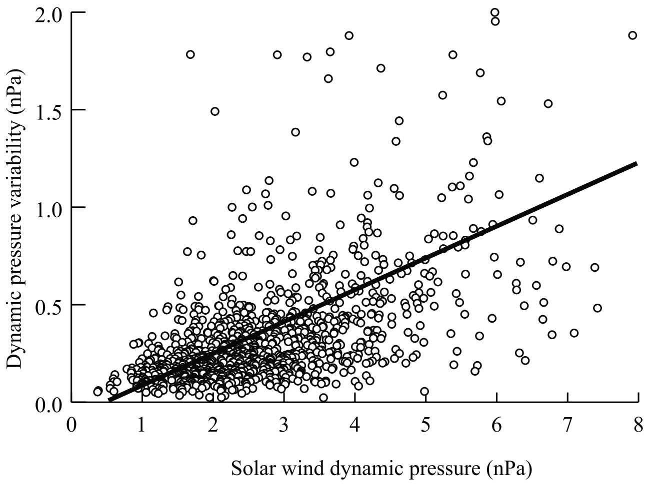

Figure 9. The variability of the solar wind dynamic pressure increases with the magnitude of the dynamic pressure.

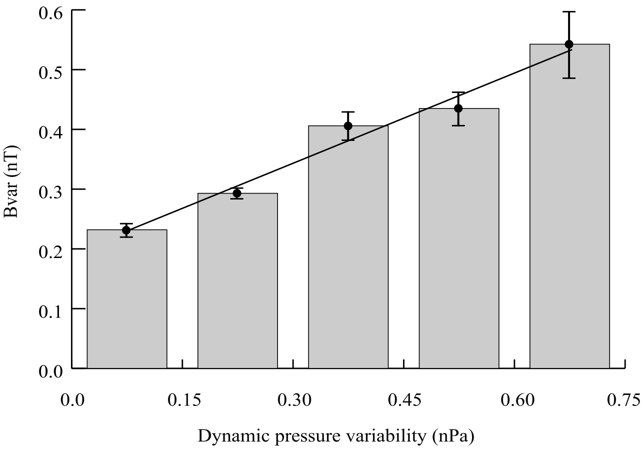

Figure 10. The variability of the geosynchronous magnetic field strength as a function of the variability of the solar wind dynamic pressure.

linear, as indicated by the trendline, which is a least squares fit to the values of B_{var} within the five bins.

[29] Finally, we consider the response of the geosynchronous magnetic field strength to variations in the solar wind dynamic pressure in terms of the direction of IMF B_z. Figure 11 shows B_{var} binned within 0.15 nT intervals of P_{var} for both northward and southward IMF. In general, within the calculated uncertainties the response of the field strength to pressure variations does not exhibit any dependence on IMF B_z. The difference in the responses for northward and southward IMF is greatest within the bin containing the highest values of P_{var}. However, as indicated by the uncertainties shown for B_{var}, the difference in the response may not be a significant one.

4. Discussion

[30] We begin the discussion of our statistical survey with the local time dependence of the variability of the geosynchronous field strength. Using our entire database of GOES magnetic field measurements, we found that the local time distribution of B_{var} was centered at 1100–1200 LT, as shown in Figure 2a. It was unclear whether the prenoon peak was associated with the solar wind-magnetopause interaction or if it was simply due to Earth's orbital motion. Simultaneous solar wind observations were available for about 50% of the data used in Figure 2a. We divided this subset into two groups based on the spiral/orthospiral orientation of the IMF. The peaks of the local time distributions for these two solar wind conditions appeared to be separated and on either side of the peak of the overall distribution. The spiral distribution had a prenoon peak centered at 1100 LT (Figure 2b) while the orthospiral distribution had a broad peak centered at 1200–1300 LT. (Figure 2c).

[31] Pressure pulses may be inherent in the solar wind. However, the solar wind dynamic pressure may also be modified significantly by processes within the foreshock, and past studies [*Sibeck and Gosling*, 1996; *Sibeck et al*, 1997] have observed that magnetosheath parameters can exhibit a high degree of turbulence during periods when the solar wind is steady. The spiral/orthospiral orientation of the solar wind determines the general location of the quasi-parallel bow shock. With the typical spiral IMF orientation the prenoon magnetopause lies behind the quasi-parallel bow shock, and this is the region where foreshock/bow shock pressure pulses would therefore strike. On the contrary, for the less common orthospiral IMF orientation, it is the postnoon magnetopause that lies behind the quasi-parallel bow shock, and this is where foreshock/bow shock pressure pulses would strike. These premises appear to be in agreement with the results of Figure 2b and Figure 2c, which suggest that the geosynchronous field has the greatest variability in the prenoon sector for spiral IMF orientation and in the postnoon sector for orthospiral IMF orientation. Hence an important source of the magnetic fluctuations at geosynchronous orbit may be compressional fast mode waves launched by pressure pulses generated in the foreshock/bow shock region impinging on the magnetopause.

[32] A comparison of the seasonal dependences of the variability of the geosynchronous field strength with the number of observations of MIEs (see Figure 4) showed weakly similar variations, with a correlation coefficient of +0.48 between the two distributions. This results offers only a suggestion that foreshock/bow shock pressure pulse induced fluctuations at geosynchronous orbit may indeed have some correspondence to MIEs.

[33] Our finding that the variability of the geosynchronous field strength around local noon (1000–1400 LT) increases strongly with solar wind dynamic pressure, as shown in Figure 6, is consistent with the concept of boundary waves on the magnetopause. An increase in P_d compresses the magnetosphere, moves the magnetopause closer to geosynchronous orbit, and increases the field strength at that location, particularly around local noon [*Rufenach et al.*, 1992; *Wing and Sibeck*, 1997]. Induced waves on the magnetopause decay with distance from that boundary. As that distance is decreased, these waves will have a greater effect on the geosynchronous field. This is what we have observed.

[34] However, it is somewhat surprising that fluctuations in the geosynchronous field do not have a noticeable dependence on IMF B_z, as depicted in Figure 5 and Figure 7. As the magnetopause approaches geosynchronous orbit,

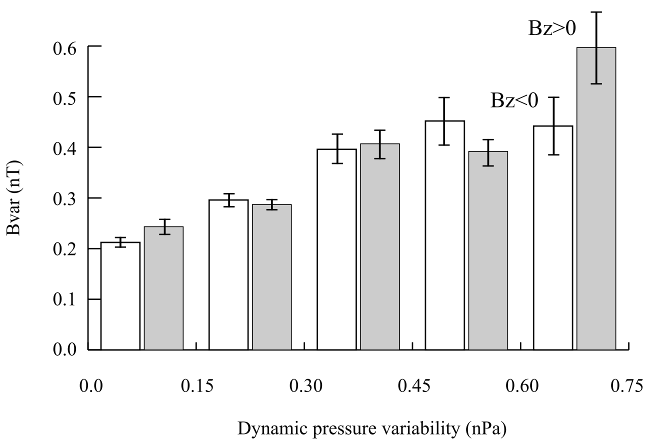

Figure 11. The dependence of B_{var} on P_{var} for (a) IMF B_z < 0 and (b) IMF B_z > 0.

the influence of flux transfer events should be greater at that location. Since flux transfer events are commonly produced by magnetic merging near the magnetopause, their occurrence rate is far greater for southward IMF and thus should enhance B_{var} for this orientation of the IMF. If the magnetopause motion is driven by pressure pulses, then there should still be a dependence on IMF B_z. *Sibeck* [1990] noted that impulsive increases in P_d are equally likely for northward or southward IMF but claimed that the magnetospheric response to these increases depends on the direction of the IMF. The amplitude of the magnetopause boundary motion should be less during periods of northward IMF than during periods of southward IMF. While we have not observed the amplitude of the boundary motion, we find no difference in the response of the magnetic field at geosynchronous orbit.

[35] Figure 8 shows that as the solar wind dynamic pressure increases, the geosynchronous field variability around local noon increases strongly for northward IMF but less so for southward IMF. Since higher dynamic pressure corresponds to greater variability in the dynamic pressure (for example, see Figure 9), the geosynchronous field appears to be more sensitive to fluctuations in the solar wind dynamic pressure for northward IMF. This result is similar to those of several past studies on magnetic responses to solar wind pressure variations for northward IMF at various locations. The response of the low-latitude geomagnetic field has been found to be greater and to correspond more closely to variations in the solar wind dynamic pressure during periods when IMF $B_z > 0$ [*Russell et al.*, 1994; *Francia et al.*, 1999]. Impulsive events were detected far more frequently by high-latitude ground magnetometers during intervals of steadily northward IMF orientation (69 events) than during intervals of steadily southward intervals (20 events) [*Sibeck and Korotova*, 1996]. The authors noted that the lower occurrence rate for IMF $B_z < 0$ may be because some events are obscured by more dramatic and significant phenomena that only occur for southward IMF orientations. In a study of magnetospheric global response to short duration solar wind pressure pulses, *Moldwin et al.* [2001] reported that the response of the magnetotail to small solar wind pressure pulses were much clearer for northward than for southward IMF orientation.

[36] An interpretation of these findings may perhaps be made by considering the global magnetospheric current systems, whose response to pressure pulses may be very different during periods of northward and southward IMF orientation. Whenever regions of enhanced solar wind density strike the dayside magnetopause, they launch fast mode compressional waves into the magnetosphere. However, the pulses are far more likely to trigger or enhance reconnection on the equatorial magnetopause during periods of southward IMF orientation. Reconnection removes magnetic flux from the dayside magnetosphere, launches fast rarefaction waves into the magnetosphere, and depresses dayside magnetospheric magnetic field strengths. Consequently, one expects the magnetospheric response to pressure pulses to be greater during periods of northward than southward IMF orientation. As a result, the increase in the variability of the geosynchronous field with solar wind dynamic pressure may be suppressed when IMF Bz < 0. This can be seen in Figure 8, which shows that the difference between the two cases (visually represented by the height difference between the two columns representing northward and southward IMF within each pressure bin) becomes significant only at the highest solar wind dynamic pressures.

[37] To consider the direct dependence of the variability of the geosynchronous field strength on dynamic pressure fluctuations, we calculated P_{var} using an error propagation equation for P_d. As shown in Figure 9, the relationship between B_{var} and P_{var} is approximately linear. As a rough pressure-balance approximation, $B^2 \propto P_d$, so $B(B_{var}) \propto P_{var}$. For small fluctuations, B is approximately constant and $B_{var} \propto P_{var}$ as suggested in Figure 10. Thus the geosynchronous magnetic field is responsive to even small pressure changes in the solar wind. This response is generally independent of the northward/southward orientation of the IMF (see Figure 11) except for the largest fluctuations in the solar wind dynamic pressure when the response appears to be enhanced for northward IMF.

5. Conclusion

[38] In this study, we have examined the variability of the geosynchronous magnetic field strength B_{var} during intervals of reduced geomagnetic activity by using over 4 years of measurements from the GOES satellites. The dependences of the variability on local time and on the season were first considered. The variability was then related to solar wind parameters, particularly IMF B_z and the dynamic pressure P_d, using simultaneous solar wind measurements by IMP 8.

[39] Using our entire database of GOES magnetic field observations, we found that the local time distribution of B_{var} exhibited a peak slightly dawnward of local noon at 1100–1200 LT. This result did not provide clear evidence of the influence of the solar wind on the geosynchronous field since a similar shift in the peak can be attributed to the motion of Earth around the Sun. However, when we examined only periods with available solar wind data and then considered spiral and orthospiral IMF orientations separately, we discovered that the peaks of the two resultant distributions appeared to be distinguishable and centered on opposite sides of local noon. The spiral distribution was centered at about 1100 LT while the orthospiral distribution was centered at 1200–1300 LT. Now the quasi-parallel bow shock is situated in front of the prenoon magnetopause for spiral IMF and in front of the postnoon magnetopause for orthospiral IMF. Hence we interpreted our result to suggest that pressure pulses originating in the foreshock/bow shock regions may have a significant effect on fluctuations in the geosynchronous field.

[40] We then compared the seasonal distribution of B_{var} to the seasonal distribution of MIEs [*Sibeck and Korotova*, 1996], which occur on magnetic field lines that map to the outer dayside magnetosphere. The two distributions both exhibited a summer minimum and similar variations in the other months and had a correlation coefficient of +0.48. Thus there was a positive, albeit weak, correlation between the seasonal distributions of the variability of the geosynchronous field strength and MIEs. This suggested that there could indeed be some relationship between pressure pulse

events at geosynchronous orbit and ground-based observations of impulsive events.

[41] In examining the response of the geosynchronous field strength to IMF orientation and solar wind dynamic pressure, we found that the variability of the field strength in the region around local noon was correlated far better with the dynamic pressure than the direction of IMF B_z. Our survey did not reveal any noticeable dependence on northward/southward IMF (see Figure 5), whereas a similar survey for solar wind dynamic pressure indicated a strong increase in the variability with respect to the pressure (see Figure 6). To consider the combined effects of both solar wind parameters, we separated the data into two groups, one in which the dynamic pressure is greater than its median value and the other in which the dynamic pressure is less than its median value. Even with this distinction, we failed to detect a dependence of the field variability on IMF orientation, as indicated in Figure 7.

[42] The effects of magnetic reconnection at the magnetopause emerged when we compared the variability for northward and southward IMF binned with respect to solar wind dynamic pressure, as shown in Figure 8. Within each pressure bin, the difference in heights between the two columns representing the conditions IMF $B_z > 0$ and IMF $B_z < 0$ may be an indication of the effect of dayside magnetic merging at the magnetopause on the variability of the geosynchronous field around local noon. When IMF $B_z > 0$, merging at the magnetopause is "off" (or at least greatly reduced), and when IMF $B_z < 0$, merging is "on." For lower solar wind dynamic pressures the variability of the geosynchronous magnetic field strength for northward IMF and for southward IMF are virtually indistinguishable. However, at the higher dynamic pressures, the variability of the geosynchronous magnetic field strength for northward IMF appears to exceed that for southward IMF. Under the latter condition, magnetic reconnection on the equatorial magnetopause is far more likely to be triggered by pressure pulses than under the former condition. Reconnection launches fast rarefaction waves into the magnetosphere. Since these waves may decrease the effect of the fast compressional waves launched by the pressure pulses, one might expect that the variability of the geosynchronous field to be greater during intervals of northward IMF, as depicted in Figure 8.

[43] Finally, we calculated the variability of the solar wind dynamic pressure using an error propagation approach and verified that it had a positive correlation to the magnitude of the dynamic pressure (see Figure 9). A plot of the variability of the geosynchronous field strength to the variability of the solar wind dynamic pressure, shown in Figure 10, indicated a nearly linear relationship between the two quantities, with a stronger response occurring for northward IMF during periods of high dynamic pressure variability (Figure 11). We conclude that the geosynchronous field is indeed responsive to fluctuations in the solar wind dynamic pressure.

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