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Evidence of different magnetotail responses to small solar wind pressure pulses depending on IMF Bz polarity

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Abstract. The response of the magnetotail to small flux rope associated pressure pulses depends on the IMF Bz polarity. Clear and large amplitude magnetotail reverse polarity South-then-North traveling compression regions (SN TCRs) are observed when the pressure pulse is associated with the northward IMF interval of the flux rope. These tail signatures correspond to small-scale (<10 minute duration) pulses of the solar wind dynamic pressure located in front of and within the small-scale flux ropes. Pressure pulses associated with IMF Bz southward are either absent or give rise to smaller amplitude compressions and less systematic lobe Bz rotations. These results suggest that the orientation of the IMF Bz plays a critical role in modulating the magnetotail response to solar wind dynamic pressure pulses.

Introduction

Transients (e.g., shocks, discontinuities, interplanetary coronal mass ejections (ICMEs) etc.) in the solar wind perturb the magnetosphere in a variety of ways depending on their amplitude, the interplanetary magnetic field (IMF) orientation, season, and geomagnetic energy state. Large scale step-function dynamic solar wind pressure enhancements often give rise to SI and SSC signatures in the dayside magnetosphere and on the ground [e.g., *Sibeck et al.,* 1989] and in the tail lobes *Collier et al.* [1998a]. It has also been shown that the low-latitude geomagnetic field responds well to solar wind pressure pulses during northward IMF conditions on the timescale of a few minutes [*Francia et al.,* 1999]. Recently, *Moldwin et al.* [2001] found that most reverse polarity traveling compression region (South-North TCRs) magnetotail lobe signatures are produced by small pressure pulses in the solar wind primarily during northward IMF. South-North TCRs are characterized by bipolar magnetic signatures that have compressions coincident with the inflection point. They are similar to plasmoid associated TCRs but have a south-north bipolar signature opposed to the north-south signature of the tailward propagating plasmoid TCRs.

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During northward IMF it is expected that the closed magnetosphere will respond to variations of solar wind pressure variations mainly due to magnetopause and magnetotail current systems. This contrasts to the magnetospheric response during southward IMF to solar wind pressure variations. During southward IMF, pressure pulses can trigger substorms, enhance the Region 1 current system due to enhanced reconnection on the dayside, as well as enhance the tail current systems *Kokubun et al.,* [1977]; *Russell et al.,* [1994]. These effects can complicate the magnetic response seen on the ground as well as in the magnetosphere.

Fast ICMEs are well studied interplanetary phenomena due to their strong geomagnetic effectiveness [e.g., *Gosling,* 1993] and because their often smooth, long-duration bipolar turnings makes them ideal to examine the geomagnetic response to different steady IMF Bz polarities [e.g., *Farrugia et al.,* 1993]. Recently, *Moldwin et al.* [2000] identified small-scale magnetic flux ropes in the solar wind with IMP 8 and Wind. These flux ropes have durations on the order of 10s of minutes, had symmetric magnetic field signatures, and had well defined magnetic core fields.

This study examines the magnetospheric global response of short duration solar wind pressure pulses by examining a suite of spacecraft and ground-based magnetometer data for four case studies when there were observations in the upstream solar wind, inner magnetosphere, on the ground, and in the magnetotail. In particular we use the bipolar IMF Bz signature of small-scale magnetic flux rope events to examine differences in geomagnetic response to different IMF polarities at short timescales in a similar fashion to how ICMEs have been used for studying the geomagnetic response during long-duration "steady" IMF Bz conditions.

Observations

Four small-scale flux rope events were identified by Wind when IMP 8 was in the magnetotail during 1997. Using estimates of the propagation times from Wind to IMP 8 distances [e.g., *Collier et al.,* 1998b] at least one compression of the magnetotail lobe was observed at the expected times. South-then-north bipolar turnings of the magnetic field were observed coincident with these compressions. This signature has been called a South-then-North Traveling Compression Region (SN TCR) [*Moldwin and Hughes,* 1994; *Moldwin et* *al.*, 2001] and is most often attributable to short duration pressure increases in the solar wind propagating past the Earth [e.g., *Slavin et al.*, 1993]. In two of the events multiple or wave SN TCRs were observed, while for the other two small-scale solar wind flux ropes single or isolated SN TCRs were observed in the magnetotail. Coincident with these small solar wind flux ropes where multiple "pressure pulses" that had durations of a few minutes and amplitudes of a few tenths of nanoPascals (pressure changes of a few to 30% with most between 5 and 20%). Though these amplitudes are small and are comparable to the uncertainty in the solar wind dynamic pressure measurements, the "pressure pulses" are seen in both the Solar Wind Experiment (SWE) and the high time resolution 3D Plasma Instrument (3DP) data. In the next sub-sections we examine the solar wind and IMF conditions for these events to examine the reason for the different magnetotail responses.

August 14, 1997 Event

A small-scale magnetic flux rope was observed by Wind on August 14, 1997. Using the measured solar wind velocity and the position of Wind, we can estimate the propagation time needed for this structure to propagate to the Earth. Figure 1 shows the solar wind dynamic pressure and IMF from Wind and the Bz and B data for IMP 8. IMP 8 is located in the northern lobe of the magnetotail 25.7 R_E downtail. We estimate the propagation time from Wind to IMP 8 by using the separation of the spacecraft and the measured solar wind velocity. Using this propagation time we can associate the pressure pulse marked by the solid vertical line (D) in the top panel to that of the SN TCR observed by IMP 8 (also marked by a solid vertical line in the bottom two panels). Note that several other higher magnitude pressure pulses are observed both behind and in front of the flux rope. The relative timing between pulses A, D and E are nearly identical to the compression signatures also labeled A, D, and E seen by IMP 8. Smaller amplitude SN TCRs are observed in the magnetotail at these times. An examination of Figure 1 shows that the short duration pressure pulse labeled D is the only pressure pulse that occurred during northward IMF. The other pressure pulses occurred when the IMF Bz component was essentially zero or negative.

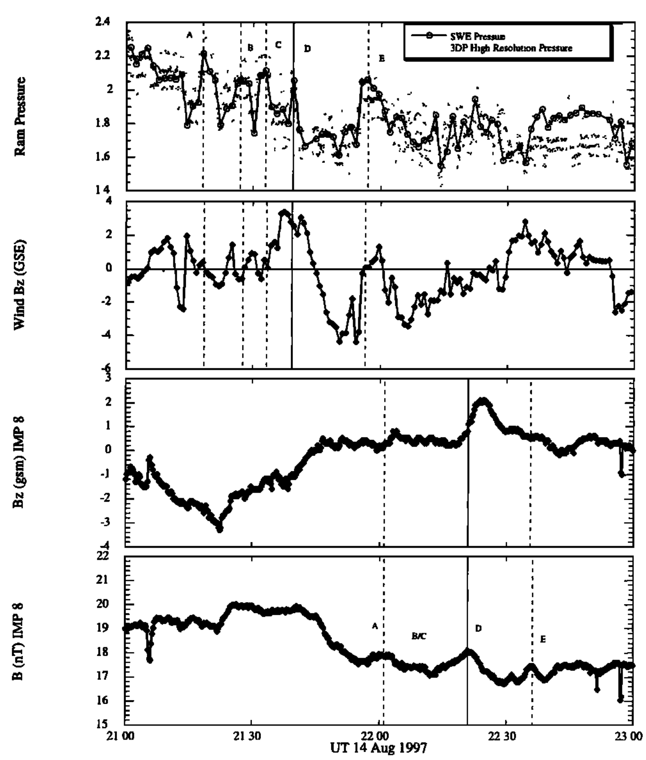

Figure 1. From top to bottom: The solar wind dynamic pressure and the IMF Bz as measured by Wind, and the Bz component and the total field of the magnetotail lobe field as measured by IMP 8 for the August 14, 1997 interval.

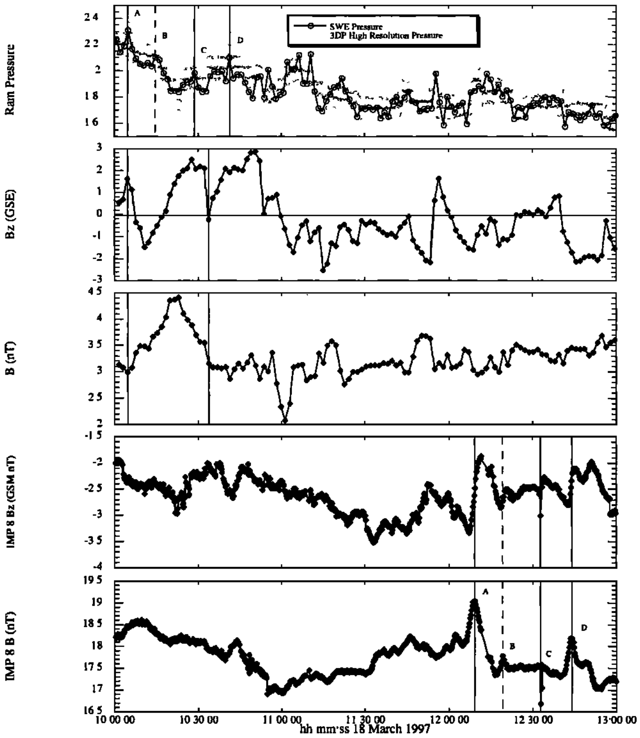

Figure 2. The top three panels show the solar wind dynamic pressure, IMF Bz and total field as measured by Wind for the March 18, 1997 small-scale flux rope. The bottom two panels show the magnetotail Bz and total field as measured by IMP 8. The vertical lines identify the SN TCR signatures. Pressure pulses in the solar wind and their corresponding magnetotail compression signatures are labeled A-D.

Ground magnetometer stations from around the world and the GOES 8 and 9 geosynchronous orbit satellites where examined during this interval for signatures of SIs. At several stations (though not all) and at the GOES spacecraft a compression of the Earth's field is observed at the time that the solar wind pressure pulse labeled D is estimated to arrive at the Earth (not shown).

March 18, 1997 Event

A 30-minute duration small-scale magnetic flux rope was observed by Wind on March 18, 1997. Wind was located at the L1 point 228 R_E upstream of the Earth. At this time IMP 8 was in the northern magnetotail lobe. Figure 2 shows the Wind solar wind dynamic pressure, the north-south component, and the total field of the IMF in the top three panels and IMP 8's GSM Bz and total field magnitude in the bottom two panels. Vertical lines in the Wind magnetic field data panels identify the extent of the small-scale solar wind flux rope. Within the solar wind dynamic

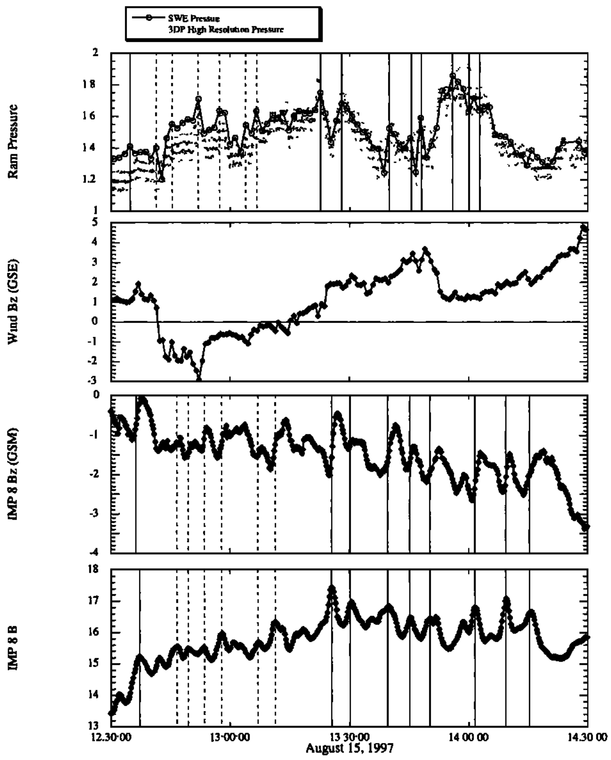

Figure 3. The solar wind IMF Bz and dynamic pressure as measured by wind for the August 15, 1997 small-scale flux rope is plotted in the top two panels. The bottom two panels show the magnetotail Bz and total field as measured by IMP 8. The vertical lines are centered on pressure pulses and magnetotail compression signatures. The solid lines signify IMF Bz north conditions and dashed lines signify IMF Bz south conditions. Note the IMP 8 data is shifted one hour to account for the propagation of the solar wind to IMP 8 distances.

pressure panel short duration pressure pulses are labeled A-D. In the IMP 8 panel, compressions are also labeled A-D. The temporal spacing between the labeled lobe compressions is consistent with the labeled Wind pressure pulses being the cause of these tail signatures. The delay time suggested by matching the relative timing between compression features is approximately 120 minutes. Using the measured solar wind velocity it is estimated that observations at Wind should take 77 $\pm$ 10 min (see *Collier et al.*, [1998b] for description of solar wind propagation method) to reach IMP 8. This discrepancy of 40 minutes, though large, is possible given the uncertainties in estimating the propagation times. This interval had a perpendicular spacecraft separation of 34.6 R_E, or just greater than the estimated perpendicular correlation scale-length of the solar wind. Given that we are able to match 4 compressions with variable temporal spacing with 4 solar wind pressure pulses gives us confidence in making this causal argument.

If this relationship is valid, a clear dependence emerges between the magnitude of the magnetotail lobe response and the polarity of the IMF. For pressure pulses that occur during northward IMF (A and D) the magnetotail lobe response is large in amplitude. For pressure pulses that occur during southward IMF (B), the magnetotail compressions are considerably weaker. In particular note intervals B and D. Both have solar wind dynamic pressure peaks of about 2.1 to 2.2 nPa, though the lobe compression magnitude of interval B that occurred during southward IMF is about 0.5 nT weaker

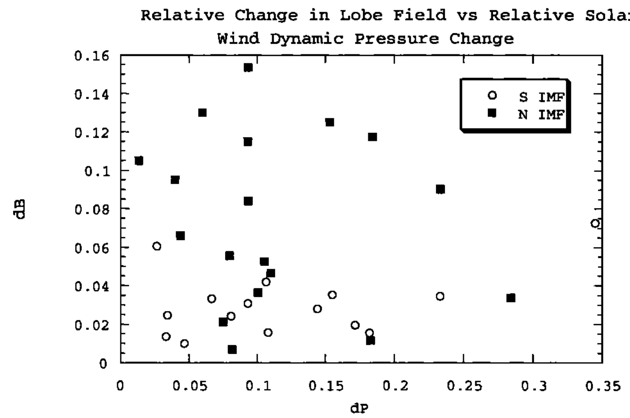

Figure 4. The relationship between the relative change in lobe magnetic field strength and the relative change in the solar wind dynamic pressure for the pressure pulse and lobe compressions observed in all four examples.

than interval D that occurred during northward IMF. There was a very small Bz signature and lobe compression associated with pressure pulse C. This pulse, though occurring during northward IMF, was the lowest amplitude pressure pulse of the four.

August 15, 1997 Event

Wind observed a small-scale magnetic flux rope in the solar wind on August 15, 1997, 128 R_E upstream of the Earth. IMP 8 was in the northern lobe at (-26, 7, 19) R_E GSM and observed a series of at least 15 south-then-north bipolar turnings whose inflection points were coincident with a compression of the magnetic field. Moldwin et al. [2001] has termed these "wave SN TCRs" and they typically have 5 to 15 minute periodicities (pc 5 wave frequencies - see *Sarafopoulos* [1995] for other examples). Figure 3 shows the dynamic pressure and IMF Bz from Wind in the top two panels and IMP 8's Bz (GSM) and total field in the bottom two panels. The vertical lines show pulses in the solar wind dynamic pressure and SN TCR intervals (though no amplitude criterion has been used in their selection it is noted that many of the identified pressure pulses are very small amplitude). The solid vertical lines represent SN TCRs and pressure pulses that occurred during the northward IMF portion of the flux rope while the dashed vertical lines represent events that occurred during the southward part of the rope. Note that though the magnitude of the solar wind pressure pulses are about the same, the SN TCRs during the northward IMF interval are cleaner (the bipolar turnings are smooth) and the compressions are larger (ranging from 0.75 to 1.75 nT compared to 0.25 to 1 nT). There is also a broad increase of the background lobe field coincident with the rotation from southward to northward IMF. We have examined ground magnetograms and geosynchronous energetic particle data for this time (not shown) and can conclude that this increase in lobe field is not due to tail substorm dynamics.

October 5, 1997 Event

A small-scale magnetic flux rope was observed by Wind on October 5, 1997. At this time IMP 8 was located in the northern lobe nearly 30 R_E downtail. Concurrent with the magnetic flux rope were superimposed relatively large amplitude, short-duration pressure pulses with a periodicity between 5 and 8 minutes. This interval is very similar to the August 15, 1997 example and therefore the data are not shown. At IMP 8 the magnetotail lobe also showed compressions coincident with south-then-north turnings with a periodicity between 5 and 8 minutes. With a 35-minute propagation delay imposed on the solar wind data there is nearly a one-to-one correlation between pressure pulses and SN TCRs. However, there is a clear difference in tail response depending on the IMF polarity. The overall background lobe field strength increases from 10 nT to 15 nT coincidently with the northward turning. There is also a change in the behavior of the Bz signatures at IMP 8 depending on whether the pressure pulse is coincident with the northward or southward part of the small-scale flux rope. For the pressure pulses seen during the northward portion, the compressions are coincident with the inflection point of a south-then-north bipolar turning. For the four pressure pulses that occurred during the southward IMF portion of the flux rope the IMP 8 compressions are coincident with minima or the inflection point of a north-then-south bipolar turning.

Figure 4 looks at the correlation between the relative magnitude of the magnetotail lobe B compression and the relative change of the solar wind dynamic pressure for the solar wind pressure pulses identified in all four of the intervals discussed. The solid squares are for the northward IMF intervals and the open circles correspond to the southward IMF events. A marked difference in the relative size of the lobe compression for similar solar wind pressure changes suggests that during IMF northward intervals the magnetotail compression responds with a higher "efficiency" than during IMF Bz south. The peak-to-peak amplitude of the bipolar signature shows similar behavior with pressure pulses occurring during northward IMF producing larger amplitude bipolar turnings.

Discussion and Conclusions

The geomagnetic field at low latitudes responds well to solar wind pressure changes (even at the level of 0.1 nPa) on the timescale of a few minutes when the IMF is steady and northward *Francia et al.* [1999]. The geomagnetic tail lobes also respond systematically to short-duration solar wind pressure pulses when the IMF is northward *Moldwin et al.* [2001]. For southward IMF conditions the geomagnetic and magnetotail response is less pronounced, absent, or more complicated [e.g., *Russell and Ginsky,* 1995; *Moldwin et al.*, 2001]. This study examined the magnetotail response to solar wind pressure pulses observed during small-scale magnetic flux ropes to examine whether the magnetospheric response changed due to IMF polarity variations on rapid (10s of minute) time scales. For this sample of four magnetic flux rope intervals that had IMP 8 in the magnetotail, clear responses were observed coincident with the passage of the pressure pulses associated with the flux ropes. There was a clear difference in magnetotail response during the northward and southward parts of the flux rope.

During the northward IMF intervals, clear SN TCR events were observed at IMP 8. During the southward IMF interval of the flux rope small-scale pressure pulses often (though not always) produced a compression. However, this compression was generally of smaller amplitude for comparable solar wind dynamic pressure pulses during northward IMF and was often not coincident with a clear south-then-north turning. This difference in behavior was seen even for pressure pulses occurring within 10 minutes of one another but on different sides of the inflection point of the solar wind flux ropes Bz bipolar turning. Therefore we conclude based on these four intervals, that the magnetotail response to small-scale solar wind dynamic pressure pulses is dependent on IMF polarity on the time scale of pressure pulse occurrence frequencies (1 to 3 mHz). Therefore studies that examine the response of the magnetotail to dynamic pressure variations need to be conscious of the different magnetospheric response depending on IMF polarity.

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