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A statistical study of transient event motion at geosynchronous orbit

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Abstract. The geosynchronous GOES 5 and GOES 6 satellites frequently observe transient events marked by magnetic field strength increases and bipolar magnetic field signatures lasting several minutes. In this study we report a survey of 87 events observed simultaneously by both GOES spacecraft (for a total of 174 individual observations) from August to December 1984. Events detected in the prenoon sector outnumbered those in the postnoon sector by about a 3 to 1 ratio. The distribution of the events versus local time exhibited a significant prenoon peak like the distribution of magnetic impulse events observed in high-latitude ground magnetometers. A cross-correlation analysis of the two GOES data sets indicated lags that range from 0 to over 2 min, with the majority of the events moving antisunward. The short lags correspond to azimuthal speeds of hundreds of kilometers per second, greater than flow speeds in the magnetosheath, but less than fast mode waves. The short lags may indicate that the events move primarily latitudinally and/or that transient events are seldom localized, but rather occur over extended, if not global, regions. Investigations of event occurrence versus interplanetary magnetic field (IMF) B_z, event motion versus IMF B_y, and correspondence between upstream plasma data and the events all indicate that pressure pulses are the likely source of many of the events. About 27% of the events with simultaneous solar wind data were preceded by sharp reversals in one or more IMF components, and nearly all of this particular group of events occurred in the dawn sector. This suggests that the pressure pulses may be commonly generated in the foreshock/bow shock region, since the prenoon magnetopause lies generally behind the quasi-parallel bow shock where such pulses are thought to be triggered by IMF discontinuities. Finally, several events in the data set were also observed by the AMPTE/CCE. These are presented as case studies.

1. Introduction

The dayside magnetopause is the location where solar wind mass, energy, and momentum are directly transferred to the magnetosphere. Transient (~1 min) variations in magnetic field, plasma, and energetic particle parameters represent one facet of this interaction. Such transient events are commonly observed by spacecraft in the dayside magnetosphere, particularly in the vicinity of the magnetopause. 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, or FTEs, by *Russell and Elphic* [1978]. They interpreted these events as flux ropes of interconnected magnetospheric and magnetosheath magnetic field lines resulting from patchy, sporadic merging at the magnetopause. Although southward interplanetary magnetic field (IMF) orientations favor 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]. Among all the different models, the sporadic merging and pressure pulse mechanisms have been developed to the point where they make a full range of predictions concerning the characteristics of individual events and their statistical occurrence patterns (see review by *Sibeck* [1994]). Because these two models predict differing patterns for event occurrence, orientation, and direction of motion as a function of IMF orientation, local time, and latitude, statistical studies have helped to determine the relative significance of each model in the production of transient events.

There have been several statistical studies of transient events observed in the vicinity of the dayside magnetopause [e.g., *Rijnbeek et al.*, 1984; *Berchem and Russell*, 1984; *Southwood et al.*, 1986; *Kuo et al.*, 1995; *Sanny et al.*, 1998]. An observation that is common to these studies is that events occur predominantly during periods of southward IMF, a basic tenet of the sporadic merging model. Hence these studies provide com-

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pelling evidence that transient events observed near the dayside magnetopause are indeed FTEs.

There have also been statistical studies of events observed deep in the magnetosphere. These investigations used either data from the AMPTE/CCE when it was in the magnetosphere far from the magnetopause [*Kawano et al.*, 1992; *Sanny et al.*, 1996] or geosynchronous observations made by the GOES spacecraft [*Borodkova et al.*, 1995]. These studies found that the occurrence of transient events did not depend strongly on IMF orientation. For example, *Sanny et al.* [1996] reported 28 events that occurred for IMF $B_z < 0$ and 24 events for IMF $B_z > 0$. Furthermore, event axis orientation did not depend on the sign of IMF B_y in the manner predicted by any merging model [e.g., *Gonzalez and Mozer*, 1974; *Crooker*, 1979]. Finally, the motion of the majority of the events agreed with the predictions of the pressure pulse model [*Sibeck*, 1990]; that is, the events move sunward just after local noon during periods of spiral IMF ($B_x \bullet B_y < 0$) and they move sunward just prior to local noon during periods of orthospiral IMF orientation ($B_x \bullet B_y > 0$). *Sanny et al.* [1996] reconciled the observations with bursty merging and pressure pulses by concluding that both mechanisms are responsible for generating transient events, with the majority of events produced by bursty merging at the magnetopause and the largest-amplitude events produced by pressure pulses. Satellites in the vicinity of the magnetopause observe all the events, whereas satellites deep within the magnetosphere observe only those events with the largest amplitudes, resulting in a data set with a majority of pressure pulse events.

The point of origin of the pressure pulses themselves has been a topic of much recent interest. Observations indicate that pressure pulses may be inherent in the solar wind [*Burlaga and Ogilvie*, 1969; *Roberts et al.*, 1987] or they may be generated in the foreshock region [*Fairfield et al.*, 1990]. Simulations by *Thomas et al.* [1995] and *Lin et al.* [1996a, 1996b] all 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 interaction of IMF discontinuities with the bow shock may also produce solar wind phenomena known as hot flow anomalies (HFAs) [*Paschmann et al.*, 1988; *Schwartz et al.*, 1988; *Thomsen et al.*, 1988]. HFAs are characterized by very hot tenuous plasma flows deflected strongly from the Earth–Sun line, and turbulent magnetic field strengths and directions. While IMF discontinuities are common [*Burlaga and Ogilvie*, 1969], HFAs have been observed only rarely (for example, *Thomsen et al.* [1988] suggested that they occur at a rate of about once a month). It is unclear whether only a small fraction of the discontinuities can produce HFAs or if HFAs are common but only observable by spacecraft in the immediate vicinity of the bow shock. Finally, *Sibeck and Gosling* [1996] and *Sibeck et al.* [1997] have found examples of highly variable magnetosheath plasma parameters during periods of nearly steady solar wind input. These studies indicate that the effects of the solar wind interaction with the bow shock may be far more dynamic than previously thought.

Transient events in the magnetosphere launch Alfvén waves that carry currents and electric fields down magnetic field lines to the ionosphere. Corresponding signatures are observed in high-latitude ground magnetograms and are called magnetic impulse events (MIEs). MIEs are characterized by changes (typically ~10^2 nT) in the vertical component of the magnetic field lasting several minutes. The nature of the transient events that produce MIEs has been extensively debated. MIEs have been considered to be the ionospheric signature of bursty merging at the magnetopause [e.g., *Sandholt et al.*, 1986; *Fukunishi and Lanzerotti*, 1989; *Mende et al.*, 1990], of magnetopause waves driven by solar wind/bow shock pressure variations [*Friis-Christensen et al.*, 1988; *Sibeck*, 1993; *Sibeck and Korotova*, 1996], or of various simultaneous effects at the magnetopause [*Lanzerotti et al.*, 1990]. 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. There is a pronounced prenoon peak and a smaller, secondary postnoon peak. The secondary peak is not observed in similar studies by *Glassmeier et al.* [1989], *Vorobjev et al.* [1994], and *Lin et al.* [1995]. Finally, MIEs generally move antisunward at velocities greater than those associated with convection [*Hughes et al.*, 1995], less than those associated with fast mode waves, but rather appropriate for features moving antisunward with the magnetosheath velocity. To be able to associate MIEs with the correct mechanism(s) is very desirable, for with this information, the solar wind–magnetosphere interaction can be monitored using readily available high-latitude ground magnetometer data in place of spacecraft observations.

In this study we have assembled a data set of 87 pairs of simultaneous event observations (which we will call "event pairs") made by the GOES 5 and GOES 6 geosynchronous spacecraft, for a total of 174 individual observations, during the period from August to December 1984. We chose this period for several reasons: first, simultaneous measurements were readily available on-line for the two spacecraft from day 229 (August 16) to day 343 (December 8) of 1984; second, the AMPTE IRM was often in a favorable upstream position for monitoring solar wind parameters during that period; and, finally, we had assembled a collection of 57 events observed by the AMPTE/CCE, which was in the outer dayside magnetosphere during that period [*Sanny et al.*, 1996]. We hoped to find some common events and therefore use the CCE as an additional monitor. There were, in fact, observations made by all three spacecraft. These observations will be discussed in a later section.

There are a variety of magnetic signatures associated with transient events observed by geosynchronous spacecraft. For example, *Borodkova et al.* [1995] provided four different classifications of such events based on their magnetic field strength fluctuations. In this study we only consider events that exhibit the "classic" FTE signature of a bipolar signature in the magnetic field component normal to the nominal magnetopause centered upon an increase in the magnetic field strength [*Russell and Elphic*, 1978]. Observations and modeling results [e.g., *Berchem and Russell*, 1984; *Farrugia et al.*, 1987; *Kawano et al.*, 1992] have shown that such signatures can be produced by bubbles or flux ropes traveling along the magnetopause surface, with northward moving events producing outward/inward bipolar signatures in the magnetic field component normal to the nominal magnetopause and southward moving events producing inward/outward signatures. Furthermore, the inward displacement of magnetospheric magnetic field lines during the passage of transient events enhances the component of the magnetospheric magnetic field in the plane of the magnetopause.

In the pressure pulse model [*Sibeck*, 1990], ripples on the magnetopause surface that radiate outward from the point where pressure pulses first strike the magnetopause produce the observed bipolar signatures and field strength increases. Transient events associated with pressure pulses travel around the magnetosphere with the magnetosheath flow, but also launch fast mode waves into the magnetosphere. Events displaying bipolar signatures normal to the magnetopause traditionally have been interpreted as evidence for bulges on the magnetopause moving either northward or southward, because there is no explanation for the bipolar signatures purely in terms of fast mode waves propagating into the magnetosphere. Geosynchronous events have also been interpreted in terms of events propagating along the magnetopause because case studies of MIEs and geosynchronous events generally find that the two phenomena appear to associate one-to-one [e.g., *Glassmeier et al.*, 1989; *Sibeck*, 1993; *Korotova et al.*, 1997, 1999], and MIEs are known to move at velocities appropriate for features traveling along the magnetopause [*Hughes et al.*, 1995].

With our assembled data set, we can investigate statistically a number of properties of geosynchronous transient events. For example, the distribution of events as a function of local time is considered. The time lag between the observations made by GOES 5 and GOES 6 provides information on the sunward/antisunward motion of transient events and their azimuthal speeds, and any dependence of properties such as these on location. Solar wind data are used to discuss the dependence of event properties on IMF B_z and B_y, discontinuities, and upstream plasma fluctuations. Finally, the additional information provided by the CCE on the eight events it observed simultaneously with the GOES spacecraft allows for a more detailed analysis of event propagation.

2. Data Sets

All magnetospheric transient events in our data set were identified from the magnetic field measurements of the GOES 5 and GOES 6 satellites [*Grubb*, 1975]. These satellites were in geosynchronous orbit, with GOES 5 leading GOES 6 by 23° in longitude. The local times (LT) of the spacecraft are related to universal time (UT) by LT = UT − 5.0 (for GOES 5) and LT = UT − 6.5 (for GOES 6). GOES data files, with a time resolution of 3 s, are available for downloading from the Web site of The Johns Hopkins University Applied Physics Laboratory (JHU/APL) at http://sd-www.jhuapl.edu. We required all our candidate events to be observed by both satellites so that lag times could be determined. Furthermore, at least one of the satellites had to be positioned on the dayside between 0900 LT and 1500 LT. Once an event was identified, we replotted the observations in boundary normal coordinates determined from a minimum variance routine [*Sonnerup and Cahill*, 1967] run upon the event itself. We kept only events that exhibited a bipolar signature in the magnetic field component normal to the nominal magnetopause centered upon an increase in the magnetic field strength. Eight of the GOES events were observed simultaneously in the outer magnetosphere by the AMPTE/CCE spacecraft, which was launched into a near-equatorial orbit with an apogee of 8.8 R_E. The CCE magnetometer data [*Potemra et al.*, 1985] have a resolution of 6.2 s and can also be obtained from the JHU/APL Web site.

IMF conditions for the events were monitored using either the AMPTE IRM [*Lühr et al.*, 1985], ISEE 1 and 2 [*Russell and Elphic*, 1978], or IMP 8 [*King*, 1982]. The time resolution of the IRM plasma and magnetic field observations was 5 s, while the resolutions of the ISEE and IMP magnetic data were

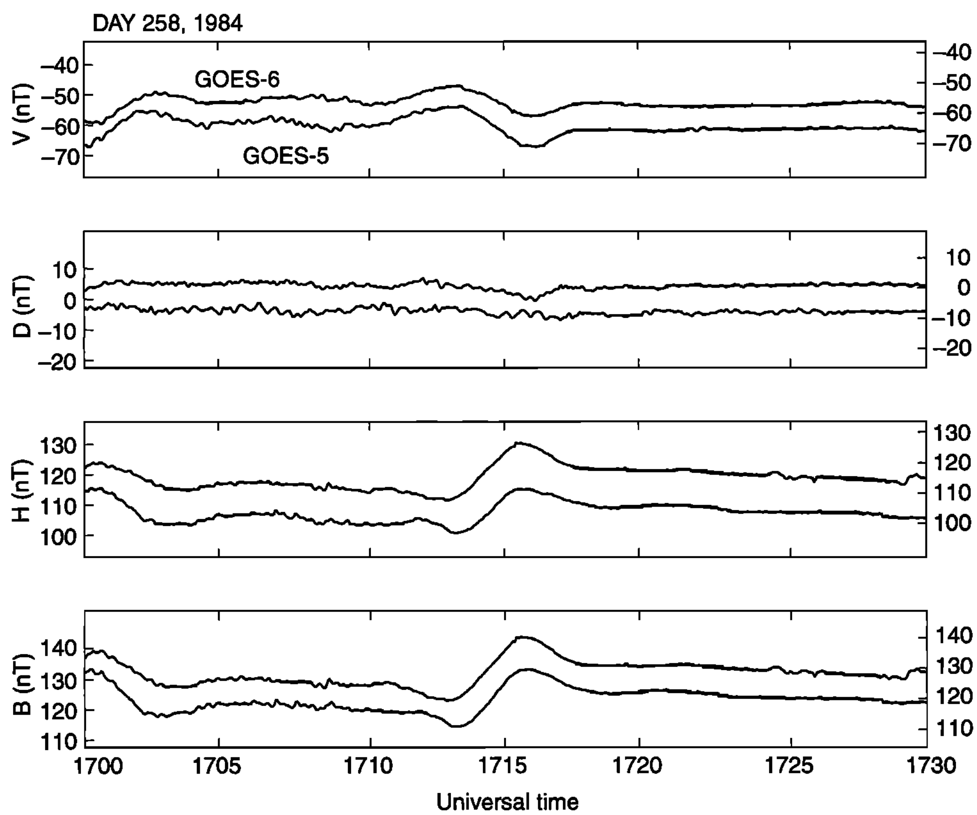

Figure 1. A comparison of GOES 5 and GOES 6 magnetic field observations in *VDH* coordinates during the interval from 1700 to 1730 UT on day 258, 1984.

Table 1. List of Events

Day	Time, UT	Magnetic Field, nT	Duration, min	Order	Lag, s	Direction[a]	IMF[b]	Monitor
230	1601	2.5	4	5-6	65	as	(+,−,+)	IMP
230	1622	4	3.5	5-6	45	as	(+,−,+/−)	IMP
230	1630	3.5	3.5	5-6	35	as	(+,−,−)	IMP
230	1735	10	3	5-6	65	as	(+,−,+/−)	IMP
232	1514	2.5	3	5-6	85	as		
232	1545	2.5	3	5-6	50	as		
241	1459	8	1.5	5-6	35	as	(−,+,−)	IMP
241	1644	9	2.5		0	neither	(−,+,−)	IMP
242	2033	7	5	5-6	25	s	(−,+,−)	IMP
250	1458	7	5	5-6	110	as	(+,+,−)	ISEE
250	1546	3.5	4.5	5-6	55	as	(+,+/−,−)	ISEE
254	1555	5.5	4	5-6	40	as	(+,−,−)	IRM
254	1602	6	2	5-6	20	as	(+,−/+,−)	IRM
254	1623	7.5	3	5-6	25	as	(+,−,+/−)	IRM
254	1642	5.5	3.5	5-6	25	as	(+,−/+,−)	IRM
254	1648	7.5	2.5	5-6	10	as	(+,+/−,−)	IRM
254	1823	7	3	5-6	25	s	(+,−,0)	IRM
256	1438	6	8	5-6	55	as	(+,−,0)	IRM
256	1449	6	3	5-6	45	as	(+,−,+)	IRM
256	1605	4	4	5-6	50	as	(+,−/+,+/−)	IRM
256	1815	4	4	5-6	10	s	(+,−,−)	IRM
256	2106	9.5	2.5		5	neither	(+,0,0)	ISEE
258	1701	9.5	3.5	5-6	40	as	(+,+/−,0)	IRM
258	1716	3	3	6-5	20	s		
259	1428	5	3	5-6	115	as	(+,−,−)	ISEE
259	1523	7	3	5-6	70	as	(+,−,−/+)	ISEE
263	1449	6	2.5		0	neither		
263	1734	8	5	5-6	15	as		
263	1815	8.5	3.5	6-5	85	as	(0,−,−)	IRM
264	1501	4	3	5-6	80	as	(−,−/+,−)	ISEE
264	1536	4	3		5	neither	(−,+,−)	ISEE
264	1617	3	2.5	5-6	20	as	(−,+,−)	ISEE
264	1820	2	3	6-5	70	as	(−,+,−)	IRM
264	1838	2	5.5	6-5	15	as	(−,+,−)	IRM
265	1557	3.5	4		5	neither	(−,+,−)	IRM
265	1741	5	6.5	5-6	80	s	(−,0,0)	IRM
265	2031	2	5.5		0	neither	(0,+,+)	IRM
268	1433	11	4	5-6	10	as	(−,0,0)	IRM
268	1932	16	5	5-6	25	s	(−,0,+)	ISEE
270	1646	10	4	6-5	30	s		
281	1450	10.5	4	5-6	20	as	(+,+/−,−)	IRM
281	1602	18	2.5	5-6	65	as		
281	1757	14.5	4	6-5	45	as	(+,+,0)	ISEE
281	1825	5.5	5.5	5-6	45	s	(+,−,0)	ISEE
283	1421	6	5	5-6	10	as		
283	1441	6.5	1.5	5-6	45	as		
286	1442	5	4	5-6	65	as		
286	1652	6.5	2.5	6-5	10	s	(+,0,+)	ISEE
287	1454	4.5	1.5	5-6	45	as		
287	1647	5	4	5-6	60	as		
287	1903	3.5	4	6-5	10	as	(+,−,+)	ISEE
289	1526	7	2.5	5-6	85	as		
298	1722	6.5	3.5		0	neither	(−,−/+,−)	ISEE
301	1650	7.5	5		5	neither		
301	1715	5.5	3	6-5	15	s		
303	1658	5	6	5-6	60	as	(+,−,0)	ISEE
303	1742	5.5	5	5-6	20	s	(+,0,+)	ISEE
305	1659	2.5	2.5	5-6	30	as		
305	1834	5	2		5	neither	(+,+,+)	IMP
310	1711	5	2.5	6-5	35	s	(+/−,−,+/−)	ISEE
310	1750	5	3.5		0	neither	(+,0,+)	ISEE
311	1524	10	5	5-6	130	as		
313	1626	5	1	5-6	35	as		
313	1701	11	1.5	5-6	70	as		
314	1558	7	4	5-6	45	as		
316	1526	10.5	4.5	5-6	80	as		
320	1721	18	2.5	5-6	50	as		
323	1737	13.5	4	5-6	10	s	(−,0,+)	ISEE
323	1752	7.5	4.5	5-6	25	s	(−,−,+)	ISEE
324	1451	7	3	5-6	80	as	(−,0,−/+)	ISEE
324	1539	5	2.5		0	neither		
324	1616	4.5	2.5	5-6	45	as	(−,+,0)	ISEE
324	1706	5.5	2		20	s	(−,+,−)	ISEE

Table 1. (continued)

Day	Time, UT	Magnetic Field, nT	Duration, min	Order	Lag, s	Direction[a]	IMF[b]	Monitor
331	1555	4.5	2	5-6	25	as	(+,+,+)	ISEE
331	1921	8	2	6-5	65	as	(+,0,+)	ISEE
332	1408	7	2	5-6	65	as	(−,+,+)	ISEE
332	1451	6	4	5-6	10	as		
333	1413	5	4	5-6	10	as	(+,−,+)	ISEE
333	1439	3.5	4	5-6	90	as	(+,0,+)	ISEE
333	1521	4	7.5	5-6	125	as	(+,+,+)	ISEE
336	1438	6	3	6-5	20	s	(+,+/−,+)	ISEE
336	1517	3	2.5	6-5	20	s	(+,+,+)	ISEE
336	1622	6	3.5	6-5	65	s	(+,+,+)	ISEE
336	1634	8	3	6-5	10	s	(+,+/−,+)	ISEE
336	1842	6.5	3.5		0	neither	(+,0,+)	ISEE
340	1504	8	2	5-6	90	as	(+,−,−)	ISEE
342	1442	4	3.5	5-6	55	as	(+,+,−)	IMP

[a]Here as denotes antisunward, and s denotes sunward.
[b]Interplanetary magnetic field is noted as positive (+) or negative (−).
A sharp reversal is denoted by +/− or −/+. Field direction is in GSM coordinates.

4 s and 15.36 s, respectively. IMF orientation data were available for 63 of the 87 events, and IRM plasma data were available for portions of seven days during late 1984.

All solar wind data files were obtained through download using the World Wide Web. The AMPTE IRM measurements were obtained from the Web site of the University of New Hampshire Experimental Space Plasma group at http://www-ssg.sr.unh.edu, while the ISEE and IMP measurements came from the Web site of the UCLA Institute of Geophysics and Planetary Physics Space Science Center at http://www-ssc.igpp.ucla.edu:80/ssc.

Figure 1 shows a sample event identified from GOES data. The magnetic field measurements are in *VDH* coordinates, where *V* is directed radially away from Earth, *D* is directed eastward, and *H* points antiparallel to Earth's dipole moment. In each panel, GOES 6 observations are positioned above those of GOES 5. The vertical scale on the right corresponds to GOES 6 field measurements, and the vertical scale on the left corresponds to GOES 5 field measurements. The bipolar signature of the event can be seen in the *V* component, which is in the general direction of the normal to the magnetopause. The lag between observations of an event by the two spacecraft is generally small enough compared to the duration of the event that only a single time of occurrence, which we take to be at the maximum of the magnetic field strength enhancement, needs to be specified. Here, the event occurred at 1716 UT on day 258, 1984.

The transient events used in this study are listed in Table 1. The events were observed between day 230 and day 342 of 1984. All observation times are in UT, so the local time locations of the geosynchronous spacecraft corresponding to any event may be found using LT = UT − 5.0 for GOES 5 and LT = UT − 6.5 for GOES 6. Because the events were detected at large distances from the magnetopause, their amplitudes were generally small. The amplitudes of the bipolar signatures of our events ranged approximately from our required threshold of 2 nT to 18 nT, with a median amplitude of 6.5 nT. Event duration, which we define as the time between peak positive and negative deflections in the bipolar signature, ranged approximately from 1 min to 8 min with a median duration of 6 min. Also shown in Table 1 are the order in which each event was observed by GOES 5 and GOES 6, the lags between the observations, and the sunward/antisunward (s/as) component of event motion as inferred from the order of observations and spacecraft positions. Finally, observations of the IMF direction in GSM coordinates during an interval approximately 5 to 10 min preceding each event are listed when available. If a field component is consistently positive or negative, it is labeled as + or −. A sharp reversal in a component of the IMF is designated as either +/− or −/+.

3. Statistical Survey and Discussion

3.1. Distribution of Events

We begin by considering the locations at which the events were observed. The events were found from GOES measurements made on the dayside over the same interval each day for several months near the end of 1984. Figure 2 shows the locations of GOES 5 and GOES 6 in the GSM *xy* plane during the occurrence of the events. While the longitudinal range over which events are observed is about the same on either side of the Sun–Earth line, the events found in the prenoon sector far outnumber those in the postnoon sector. Of the 174 individual observations, 129 were made prior to local noon and 45 were made after local noon, representing nearly a 3:1 ratio in favor of prenoon events. Figure 3a shows the distribution of these observations as a function of local time. They range from 0745 LT to 1610 LT, nearly symmetric about local noon; however, the peak of the distribution occurs in the prenoon sector at around 1000 LT.

The preponderance of events in the prenoon sector suggests that many of the events may be produced by pressure pulses generated in the foreshock/bow shock region since the prenoon magnetopause lies generally behind the quasi-parallel bow shock, where such pulses are thought to be produced. There should be no bias for either FTEs or events associated with pressure pulses inherent in the solar wind to be produced in the prenoon sector.

Figure 3b is reproduced from *Sibeck and Korotova* [1996]. It shows the distribution of MIEs detected by high-latitude ground magnetometers. The double-peaked pattern consists of a pronounced prenoon peak between 0800 and 1000 LT and a smaller, secondary postnoon peak between 1200 and 1400 LT. Only the prominent prenoon peak appears in all MIE distributions detected by ground stations at geomagnetic latitudes rang-

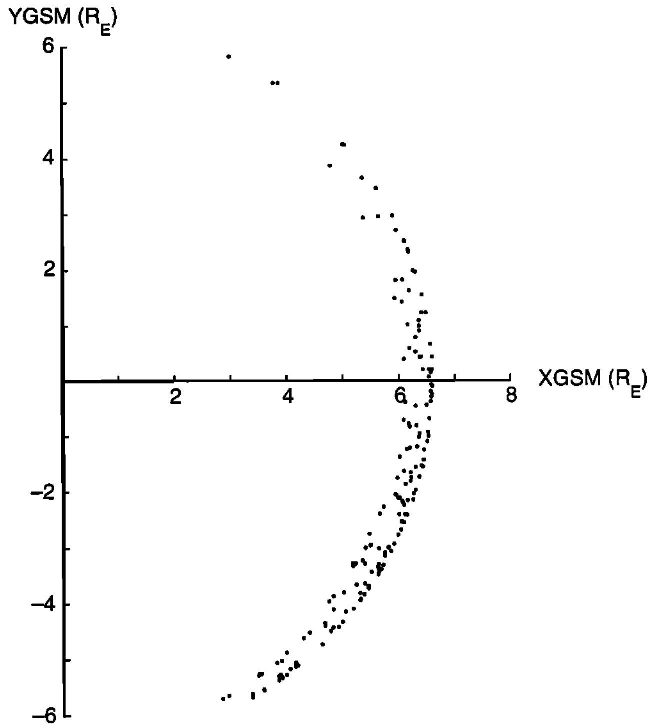

Figure 2. Positions of GOES 5 and GOES 6 in the GSM *xy* plane during their observations of the transient events used in this study.

ing from about 60° to 80° [*Glassmeier et al.*, 1989; *Vorobjev et al.*, 1999]. A comparison of Figures 3a and 3b shows both similarities and differences between the distributions. In both cases the majority of events occur in the prenoon sector. The peak of the distribution of geosynchronous transient events occurs between 0900 LT and 1100 LT, slightly later than the primary peak of the MIE distribution. However, there is no postnoon secondary peak evident in the transient event distribution.

It is impossible to infer with much certainty from Figure 3 that the distribution of MIEs may mirror that of geosynchronous transient events produced by foreshock/bow shock pressure pulses. If the secondary postnoon peak is truly a "quirk" as suggested by *Lanzerotti et al.* [1991], then the similarities of the distributions are enhanced. In particular, if several more events had been observed during the 1100 to 1200 LT interval in the study by *Sibeck and Korotova* [1996], then the presence of the secondary peak would be significantly diminished. Furthermore, a possible explanation for the lack of MIEs near local noon may lie in the fact that ground events are generated by azimuthal gradients in the pressure applied to the magnetosphere [*Southwood and Kivelson*, 1990]. If many pressure fronts strike the subsolar magnetopause straight on, there will be many instances when transient pressure increases produce no ground events near local noon. However, the suggestion that MIEs may be a result of various simultaneous effects at the magnetopause, both with and without any bias toward the prenoon sector, cannot be discounted. Our distribution only suggests that foreshock/bow shock pressure pulse induced events may represent a significant contribution to the production of MIEs.

3.2. Motion of Events

Next, we consider the motion of the events. This is investigated using the 87 event pairs in the data set that were observed by both GOES spacecraft. In general, the signatures seen at each satellite were very similar, but occurred with a slight time difference or lag. During our survey, we did not find any events that exhibited a clear signature at one spacecraft and a complete lack of any signature at the other spacecraft. Furthermore, the sense of the bipolar signature (increase/decrease or vice versa) for any event was always the same for GOES 5 and GOES 6.

To determine the lag, we selected an interval, typically about 20 min, surrounding the variation in the magnetic field strength associated with an event observed by GOES 5. By comparing this interval to intervals of equal length in the GOES 6 data (which also exhibit the event signature) over a range of lags centered about zero, we can determine the cross-correlation coefficient for the two sets of measurements as a function of the lag. The value of the lag at the maximum cross-correlation coefficient represents the time difference between the observations of the event by the two GOES satellites, and the sign of this lag indicates the order in which the spacecraft see the event. This order and the known positions of GOES allow us to determine whether an event is moving sunward or antisunward and to estimate roughly the azimuthal speed of the event.

Figure 4 shows an example of the analysis used to determine the lag. The top panel shows the increase in the magnetic field strength associated with the event observed by GOES 5 and GOES 6 at 1735 UT on day 230, 1984. The bottom panel

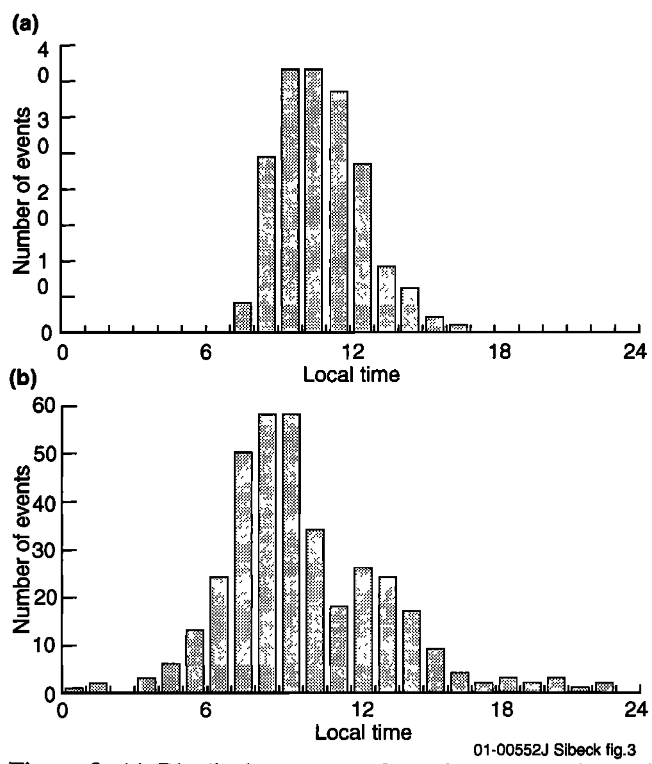

Figure 3. (a) Distribution pattern of transient events observed at geosynchronous orbit as a function of local time. (b) Distribution pattern of high-latitude magnetic impulse events as a function of local time (reproduced from *Sibeck and Korotova* [1996]).

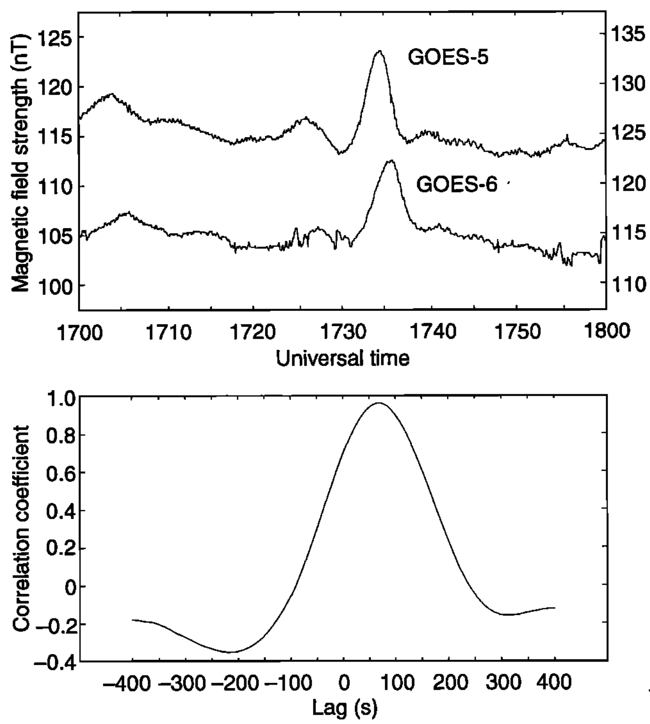

Figure 4. Cross-correlation analysis on the magnetic signature of a transient event (event of day 230 at 1735 UT) seen by GOES 5 and GOES 6 yields the time lag between the observations.

shows the cross-correlation function determined as a function of the lag between the observations. The maximum in this function occurs at a lag of +65 s, indicating that the event was seen first at GOES 5, then 65 s later at GOES 6. A negative value of the lag would indicate that the event was first observed by GOES 6. We did not find any dependence of the lag on either the amplitude or the duration of the events.

The average lag of the 87 event pairs in our data set was about 40 s. Twelve of these were found to have lags of under 10 s and are of little value in investigating the motion of the events. The 12 short-lag events were found to be distributed nearly uniformly from about 0900 MLT to 1500 MLT. A very short lag may indicate either that the event, if localized, originated between the spacecraft or that the compression of the magnetopause may have been global in nature. As a result, they are not included in the plot of Figure 5, which shows the motion associated with the remaining 75 event pairs in the GSM xy plane. The direction of motion of an event is represented in Figure 5 by a vector that originates at the midpoint between GOES 5 and GOES 6. The vector is directed from one satellite to the other, indicating the order in which the event was observed. As indicated in the figure, the motion of these events is generally antisunward. There are 56 antisunward events compared to 19 sunward events, for about a 3 to 1 ratio. Most of the sunward events occur near local noon. This is illustrated in Figure 6a, where the rate of occurrence of antisunward events is compared to that of sunward events within three longitudinal sectors with respect to local noon. The 75 events are divided into three groups. The first group, labeled 1–25, consists of the events that are closest longitudinally to local noon. Their longitudes range from less than 1° to about 13° on either side of local noon. Within this group, the number of antisunward events (12) and the number of sunward events (13) are nearly equal, indicating there is no preferred direction of motion near local noon. The next group, 26–50, consists of events at longitudes ranging from approximately 15° to 32° on either side of local noon. Here, the motion is predominantly antisunward, with only three of the 25 events moving sunward. The final group, 51–75, are at longitudes ranging from approximately 34° to 52°. The statistics are the same as those of the previous group, with 22 events moving antisunward and three events moving sunward.

In summary, we have found that in the vicinity of local noon, there is no clear tendency for magnetospheric transient events to move sunward or antisunward. However, away from local noon, nearly 90% of the events (44 out of 50 in this study) move antisunward.

This result is consistent with the idea that events are generated by pressure variations, either inherent in the solar wind or associated with the bow shock. These variations should first strike the dayside magnetopause near local noon. The ripples produced are then carried antisunward with the magnetosheath flow. As a result, a spacecraft that is very close to local noon may observe sunward and antisunward motion with nearly equal probability, whereas a spacecraft distant from local noon generally sees antisunward events. This result may also be explained by the magnetic merging model. Events produced by magnetic merging move in response to pressure gradient and magnetic curvature forces (for example, see the discussions by *Crooker* [1979]; *Cowley and Owen* [1989], and *Gosling et al.* [1990]). The pressure gradient force generally points antisunward away from the subsolar point. However, magnetic

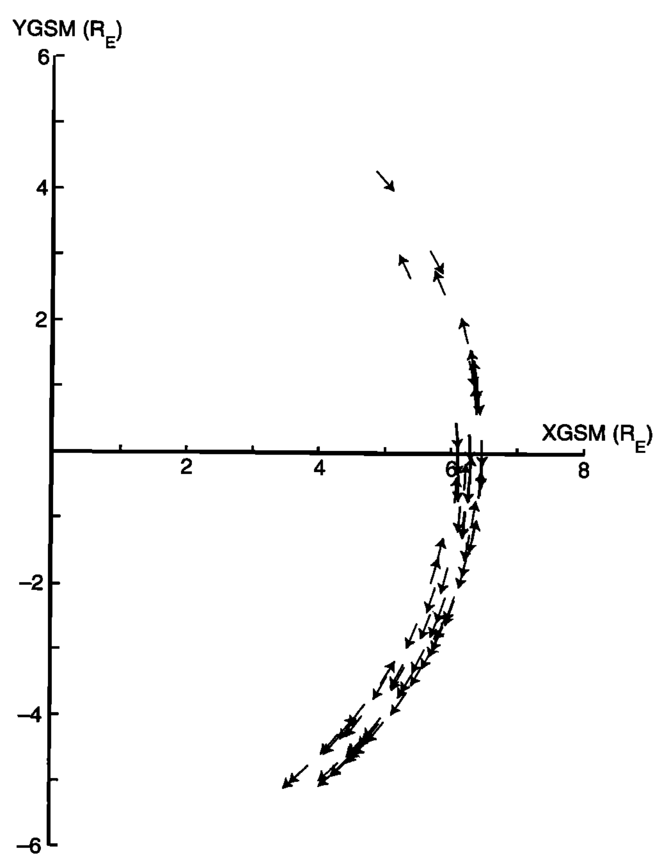

Figure 5. Motion of transient events at geosynchronous orbit in the GSM xy plane as inferred by cross-correlation analysis.

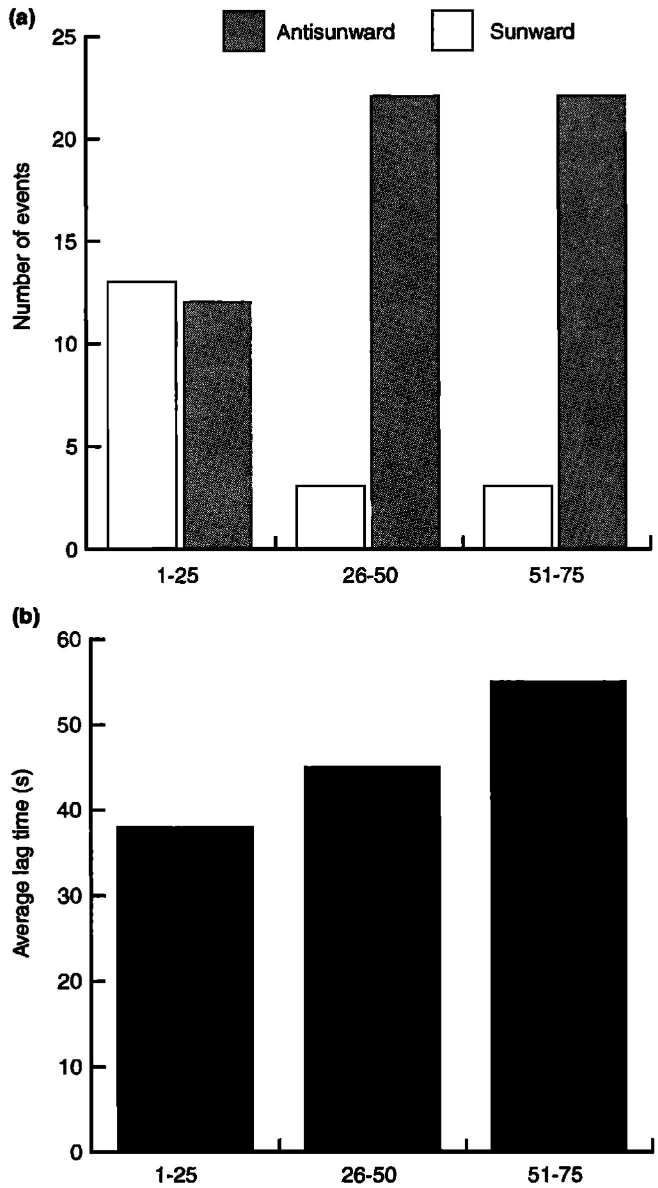

Figure 6. (a) A comparison of the number of events with sunward and antisunward motion. Events are divided into three groups based on longitude with respect to local noon. The group consisting of events 1–25 had longitudes ranging from less than 1° to about 13° on either side of local noon. Events 26–50 are from about 15° to 32°, and events 51–75 are from 34° to 52°. The group closest to local noon (events 1–25) does not exhibit any bias toward either type of motion, whereas antisunward motion is dominant in the other two groups. (b) The average lag time determined for the three groups increases with distance from local noon.

curvature forces depend upon location and the IMF orientation. Pressure gradients only dominate curvature forces at locations far away from noon, so the merging model also accounts for the possibility of sunward motion in the vicinity of noon.

If the transient events propagate azimuthally around the magnetosphere as has been supposed, then the lags and the known separation of the spacecraft allow us to obtain an estimate for the speeds of the events. The lags determined for our 87 event pairs range from 0 to 130 s with a median lag of 30 s. This median lag corresponds to an azimuthal speed of nearly 600 km/s, which is much greater than the magnetosheath flow velocity anywhere outside the dayside magnetosphere [*Spreiter et al.*, 1966]. Events with azimuthal speeds of the order of the magnetosheath flow velocity should have lags of about 80 s and higher. There are only 13 such events, nearly all of which are in the prenoon sector far from noon. Figure 6b shows the average lags for the events grouped within the three longitudinal sectors discussed earlier. The average lag is shortest for the group that is closest to local noon and increases for the sectors that are farther away.

Two primary results arise from our analysis of the time lags between event observations by GOES 5 and GOES 6. First, the majority of events exhibit lags corresponding to azimuthal speeds much greater than the magnetosheath flow velocity. Second, the lags increase (or the azimuthal speed decreases) for events with greater displacements from local noon. One explanation for the short lags is that for some events, the motion is not simply azimuthally dawnward or duskward, but has a significant northward/southward component. Since the GOES spacecraft are equatorial satellites, this component is likely to produce rather short lags. This point will be investigated further in the next section. A second explanation is that rather than first touching a single point on the magnetopause and then spreading out, discontinuities may nearly simultaneously strike the magnetopause over a range of local times, generally about local noon. The effective speed at which they move along the magnetopause may then be much higher than any observed magnetosheath velocity. Under such circumstances the most accurate estimates of the azimuthal speed will be made by spacecraft at locations that are far from local noon. This is consistent with our results that the longest lags are observed consistently when the GOES spacecraft are in the early prenoon sector. The final alternative is that the events are produced by fast mode waves propagating through the magnetosphere. While this would explain the short lags, it would not account for the bipolar signatures or previously established relationship with slower moving MIEs.

3.3. Solar Wind Observations

Data on the orientation of the IMF were available for 63 of the 87 events (see Table 1). We begin by considering the dependence of event occurrence as a function of IMF B_z. FTEs occur predominantly during periods of southward IMF, when magnetic merging is favored, but pressure pulse events have no dependence on the sign of B_z. Of the 63 events with accompanying IMF data, 46 occurred when B_z was either clearly positive or clearly negative. The number of events with positive B_z was 22, and the number with negative B_z was 24. If our data set of events were dominated by FTEs, then most should occur for negative B_z. Since this is not the case, we expect that while there may be FTEs among our events, it is unlikely that they are in the majority.

Next, we investigate the motion of the events based on the magnetic merging model. As mentioned previously, the motion of an FTE is governed by the pressure gradient and magnetic curvature forces. In general, the pressure gradient force points antisunward away from the subsolar point, while magnetic curvature forces depend upon location and the IMF orientation. When the IMF points duskward, newly merged magnetic field lines connected to the northern ionosphere experience dawnward and northward curvature forces, whereas field lines connected to the southern ionosphere experience duskward and southward curvature forces. When the IMF points dawnward,

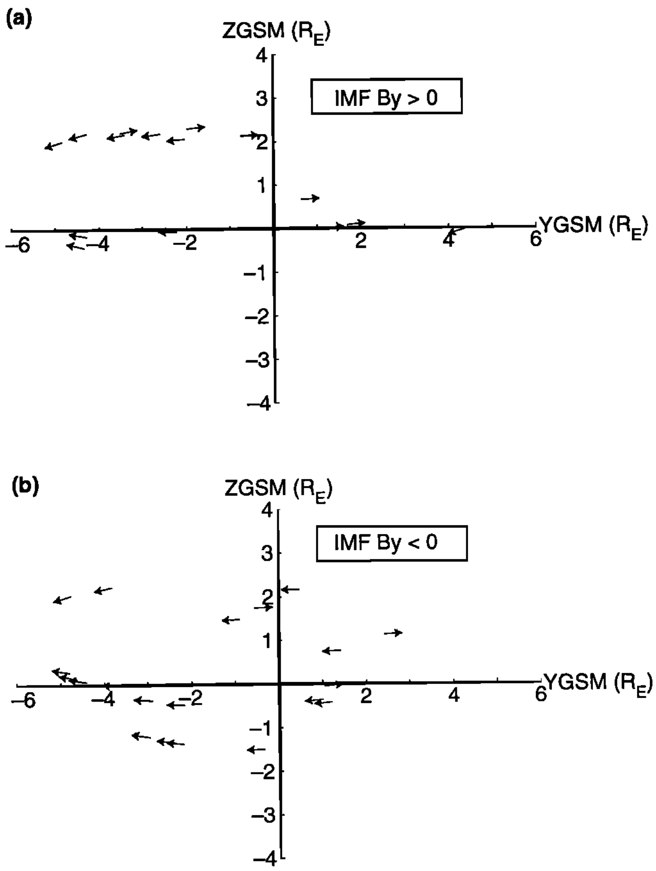

Figure 7. Motion of transient events at geosynchronous orbit in the GSM *yz* plane for (a) positive IMF B_y and (b) negative IMF B_y.

the sense of the magnetic curvature forces reverses. It is predicted that merging should occur along a tilted line passing through the subsolar point [*Sonnerup*, 1974; *Gonzalez and Mozer*, 1974]. For duskward IMF (positive IMF B_y), the merging line tilts from southern dawn to northern dusk, but for dawnward IMF (negative IMF B_y), the merging line tilts from northern dawn to southern dusk. This suggests that when IMF $B_y > 0$, there may be sunward and northward moving events in the postnoon sector, but sunward and southward moving events in the prenoon sector. However, when IMF $B_y < 0$, sunward events in the postnoon sector move southward, and those in the prenoon sector move northward. Such sunward moving events are most likely to occur near local noon, where pressure gradient forces are small and magnetic stresses can be large.

Among the 63 events with accompanying IMF data, 35 were detected when the IMF had a steady dawnward or a steady duskward orientation. Of this number, 15 occurred when $B_y > 0$ and 20 occurred when $B_y < 0$. The plots of Figure 7 show the motion of these 35 events in the GSM *yz* plane as determined by the order in which they were observed by the GOES spacecraft. The 15 events of Figure 7a were observed when IMF B_y was positive. There is a sunward moving event after local noon, and three sunward events before local noon. We checked the northward/southward motion of these events by considering the sense of the bipolar magnetic field signature in the direction normal to the magnetopause. A bipolar outward/inward signature indicates northward motion, whereas an inward/outward signature indicates southward motion. None of the four sunward events had a northward/southward component consistent with that predicted by the merging model. In Figure 7b, where IMF B_y was negative, there is one sunward moving event before noon and four sunward events after noon. Here, four of the five events did move according to the merging theory. Our overall results are that for the nine sunward events, four had a northward/southward motion that was in agreement with the prediction of the merging model, but five moved in a manner that was opposite to the prediction. The success rate of 4/9 or 44% is slightly worse than the 50% success rate expected by chance, suggesting that the events are unrelated to reconnection at the magnetopause.

The pressure pulse model also makes predictions of the occurrence of sunward events based on solar wind conditions. Sunward events are expected to occur shortly after local noon during periods of spiral IMF orientation and prior to local noon during periods of orthospiral IMF [*Sibeck*, 1990]. There are 19 sunward events in our data set. Nine of these events were observed when the two GOES spacecraft were positioned on opposite sides of local noon and could not be characterized either as prenoon or postnoon events. Of the remaining 10 events, four were observed with both spacecraft in the postnoon sector and six with both spacecraft in the prenoon sector. First, we consider the postnoon events. None of these events occurred when the IMF was orthospiral. In two cases the IMF had a nearly radial orientation and could not be considered as spiral or orthospiral. The other two cases occurred when the IMF was spiral. For the sunward events in the dawn sector, solar wind conditions were available in five of the six cases. None of the events occurred when the IMF was spiral. Two events occurred for an orthospiral IMF orientation, two were accompanied by a sharp transition from an orthospiral to a spiral direction, and one occurred during a nearly radial IMF. Because of the small number of sunward events, these results by themselves cannot be considered as evidence favoring the pressure pulse mechanism as the source of geosynchronous transient events. Nevertheless, these results, along with our earlier findings, are consistent with the predictions of that theory.

The connection between magnetic fluctuations seen by the GOES spacecraft and plasma data from the IRM during this period (and for many events in our data set) has already been established by *Fairfield et al.* [1990]. They reported many instances when brief enhancements in the kinetic pressure in the upstream solar wind corresponded to compressions of the magnetic field in the subsolar equatorial magnetosphere. Furthermore, the upstream field strength and the density associated with the perturbations were highly correlated, which is directly opposite to the expectation that they would be anticorrelated in the undisturbed solar wind. The authors concluded that the pressure enhancements were not inherent in the solar wind, but were the result of solar wind/foreshock/bow shock interactions.

Consequently, we inspected solar wind observations for evidence of IMF and plasma discontinuities shortly prior to our events. Of the 63 events accompanied by solar wind data, 17 were preceded by sharp reversals in one or more components in the IMF, considered to be a catalyst in the formation of hot flow anomalies and strong foreshock pressure pulses [*Thomsen et al.*, 1988]. Fourteen events were seen when both GOES spacecraft were in the dawn sector. The remaining three occurred when the two spacecraft straddled local noon. We checked the IMF orientation at the times of our 14 prenoon events. For four of five cases with steady IMF, the foreshock

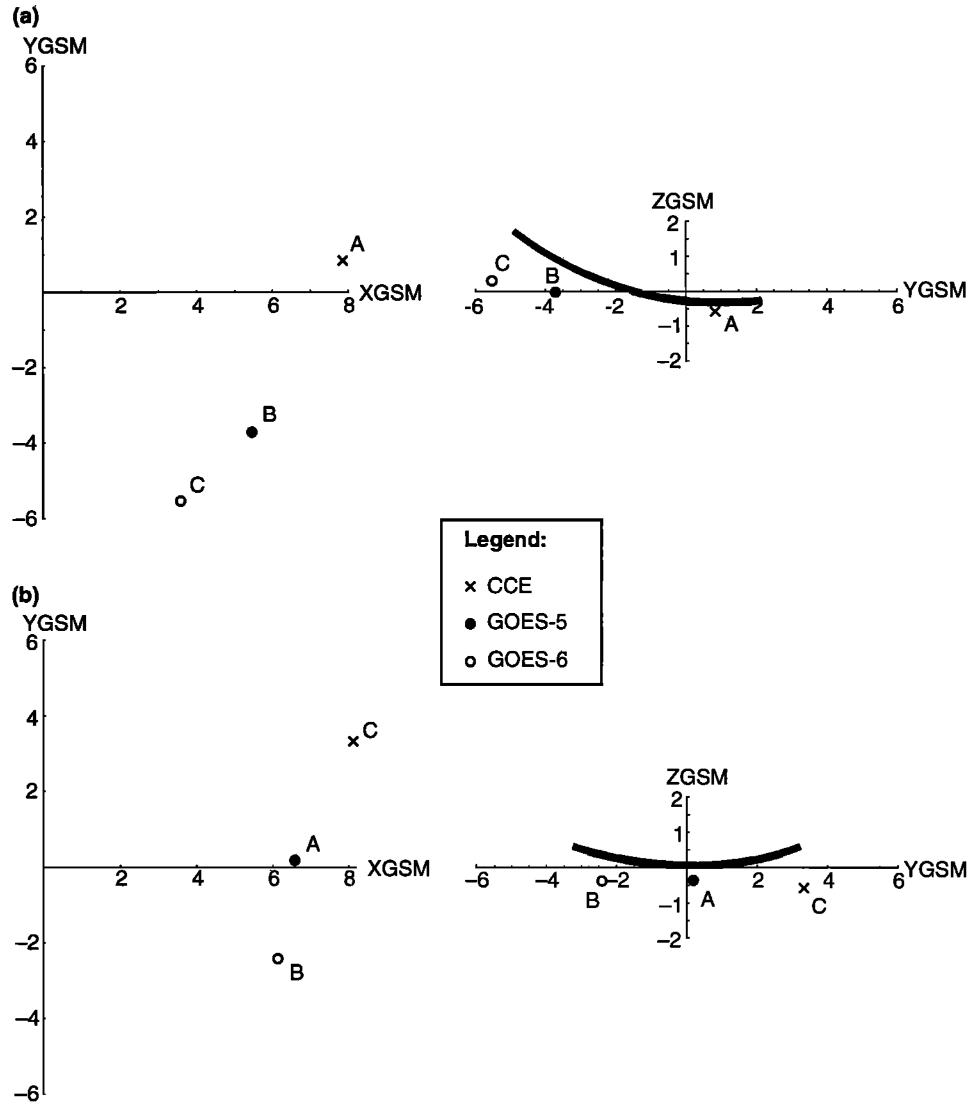

Figure 8. Positions of the two GOES spacecraft and the AMPTE/CCE when they observed the events that occurred at (a) 1438 UT on day 256 and (b) 1701 UT on day 258. The solid curves indicate suggested southward moving wave fronts.

lay prior to noon, while in the fifth case, the IMF was radial. In eight of 10 cases with B_y reversals, the foreshock moved from postnoon to prenoon. In the other two cases with B_y reversals, the foreshock moved from prenoon to postnoon. The remaining two cases consisted of one with sign reversals in both B_y and B_z and one with sign reversals in both B_x and B_z. For both of these, the foreshock went from prenoon to postnoon. Thus in no instance did we observe a prenoon event with the foreshock remaining solely postnoon before and after the event, which is consistent with the pressure pulse model.

3.4. Simultaneous CCE Observations

During late 1984 when the GOES events used in this study were observed, the AMPTE/CCE spacecraft was also in the dayside magnetosphere. In a previous work [*Sanny et al.*, 1996], we identified 57 events observed by the CCE when it was near its apogee of 8.8 R_E. Of the 57 CCE events, 23 were observed when the GOES spacecraft were in the dayside sector used in this study (at least one of the two spacecraft between 0900 and 1500 LT). In this group of 23, eight had clear signatures that were also seen by GOES 5 and GOES 6. The other 15 CCE events did not exhibit signatures at GOES that were distinguishable from the ambient noise. We determined the lags between the CCE observations and those made by the GOES spacecraft using the cross-correlation analysis discussed earlier.

Although the CCE was closer to the magnetopause than the two GOES spacecraft, it was not always the first to observe an event. Rather, the order in which a disturbance was seen appears to be governed by the longitudinal positions of the spacecraft. In all eight cases the spacecraft closest to the noon meridian is the first to observe the event. This happened to be the CCE on four occasions and GOES 5 on the other four occasions. We present two examples in Figure 8, one with the CCE closest to noon and the other with GOES 5 closest to noon.

Figure 8a shows the positions of the three spacecraft during an event observed at 1438 UT on day 256. The left plot depicts the spacecraft in the GSM xy plane, and the right plot depicts the spacecraft in the GSM yz plane. Solar wind data from the IRM indicated that the IMF had a spiral orientation and that B_z was neither clearly positive or negative. The event was detected first by the CCE, then 70 s later by GOES 5, and 55 s after that by GOES-6. The order in which the event was observed as designated by the A-B-C sequence as shown. From the left plot of Figure 8a, the determined lags appear to indicate that the event originated near noon and traveled antisunward in the prenoon sector. The right plot of Figure 8a shows that all three spacecraft were close to the magnetic equator: GOES 5 was nearly on the equator, while GOES 6 and the CCE were north and south of the equator, respectively. As discussed by *Sanny et al.* [1996], the CCE observed a bipolar event signature (−,+) in the magnetic field component normal to the nominal magnetopause, which indicated southward event motion. Furthermore, a minimum variance calculation [*Sonnerup and Cahill*, 1967] on the signature indicated that the axis was essentially parallel to the magnetic equator. The bipolar signature at the GOES spacecraft had the same variation (−,+) as seen by the CCE, indicating the event also had a southward component to its motion. A minimum variation calculation on the stronger GOES signature (GOES 5) showed that the axis lay from northern dawn to southern dusk. Although GOES 6 was slightly north of GOES 5, it saw the event 55 s later than GOES 5. These observations suggest that the event may have originated north of the magnetic equator, likely on the postnoon side from the spiral orientation of the IMF. At the CCE the propagation of the event was primarily southward. It swept southward and antisunward across the GOES spacecraft, but the orientation of the ripples in the magnetopause was such that the disturbance was first observed by GOES 5 and then GOES 6. The thick curved lines shown in the right plots represent rough guesses of the geometry of the ripples of the events as they propagate past the spacecraft.

Figure 8b shows the positions of the three spacecraft for the event of 1701 UT on day 258. Corresponding solar wind data indicated that the orientation of the IMF shifted from orthospiral to spiral immediately preceding the event and the IMF had a B_z component that was neither clearly positive or negative. As shown in the left plot, the event was detected first at GOES 5, which was very close to magnetic noon. It reached GOES 6 and the CCE about 40 s and 55 s after the GOES 5 observation, respectively, suggesting that the disturbance originated near noon and traveled antisunward in both the dawn and the dusk sectors. The positions of the spacecraft in the GSM *yz* plane are shown in the right plot. All three spacecraft are slightly south of the magnetic equator and all detected a bipolar signature with a (−,+) variation in the field component normal to the nominal magnetopause, indicating the event was moving southward. It is interesting to note that for this case, although the two GOES spacecraft were aligned at almost exactly the same latitude, the event was observed at GOES 6 about 40 s after GOES 5. This information, together with the lags, is consistent with a picture of a localized disturbance emanating from a location near the subsolar point, slightly north of the equator.

To summarize, from the lags found for the eight events observed simultaneously by CCE and the two GOES spacecraft, the order in which an event is observed appears to be most strongly correlated with position relative to magnetic local noon, with the spacecraft closest to local noon observing the event first. The order does not seem to be determined by distance from the magnetopause or the positions of the spacecraft relative to the magnetic equator.

4. Conclusion

In this study we have examined the distribution and motion of transient events whose magnetic signatures were observed at geosynchronous orbit by the GOES 5 and GOES 6 pair. Observations made in the prenoon sector outnumbered those in the postnoon sector by about a 3 to 1 ratio. Although the distribution had a range that was nearly symmetric about local noon, it peaked at about 1000 LT. Such a distribution suggests that a number of events in our data set were produced by pressure pulses generated in the foreshock/bow shock region. The prenoon magnetopause lies generally behind the quasi-parallel bow shock, where these pulses are thought to be produced. FTEs or transient events associated with pressure pulses inherent in the solar wind should not exhibit any bias toward the prenoon sector.

We compared the distribution of our geosynchronous events with the distribution of MIEs seen by high-latitude ground magnetometers. The two patterns were similar in that both were characterized by predominant prenoon peaks. Secondary postnoon peaks are seen in some MIE distributions. The role (or existence) of the secondary peak is unclear. Its physical significance may be questionable, for its appearance would be greatly diminished if only several more ground events were detected between 1100 LT and 1200 LT [*Sibeck and Korotova*, 1996]. Alternately, the absence of MIEs near local noon may be a result of the fact that ground events are generated by azimuthal gradients in the pressure applied to the magnetosphere [*Southwood and Kivelson*, 1990]. A pressure front that strikes the subsolar magnetopause straight on will not produce a ground event near local noon. Of course, the secondary peak may be the result of an actual effect at the magnetopause, and MIEs may be produced by various simultaneous processes at the magnetopause, both with and without any bias toward the prenoon sector. Our result only shows that foreshock/bow shock pressure pulse induced events may represent a significant contribution to the production of MIEs.

A cross-correlation analysis on the data from the two spacecraft yielded values for the lags between their observations of the events. We interpreted these lags as an indication of the propagation of the events, which we assumed to be azimuthal. The motion of the geosynchronous events, as determined by the order in which they were observed by the GOES pair, was predominantly antisunward (nearly 90%) away from noon. In the vicinity of local noon, the number of sunward and antisunward events was about equal. This result can be explained by either the pressure pulse model or the magnetic merging model, both of which predict primarily antisunward motion away from noon and a higher probability of sunward motion near noon.

The values of the lags ranged from 0 to about 130 s. For many events the azimuthal velocity as determined from the lag exceeded the magnetosheath flow velocity significantly. Also, the lags had a tendency to increase away from local noon. The events with the longest lags, that is, those events whose azimuthal velocities were comparable with the magnetosheath flow velocity, were clustered in the prenoon sector well away from local noon. While the short lags may be related to the northward/southward component of the motion of the events, the results shown in Figure 8 favor longitudinal position as the primary factor in determining the order an event is observed. Another explanation, from the pressure pulse model, is that discontinuities may not generally impinge on the magnetopause over a very localized region. When interplanetary magnetic field lines and discontinuities encounter the bow shock, they slow down with the shocked solar wind flow in the magnetosheath. As a result, the field lines and discontinuities bow to drape around the magnetosphere and may nearly simultaneously strike the magnetopause over a range of local times and latitudes. The effective speed at which they move along the magnetopause may then be much higher than any observed magnetosheath velocity. Finally, if magnetic merging is the primary source for our events, it must be sudden and occur over a wide range of local times in order to explain the short lags.

Our results on event distribution and motion did not provide compelling evidence for either the merging model or the pressure pulse model. Either model could have been used to explain the findings, except perhaps for the dominance of prenoon events. This bias suggested that solar wind/foreshock/bow shock interactions may have been the primary source of the events. In attempting to better distinguish between the two models, we considered simultaneous solar wind observations, which were available for 63 of our 87 events. We began by investigating the dependence of event occurrence versus the sign of IMF B_z. FTEs occur predominantly during periods of southward IMF, when magnetic merging is favored; however, pressure pulse events have no dependence on IMF B_z. We found that the number of events that occurred for positive B_z and negative IMF B_z were nearly the same (22 and 24, respectively). Hence event occurrence did not depend on the sign of B_z. Next, we considered the sunward moving events. The merging theory predicts that for positive IMF B_y, sunward and northward motion should occur after local noon, while sunward and southward motion should occur prior to local noon. This is reversed during periods of negative IMF B_y, when sunward and southward motion should occur after local noon, and sunward and northward motion should occur prior to local noon. We found that less than 50% of the sunward events moved according to these predictions of the merging model. We therefore concluded it was unlikely that reconnection at the magnetopause was a factor in determining sunward motion. According to the pressure pulse model, sunward events occur shortly after local noon during periods of spiral IMF orientation and prior to local noon during periods of orthospiral IMF. Here we found the sunward motion to be generally consistent with these predictions. However, since there were only 10 candidate events for this test, the results are not statistically significant. Nonetheless, like the results for IMF B_y and B_z, they indicate that the primary source of the observed geosynchronous events may be pressure pulses.

If pressure pulses were indeed the source for our events, it would be interesting to consider their point of origin: Were they inherent in the solar wind, or were they a result of interactions between the solar wind and the foreshock/bow shock? The dominance of prenoon events in this study suggests that it may be the latter case since the prenoon magnetopause lies generally behind the quasi-parallel bow shock, where such pulses are thought to be produced. In addition, about 90% of the events that were preceded by sharp reversals in one or more components in the IMF were detected prior to local noon. Such reversals are considered to be a catalyst in the formation of foreshock pressure pulses. The relationship between events seen by the GOES spacecraft and plasma data from the IRM during this period had already been established by *Fairfield et al.* [1990], who determined that in general, the upstream field strength and the density associated with the perturbations were highly correlated, indicating that the fluctuations originate in the foreshock. These various results all suggest that the pressure pulses that produced our geosynchronous events were not inherent in the solar wind, but a result of interactions between the solar wind and the foreshock/bow shock.

Finally, we examined eight cases in which an event was simultaneously observed by the AMPTE/CCE and the two GOES spacecraft. In all eight cases the event was first seen by the spacecraft that was closest to local noon. This indicates that the order in which an event is observed is most strongly dependent on longitudinal position with respect to local noon rather than distance from the magnetopause or latitude.

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