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Interplanetary magnetic field control of dayside transient event occurrence and motion in the ionosphere and magnetosphere

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Abstract. The pressure pulse model for dayside transient ionospheric events predicts dawnward moving events at and prior to local noon during periods of spiral interplanetary magnetic field (IMF) orientation, but duskward moving events at and after local noon during rarer periods of orthospiral IMF orientation. We use this model to interpret ground and geosynchronous magnetometer observations of a duskward-moving transient event that occurred on 10 August 1995 during a period of orthospiral IMF orientation. We then survey geosynchronous GOES–8, 9, and 10 magnetometer observations to determine the directions of motion for 67 isolated magnetic impulse events seen in South Pole magnetograms from 1995–1999. The occurrence patterns and directions of motion inferred from both case and statistical studies are consistent with pressure pulse model predictions.

Key words. Interplanetary physics (Interplanetary magnetic fields; discontinuities) – Magnetospheric physics (Magnetosphere-ionosphere interactions)

1 Introduction

Abrupt variations in the solar wind density (and dynamic pressure) have frequently been invoked to explain isolated transient events in the dayside magnetosphere and high-latitude ionosphere (e.g. Friis-Christensen et al., 1988; Sibeck, 1990). Although some pressure variations originate in the solar wind (e.g. tangential discontinuities and interplanetary shocks), the largest and most prevalent variations form via kinetic processes that excavate cavities and generate density variations at the edge of the foreshock (Thomas and Brecht, 1988; Fairfield et al., 1990). The solar wind flow sweeps the density variations into the bow shock, where they launch fast mode waves that propagate through the magnetosheath. Because the sum of the fast mode and magnetosheath velocities approximately equals that of the unperturbed solar wind, the pressure fronts within the magnetosheath keep pace with and maintain the orientation of the prevailing solar wind discontinuities (Thomas et al., 1995). Once they strike the magnetopause, the pressure fronts launch fast and intermediate mode waves into the magnetosphere (Tamao, 1964). The fast mode waves propagate across magnetic field lines to produce transient events in the equatorial magnetosphere, whereas the intermediate mode waves propagate along magnetic field lines to produce transient events in the high-latitude dayside ionosphere (Southwood and Kivelson, 1990; Glaßmeier and Heppner, 1992).

The pressure pulse model makes three crucial predictions concerning transient event occurrence patterns in the magnetosphere and ionosphere (Sibeck, 1990). First, in contrast to models for transient events produced by bursts of merging on the equatorial magnetopause (e.g. Rijnbeek et al., 1984), the pressure pulse model predicts no dependence of event occurrence on the north/south polarity of the IMF. Second, the model predicts that the spiral/orthospiral orientation of the IMF controls the local times at which transient magnetospheric and ionospheric events occur. Here orthospiral refers to IMF longitudes ($0° < \Lambda < 90°$ and $180° < \Lambda < 270°$), spiral refers to IMF longitudes ($90° < \Lambda < 180°$ and $270° < \Lambda < 360°$), longitude $\Lambda = 0°$ points sunward, and $\Lambda = 90°$ duskward. During periods of spiral IMF orientation, the foreshock lies upstream from the pre-noon bow shock and the model predicts a preponderance of pre-noon magnetospheric and ionospheric events. However, during periods of orthospiral IMF orientation, the foreshock lies upstream from the post-noon bow shock and the model predicts a preponderance of post-noon events. Finally, the model predicts that pressure variations sweep dawnward across the bow shock and magnetopause during periods of spiral IMF orientation, but duskward during periods of orthospiral IMF orientation. Summarizing, the pressure pulse

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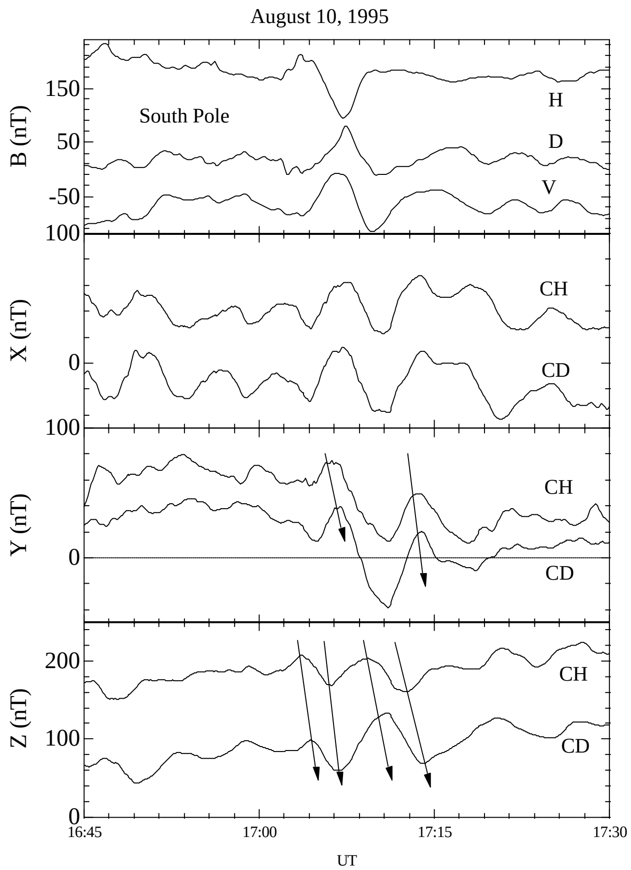

Fig. 1. Ground magnetograms from 16:45 to 17:30 UT on 10 August 1995. The top panel shows the H (north/south), D (east/west), and V (downward/upward) components of the South Pole magnetogram. The other three panels show the geographic X (north/south), Y (east/west), and Z (downward/upward) components of the Coral Harbour and Cape Dorset magnetograms for the same time interval. Arrows indicate the motion of specific features from Coral Harbour to Cape Dorset.

model predicts dawnward-moving magnetospheric and ionospheric events during periods of spiral IMF orientation and duskward moving events during rarer periods of orthospiral IMF orientation.

Several statistical studies have addressed the first prediction. Konik et al. (1994) and Sibeck and Korotova (1996) reported that transient events observed in the high-latitude dayside ionosphere exhibit only a slight tendency to occur for northward IMF orientations. Rather than providing information about their generation mechanism, this tendency may simply reflect difficulties in identifying the relatively low-amplitude events during the periods of intense geomagnetic activity that are expected for southward IMF orientations. Several statistical studies have partially addressed the second prediction. Glaßmeier et al. (1989), Lanzerotti et al. (1991), and Sibeck and Korotova (1996) all reported a strong tendency for transient events in the high-latitude dayside ionosphere to occur prior to local noon, as might be expected for the prevailing spiral IMF orientation. No statistical survey has addressed the third prediction. Nevertheless, Korotova et al. (1995; 1997; 2002) have reported several case studies in which the direction of event motion through the high-latitude dayside ionosphere was consistent with the predictions of the pressure pulse model.

This paper addresses the remaining predictions of the pressure pulse model by presenting separate statistical surveys of transient event motion and occurrence patterns in the high-latitude dayside ionosphere for spiral and orthospiral IMF orientation. A case study of a transient event produced by solar wind pressure variation demonstrates the techniques used. It is followed by a statistical study demonstrating that transient events occur prior to local noon and move dawnward during periods of spiral IMF orientation, but that they occur after local noon and move duskward during periods of orthospiral IMF orientation.

2 Case study: 10 August 1995

The top panel of Fig. 1 presents the north (H), east (D), and downward (V) components of the magnetic field observed by the South Pole (SP, Λ=75° MLT=UT−3.5 h) ground magnetometer (Lanzerotti et al., 1990) from 16:45 to 17:30 UT on 10 August 1995 at 10–s time resolution. An isolated event from 17:03 to 17:12 UT exhibited ∼100 nT peak-to-peak variations in each of the three components of the magnetic field.

Unfortunately, the density of ground magnetometer sites in Antarctica does not suffice to determine the direction of event motion. We therefore seek evidence for corresponding transient events in the denser MACCS network of North American ground magnetometers (Hughes et al., 1995). The lower three panels of Fig. 1 present Coral Harbour (CH, Λ=74.54°, MLT=UT–5.6 and Cape Dorset (CD, Λ=74.38°, MLT=UT–4.9) ground magnetometer observations at 5–s time resolution. An isolated (only several cycles) transient event can be observed in the Y and Z components of both ground magnetograms from 17:05 to 17:15 UT. As illustrated by the arrows, each feature within this event moved duskward through local noon from CH to CD. Peak-to-peak lag times ranged from 20 to 55 s, corresponding to azimuthal velocities of ∼7 to 16 km/s. These velocities are similar to those obtained by Korotova et al. (2002). We estimate the corresponding azimuthal velocity at the magnetopause (∼10 R_E) to be ∼440 km/s, close to magnetosheath flow speeds. A Pc5 pulsation with amplitude of ∼10 nT and a period of ∼420 s precluded using X component observations to time the motion of the transient event.

We sought but failed to find evidence for the transient event in observations by the MACCS ground magnetometers located at latitudes higher than 77°. According to observations by the DMSP F10 and F12 spacecraft during and bounding this interval (P. T. Newell, personal communication, 2004), the inner edge of the low-latitude boundary layer (LLBL) was located near 76.4° geomagnetic latitude at 10.9 MLT, i.e. very near the latitudes of CH and CD. We

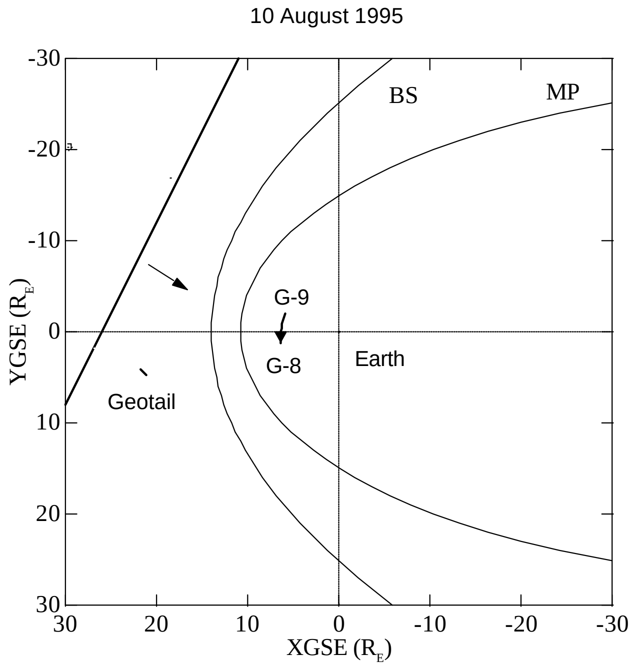

Fig. 2. Projections of the GOES–8, GOES–9, and Geotail spacecraft trajectories from 16:30 to 17:30 UT in the geocentric solar ecliptic (GSE) x–y plane. The figure also displays the nominal locations of the bow shock and magnetopause. The solid line shows the orientation of the 17:06 UT IMF discontinuity observed by Geotail.

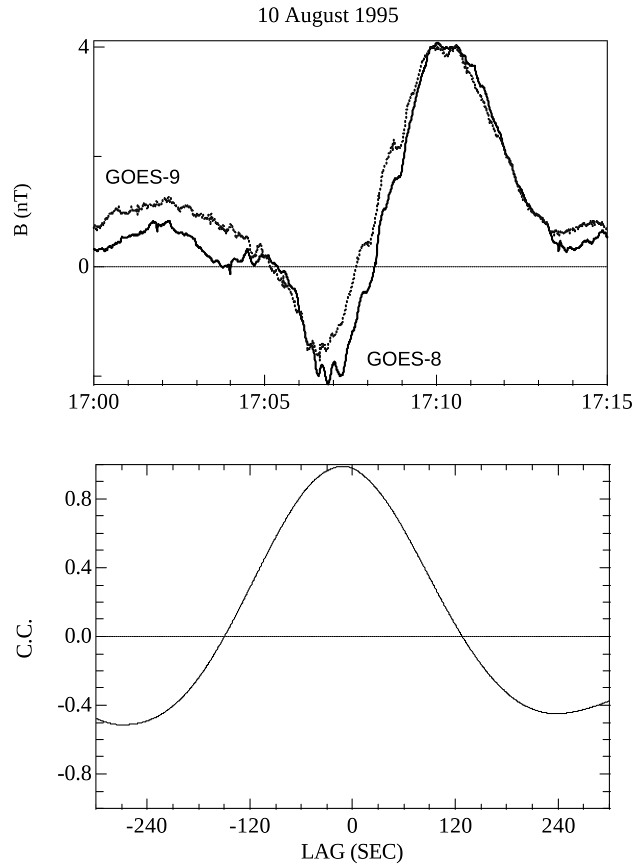

Fig. 3. The top panel presents GOES–8 and GOES–9 total magnetic field observations from 17:00 to 17:15 UT on 10 August 1995. The lower panel shows results from a cross-correlation of GOES–8 and –9 observations at various lag times measured positive from GOES–8 to GOES–9.

suggest that the magnetometers at higher latitudes were located on open geomagnetic field lines, which map to more distant locations on the magnetopause and where no event or distorted event signatures are expected.

We can also determine the direction of event motion from geosynchronous observations. Figure 2 presents the trajectories of the GOES–8 and GOES–9 in the GSE x–y plane from 16:30 to 17:30 UT on 10 August 1995. GOES–8 (at 74.6° W, LT=UT−5) moved through local noon from 11:30 to 12:30 LT, while GOES–9 (at 90° W, LT=UT−6) moved from 10:30 to 11:30 LT. Figure 3 presents 0.5–s time resolution GOES–8 and GOES–9 observations (Singer et al., 1996) of the total magnetic field strength from 17:00 to 17:15 UT. The observations were detrended by removing cubic fits over the hour-long interval from 17:00 to 18:00 UT. From ∼17:02 to 17:13 UT both spacecraft observed similar negative/positive impulses in the magnetic field strength with ∼6 nT amplitude, corresponding to the ground transient event. Close examination of the traces reveals that GOES–9 observed the event before GOES–8, indicating duskward event motion just prior to local noon. An arrow in Fig. 2 illustrates the direction in which the transient event propagated. We determined the azimuthal velocity of the abrupt increase in the magnetic field strength by cross-correlating the 15-min interval of GOES–8 data shown in the figure against 15-min intervals of GOES–9 data, beginning at times ranging from 16:55 to 17:10 UT. The peak correlation coefficient occurred for a lag of 11.5 s from GOES–9 to GOES–8, indicating a duskward azimuthal velocity of ∼956 km s^{-1}. The event appears to propagate at speeds greater than those expected for magnetosheath flows and it seems likely that it originates between the spacecraft. Both the ground and geosynchronous observations indicate duskward event motion. To confirm the interpretation of the event in terms of pressure pulse driven magnetopause motion, we inspect simultaneous solar wind observations for evidence of an orthospiral IMF orientation and a density pulse. As shown in Fig. 2, from 16:30 to 17:30 UT Geotail was favorably situated immediately upstream from the subsolar bow shock, where it moved antisunward from GSE (x, y, z) = (21.7, 4.1, −1.0) to (21.1, 4.8, −0.9) R_E.

Figure 4 presents Geotail magnetic (Kokubun et al., 1994) and LEP (Mukai et al., 1994) observations in GSM coordinates at 12– and 3–s time resolution, respectively. At 17:05 UT, there was a transient increase in the solar wind density and pressure from ∼2.6 to 4.3 cm^{-3} and from 1.2 to 1.8 nPa, respectively. At 17:06 UT, the IMF rotated from an antisunward and northward to a duskward and slightly sunward orientation. Note that the northward and duskward IMF

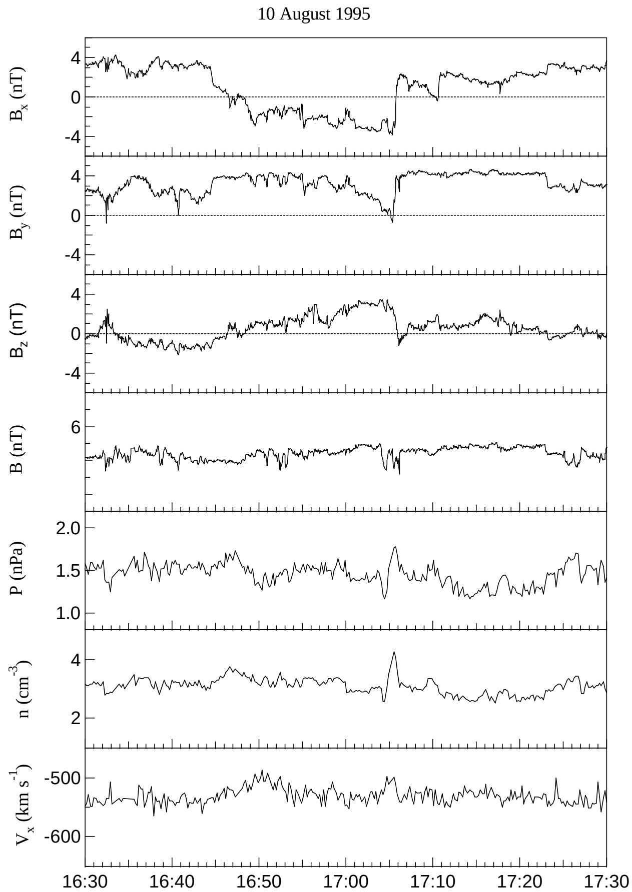

Fig. 4. Geotail magnetometer and plasma moment observations from 16:30 UT to 17:30 UT on 10 August 1995. From top to bottom the panels show three components of the magnetic field in GSM coordinates, the total magnetic field strength, the plasma pressure, the plasma density for the ions (5 keV to 40 keV), and the component of the plasma velocity along the Sun-Earth line. Editor–B observations from LEP instrument in RAM-B solar wind mode are presented. They are for qualitative use only.

orientations rule out an explanation of the transient magnetospheric and ionospheric events in terms of magnetic merging. Northward IMF orientations do not favor reconnection on the subsolar magnetopause, while duskward IMF orientations result in events whose footprints in the northern ionosphere move dawnward.

We associate the 17:05 UT solar wind density/pressure increase with the 17:02–17:13 UT magnetospheric and ionospheric event. To test this hypothesis, we must show that the timing could be correct and that this solar wind feature should have swept duskward across the magnetosphere. Although we have no means of determining the orientation of the 17:05 UT density discontinuity, it seems likely that it is similar to that of the 17:06 UT IMF discontinuity. We calculated the normal to the IMF discontinuity as the cross-product of the upstream and downstream magnetic fields at 17:05:08 UT and 17:06:28 UT. The normal pointed in the GSE (x, y, z)=(-0.52, 0.26, -0.81) direction, i.e. antisunward, duskward and strongly southward. Figure 2 presents the projection of the discontinuity front and normal in the X-Y plane. Given the uncertainties in normal determination, the density and IMF discontinuities should have encountered Geotail and the pre-noon bow shock/magnetopause nearly simultaneously, then sweep duskward past the subsolar magnetopause. Since this was in fact the case, we conclude that the duskward motion of the transient magnetospheric and ionospheric events is fully consistent with the predictions of the pressure pulse model.

3 Statistical study

We wish to validate the predictions of the pressure pulse model for event motion and occurrence patterns on a statistical basis. To do so, we identified a total of 86 impulsive, widespread, and prominent events in dayside South Pole ground magnetograms from August 1995 to May 1999. Each event exhibited a duration less than 15 min (impulsive), occurred at two or more ground stations in the West Coast of Greenland or MACCS chains (widespread), and exceeded 40 nT in the H-component of at least one station (prominent). We examined simultaneous 0.5–s time resolution geosychronous GOES–8 (LT=UT$-$5), -9 (LT=UT$-$9), and -10 (LT=UT$-$7 or -9) magnetometer observations. For 67 of the 86 events, the GOES spacecraft were located in the dayside magnetosphere, an IMF trigger could be observed, and the spiral/orthospiral orientation of the IMF was well determined. Of these 67 events, the geosynchronous spacecraft observed 45 positive impulses or step function variations, 19 bipolar (negative/positive or positive/negative) impulses, and 3 negative impulse or step function decreases. Peak-to-peak amplitudes ranged from 2 to 16 nT.

We then inspected lagged IMF observations in geocentric solar magnetic (GSM) coordinates by the Wind (Lepping et al., 1995), IMP–8 (King, 1982), Geotail (Kokubun et al., 1994), and Interball-1 (Klimov et al., 1997) spacecraft. When observations from more than one spacecraft were available, we used those from the spacecraft closest to Earth and then from the spacecraft closest to the Sun-Earth line. Consistent with previous studies (e.g. Lanzerotti et al., 1991; Sibeck and Korotova, 1996), 34 events occurred for steadily northward IMF orientations, 30 for steadily southward IMF orientations, and 3 for near-radial IMF orientations.

To test whether or not the events tend to occur behind the quasi-parallel bow shock, we plotted their occurrence patterns as a function of local time separately for spiral and orthospiral IMF orientations. We defined the local time of occurrence as that of the position corresponding to the midpoint separating individual spacecraft pairs. We determined the orientation of the IMF based on the signs of B_x and B_y when these parameters were steady for at least 10 min. When the IMF was variable we calculated the orientation of discontinuities corresponding to our events as the cross product of the downstream and upstream magnetic fields. As the orientation of these discontinuities determines the lag times required to reach the various spacecraft, we confirmed the normals with timing calculations. Of the 67 events, 32 occurred for spiral IMF orientations, while 35 occurred for orthospiral orientations. Figure 5 presents occurrence patterns for the events as a function of local time. The distribution for events occurring for spiral IMF orientations peaks from 06:00 to 10:00 LT, whereas that for orthospiral IMF orientations peaks after 11:00 LT. Alternatively, 80% of the spiral IMF events occur prior to 11:00 LT, while 80% of the orthospiral events occur after 10:00 LT. The differing distribution patterns are consistent with the prediction of the pressure pulse model for event occurrence patterns to peak prior to local noon during periods of spiral IMF orientation, but at and after local noon during periods of orthospiral IMF orientation.

To determine the azimuthal velocities at which the signatures propagated through geosynchronous orbit, we detrended hour-long intervals of the magnetic field strength observations and then cross-correlated 15 min intervals encompassing the events. Time lags between the spacecraft for peak correlation coefficients ranged from 2 s to 300 s, resulting in azimuthal velocities ranging from 80 km/s^{-1} to several 1000 km s^{-1}. Figure 6 presents the distributions of dawnward- and duskward-moving events as a function of local time for spiral and orthospiral IMF orientations. As predicted by the pressure pulse model, almost all events moved duskward during periods of orthospiral IMF orientation. Equally consistent with the model predictions, almost all events moved dawnward during periods of spiral IMF orientation. Efforts to identify variations in the magnitude of the event velocities versus local time were unsuccessful.

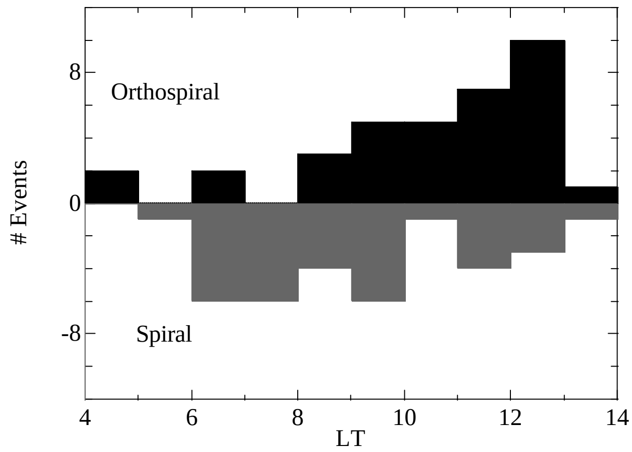

Fig. 5. The distribution of events versus local time for both spiral and orthospiral IMF orientations.

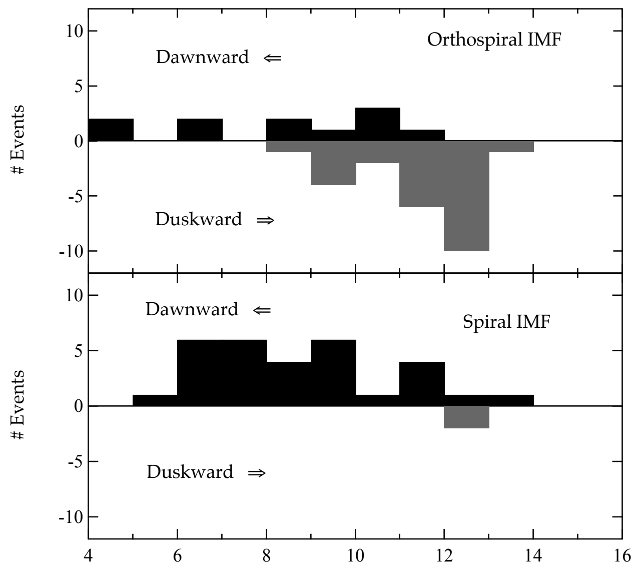

Fig. 6. The distribution of dawnward and duskward moving events versus local time for orthospiral (top panel) and spiral (bottom panel) IMF orientations.

4 Conclusions

We have presented the results of a statistical survey of transient event occurrence patterns and motion. We used South Pole ground magnetometer observations to identify the events, then determined their motion by cross-correlation of high time resolution GOES geosynchronous magnetometer observations. During periods of spiral IMF orientation, events tend to occur prior to local noon and move dawnward. During periods of orthospiral IMF orientation, events tend to occur at and after local noon and move duskward. These results are fully consistent with the predictions of the pressure pulse model. Because the events show no tendency to occur for southward IMF orientations, it seems unlikely that they result from bursts of merging on the equatorial magnetopause.

The results of this study should be compared with those obtained by Sanny et al. (2001), who surveyed the occurrence patterns and motion of a particular category of event at geosynchronous orbit, namely flux transfer events. Each of these events was identified on the basis of bipolar signatures in the direction normal to the nominal magnetopause and impulsive increases in the magnetic field strength. Although they found a striking tendency for the events to occur prior to local noon, their study included too few sunward moving events to determine the role played by the IMF in determining event motion. As they suggested, it seems likely their FTEs simply represent a subset of the transient compressions which pressure pulses generated within the foreshock create when they strike the magnetosphere.

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