The Solar Wind and Geomagnetic Activity as a Function of Time Relative to Corotating Interaction Regions

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Corotating interaction regions during the declining phase of the solar cycle are the cause of recurrent geomagnetic storms and are responsible for the generation of high fluxes of relativistic electrons. These regions are produced by the collision of a high-speed stream of solar wind with a slow-speed stream. The interface between the two streams is easily identified with plasma and field data from a solar wind monitor upstream of the Earth. The properties of the solar wind and interplanetary magnetic field are systematic functions of time relative to the stream interface. Consequently, the coupling of the solar wind to the Earth’s magnetosphere produces a predictable sequence of events. Because the streams persist for many solar rotations, it should be possible to use terrestrial observations of past magnetic activity to predict future activity. Also, the high-speed streams are produced by large unipolar magnetic regions on the Sun, so that empirical models can be used to predict the velocity profile of a stream expected at the Earth. In either case, knowledge of the statistical properties of the solar wind and geomagnetic activity as a function of time relative to a stream interface provides the basis for medium-term forecasting of geomagnetic activity. In this report, we use lists of stream interfaces identified in solar wind data during the years 1995 and 2004 to develop probability distribution functions for a variety of different variables as a function of time relative to the interface. The results are presented as temporal profiles of the quartiles of the cumulative probability distributions of these variables. We demonstrate that the storms produced by these interaction regions are generally very weak. Despite this, the fluxes of relativistic electrons produced during these storms are the highest seen in the solar cycle. We attribute this to the specific sequence of events produced by the organization of the solar wind relative to the stream interfaces. We also show that there are large quantitative differences in various parameters between the two cycles.

1. INTRODUCTION

At the Earth, the declining phase of the solar cycle is characterized by weak magnetic storms that recur with a period of 27 days. There are no obvious features in the Sun's
photosphere to account for these storms so it was originally postulated that they were caused by magnetically effective or “M regions” [Chapman and Bartels, 1962]. With the advent of the space age it was found that these storms began with the arrival of a high-speed stream of solar wind [Hundhausen, 1972]. When these streams were tracked back to the Sun and compared to maps of the solar magnetic field it was evident that the high-speed streams originated in large regions of unipolar magnetic field. With the launch of Skylab in 1973 it was shown that above these magnetic regions the corona was much darker than elsewhere. These regions were therefore named coronal holes.

It is neither the coronal holes nor the high-speed stream that cause these magnetic storms. Instead it is the interaction region between the high-speed stream and the slow solar wind ahead of it that creates the conditions that drive geomagnetic activity (see Balogh et al. [1999] for summary of properties of CIRs). This region is centered on the interface between the two streams [Gosling et al., 1978]. Because of the interplanetary magnetic field (IMF) the two streams can not interpenetrate. Consequently the high-speed plasma is slowed and deflected east of the Sun while the slow-speed plasma is accelerated and deflected west of the Sun. The plasma and magnetic field on either side of the interface is compressed with the total pressure and total magnetic field rising to peak values at the interface.

Since the Sun is rotating the stream interface is a spiral intermediate to that expected in the two streams. The peak in plasma pressure at the interface propagates outward into both streams carrying information about the presence of the interface. Inside of 1 AU these are ordinary pressure waves, but beyond this distance changes in the properties of the solar wind with distance cause these two waves to develop into shocks. The region between the two waves is called a rotating interaction region or CIR.

There are several factors associated with the CIR that cause geomagnetic activity. First is the compression of the magnetic field [Belcher and Davis, 1971]. A stronger magnetic field means a larger z-component of the magnetic field in GSM coordinates. When this component is negative the IMF merges with the Earth’s magnetic field and drives magnetic activity. Second is the possibility that there is an increase in the fluctuations of the IMF near the interface because of the shear in velocity across the interface [Belcher and Davis, 1971]. More and larger fluctuations lead to stronger GSM $B_z$ and more geomagnetic activity. A third and more important factor is that high-speed streams tend to be filled with Alfvén waves propagating away from the Sun [Belcher and Davis, 1971]. Following the interface the field contains large amplitude fluctuations, which if southward in GSM coordinates, drive activity. Finally, a fourth factor is the high solar wind velocity on the Sunward side of the interface.

The actual driver of geomagnetic activity is the GSM dawn-dusk electric field, $V_{B_z}$. The combination of large $V$ and frequent strong intervals of southward $B_z$ causes elevated geomagnetic activity.

The association of geomagnetic activity with stream interfaces leads to the possibility of forecasting geomagnetic activity based on predictions of the arrival of the interface. Activity is weak before the interface, very strong at the interface, and then decaying slowly after the interface. This type of forecasting has been referred to as “probabilistic forecasting by air mass climatology” [McPherron and Siscoe, 2004]. In this case the air mass is the CIR and the climatology is the average behavior of various indices of magnetospheric activity relative to the interface.

The purpose of this paper is to investigate the average behavior of a number of solar wind and magnetospheric variables relative to a stream interface. We are able to do this well in two solar cycles since full-time monitoring of the solar wind began in January 1995 and continues now 10 years later. The minimum of the previous cycle #22 occurred in June 1996 and the minimum of cycle #23 is expected in December 2006. Thus we have data from the declining phase of an even-numbered and an odd-numbered solar cycle. In this paper we compare the behavior of the solar wind and geomagnetic activity relative to stream interfaces in 1995 and 2004.

Our primary analysis technique is superposed epoch analysis of an ensemble of traces of a given variable relative to the times of the stream interfaces in each year. The results are presented as time series plots of the quartiles of the cumulative probability distributions. The range between the upper and lower quartile at any given epoch time provides a means of probabilistic forecasting provided one can predict the arrival time of the interface.

Some of our results for the solar wind plasma are well known from previous analysis [Borrini et al., 1981; Gosling et al., 1978; Gosling et al., 1981]. However, we have extended the previous work by including the behavior of the interplanetary magnetic field (not previously published), and of several magnetospheric activity indices. A crude analysis of some of the latter has been published [Schatten and Wilcox, 1967; Wilcox and Ness, 1965; Wilcox et al., 1967]. Also new is our comparison of the behavior of the solar wind and indices in two successive solar cycles.

We will show that all solar wind variables exhibit highly systematic behavior relative to the time of an interface, but that there is a significant quantitative difference between the two solar cycles. We attribute this difference to a combination of three factors. The first is the Russell-McPherron (RM) effect [Russell and McPherron, 1973]. The RM effect is most important around the equinoxes when at certain universal times each day the Earth’s dipole approaches a tilt of 34° with
respect to the ecliptic pole. Since the GSM-z axis is defined as a vector perpendicular to the Sun vector lying in a plane containing the Sun vector and the dipole, it is also tilted towards the ecliptic plane by this amount. An interplanetary magnetic field lying in the ecliptic plane along the Parker spiral then has a large projection of By on the GSM-z axis. If this projection is negative magnetic reconnection and geomagnetic activity are produced. Since the GSM coordinate system is fixed in the Earth with its x-axis pointing to the Sun this system rotates once per year. Thus the orientation of the GSM-y axis reverses from one equinox to the next, reversing the sign of the IMF By projection on GSM-z. A mnemonic rule characterizing which orientations of the IMF are geo-effective is “spring to fall away”. Here “to” means the IMF points inward towards the Sun and “away” means it points outward.

The second factor is the Rosenberg-Coleman (RC) effect [Rosenberg and Coleman, 1969] which is also most important near the Equinoxes. The rotation axis of the Sun is tilted 7° with respect to the ecliptic plane so that near spring equinox on March 5 the Earth is at maximum southern heliographic latitudes and near fall equinox on September 6 it is at maximum northern latitudes. Rosenberg and Coleman discovered that the dominant polarity of the IMF at times of most northern and southern latitude is the same as the polarity of the corresponding pole on the Sun. Thus when the northern pole of the Sun is positive the IMF is away from the Sun above the heliographic equator. The Earth is above the equator in fall and according to the RC effect will be dominated by IMF pointing away from the Sun. According to the RM rule this is a geo-effective orientation. Six months later the Earth will be at high southern latitudes where the IMF is toward the Sun. This situation is also geo-effective. Thus throughout an 11-year solar cycle the ordinary IMF is conducive to the production of geomagnetic activity. Observations of the solar magnetic field have established that the phase of the 22-year cycle is such that the Sun’s north magnetic pole becomes positive (outward field) just after the maximum of even numbered cycles. The last even cycle #22 reached maximum in August 1989. Thus from about 1991 to 2002 the orientation of the IMF was conducive to geomagnetic activity.

About two years after solar maximum the polarity of the Sun’s magnetic field reverses. In 2002 the northern pole became negative and the IMF above the equatorial plane was toward the Sun. The Earth is above the equator in fall and needs an IMF pointing away from the Sun to produce geomagnetic activity. Thus this orientation of the IMF is not geo-effective. This situation persists for the entire 11-year cycle until the solar field again reverses. This combination of the RM and RC effects creates a 22-year cycle in geomagnetic activity.

In addition to the two preceding geometrical effects there appears to be an intrinsic 22-year variation of solar activity such that “…the maxima of odd-numbered cycles in even-odd pairs are always larger.” [Cliver et al., 1996]. This 22-year cycle of sunspot activity is called the “Hale cycle” [Hale et al., 1919]. Cliver et al. argue that this variation in solar activity is the primary cause of the 22-year cycle in geomagnetic activity.

2. DATA BASE AND ANALYSIS METHOD

The data used in this investigation were obtained from the NSSDC as either binary CDFs or ASCII files. For download we selected a subset of the original data corresponding to plasma and magnetic field measurements in GSE coordinates. These data were interpolated to 1-minute resolution using cubic splines. The data were then propagated to the subsolar bow shock (+17 Re, 0, 0) using a modified version of the Weimer minimum variance algorithm [Bargatze, 2005; Weimer et al., 2003]. At the chosen point the data were again interpolated to 1-minute samples and the results transformed to GSM coordinates.

An interactive program was developed to display the data at high resolution so that a cross hair could be used to define the time of a stream interface imbedded within a corotating interaction region. Figure 1 shows the parameters used to define an interface in this analysis. They include solar wind velocity and density, IMF field strength, and the azimuthal flow angle in GSE coordinates. A stream interface was
defined by the following criteria. (1) The solar wind velocity changed rapidly from a value below to a value above 500 km/s. (2) The velocity decreased slowly from its elevated value over a number of days. (3) A peak in density followed by a peak in total field was associated with the rapid rise in velocity. (4) The azimuthal flow changed from positive to negative angles. The time of the zero crossing in flow angle was selected as the time of the stream interface.

These criteria are based on previous results reported by Gosling [1978] and Borrini et al., [1981]. Although these studies used different reference times in their superposed epoch analysis than we have they found that solar wind velocity is below 400 km/s before a CIR and near 600 km/s after the CIR. They also found that the velocity increase occurs in about 3-4 days, but the decrease takes 10 days. They showed that the solar wind density and thermal pressure peak near the time of most rapid rise in velocity. In examining plots of solar wind data we found that the time of most rapid rise in velocity is close to the time of a significant zero crossing in the azimuthal flow angle of the solar wind. Taking into consideration the physical explanation for the formation of a CIR it is clear that the zero crossing of the flow angle is the boundary between the slow-speed and high-speed plasma flows. Comparison of the alpha to proton density ratio in regions of positive and negative flow angles demonstrates that the two plasmas are quite different.

Stream interfaces satisfying these criteria are generally observed only in the declining phase of the solar cycle a few years before solar minimum. In the last solar cycle (#22) well developed streams were observed in the years 1994-1996. Since we do not have high resolution solar wind data for the year 1994, and because the stream structure vanished in mid-1996, for this study we used data only from the year 1995. A total of 26 interfaces were found in this year. For the current solar cycle (#23) we used data for the year 2004, the last year for which complete data is available. In 2004 we identified 42 interfaces.

A stack plot showing the recurrent nature of high-speed streams during 2004 is presented in Figure 2. Each trace in the figure displays 30 days of data starting three full days before the start of a 27-day Bartel’s rotation interval and ending two days after. The time axis is day in the rotation interval. The vertical dashed line on the left denotes the beginning of day 1 of each 27-day interval. The dashed line at the right signifies the end of day 27 and also the beginning of day 1 of the next interval. The times of stream interfaces are shown by triangles. A persistent stream interface occurring on about the 15th day of each Bartel’s rotation period is evident near the middle of each trace.

The lists of stream interface times were used to select 10-day segments of data centered on every stream interface identified in a particular year. These segments were stored as rows of an “ensemble array” for each year. An analysis window of width 2-hours (121 samples) was stepped across the array to determine the cumulative distribution function (CDF) as a function of epoch time. In each step all data points falling within the window (121 * # events) were used to calculate a CDF. The CDF was then sampled at all equally spaced values of the independent variable lying within the range of the lower and upper limits of the graph. If there were no occurrences of a particular value in the analysis window the CDF was set to a flag. The array was then contoured at 10-percetile levels. A plot showing the CDFs of solar wind velocity for the years 1995 and 2004 is presented in Figure 3. Heavy lines in these panels depict the quartiles of the CDF.

The presence of persistent high-speed streams in both years is clearly evident. Before the stream interface the
median solar wind velocity is about 350 km/s. At the interface the velocity has increased and is rising at its most rapid rate. Two days after the interface the median velocity peaks at >500 km/s and thereafter decays slowly. The streams in 1995 are somewhat better developed than those in 2004 with more contrast between the low velocities before the interface and high velocities after. Possibly this is because the streams are not yet fully developed in 2004.

The same superposed epoch analysis was performed for a number of solar wind and magnetospheric variables using the times of the stream interfaces as epoch zero. In the following presentation we show only the quartiles of each cumulative probability distribution.

3. RESULTS OF ANALYSIS

3.1. Variations of Solar Wind Near Stream Interface

Results of our superposed epoch analysis are summarized in Figures 4-7. Figure 4 presents results for five solar wind variables in the two different years. From the top down these include azimuthal flow angle, solar wind velocity, density, mean ion thermal speed, and total pressure given by the sum of the magnetic and thermal pressure. The vertical dashed line at zero epoch time is the time of the stream interface. The range of variation defined by the upper and lower quartiles of the ensemble of each variable is shown by shaded patches. Superimposed on each patch is a heavy line depicting the median variation of the variable. Data for 1995 are presented on the left side and data for 2004 are on the right side. We begin by describing the behavior of each variable in the year 1995 and then later contrast the behavior in the two years.

The top panel presents the azimuthal flow angle used to define the time of stream interfaces. The flow direction changes systematically over a two-day interval peaking six hours before and after the interface. The median deflection at the extrema is about five degrees. The sense of the deflection before the interface is westward in the direction of the Earth’s motion. This graph verifies the well known result that the flow of the solar wind is deflected westward before the interface between a high-speed and slow-speed stream, and is deflected eastward behind.

The second panel repeats the quartiles of the solar wind velocity discussed above. The velocity begins to increase about 8 hours before the interface, and is increasing most rapidly at the interface. Median velocity peaks about two days after the interface.

The third panel presents the quartiles of the solar wind density. Density begins to slowly increase from a value near 8 particles per cc about 2.5 days before the interface. It reaches a peak of 25 per cc a few hours before the interface and at the interface drops rapidly to a constant value of about 4 per cc. The variation is quite asymmetric relative to the interface with all of the increase and the peak occurring before the interface.

The mean thermal speed of the ions is presented in the fourth panel. In the low velocity solar wind before the stream interface the thermal speed is low with a value near 25 km/s. About 12 hours before the interface the thermal speed begins to increase achieving a peak value of 60 km/s about 4-6 hours after the interface. It subsequently decreases slowly as the bulk velocity also decreases.

The bottom panel presents the total pressure (sum of thermal and magnetic pressure) of the solar wind. Pressure begins to increase 12 hours before the interface. It reaches its
peak value exactly at the interface, and then decreases to normal values about a day after the interface.

The behavior of these five solar wind plasma parameters during the current solar cycle is shown in the panels on the right side of Figure 4. Qualitatively the behavior is the same as in 1995, but quantitatively the streams appear to be weaker. Difference in peak values range from 25% to 50% lower. This difference could be a result of the streams not being fully developed. However, it is also possible that the current solar cycle is producing weaker streams, and as we will show below, weaker magnetospheric activity.

### 3.2. Variations of the Interplanetary Magnetic Field

The behavior of the IMF near a stream interface is summarized in Figure 5. The top panel is a repeat of the azimuthal flow angle used to define the time of a stream interface. Panel 2 presents the total magnetic field. The behavior of the total magnetic field is nearly identical to that of the total pressure shown in the previous figure. It begins to increase 12 hours before the interface; reaches a maximum of 15 nT at the interface; and returns to normal about a day after the interface.

The third panel shows IMF $B_z$ in GSE coordinates. $B_z$ is highly variable on the time scale of these plots and the quartiles reflect the magnitude of fluctuations. These are controlled by the behavior of the total field relative to the stream interface. Thus $B_z$ begins to increase 12 hours before the interface; peaks at the interface with values near 5 nT; and it decays back to near normal values within a day. There is some indication that the level of fluctuations is marginally higher than normal for at least two days after the interface. A careful examination of the median trace reflects the unusual behavior that occurred in the 22nd solar cycle. At stream
interfaces the median $B_z$ was biased southward. Both this and the increased magnitude of fluctuations are partially responsible for elevated magnetic activity at the times stream interfaces pass the Earth.

Panel 4 presents the dawn-dusk component of the solar wind electric field ($V_{\text{Bz}}$) in GSM coordinates. This quantity is the primary driver for geomagnetic activity. Fluctuations in $E_y$ are very strong at the interface but are elevated for many days afterward. To some extent this reflects the behavior of fluctuations in $B_z$. However, it is primarily a consequence of the high velocity of the stream following the interface. A second and very important characteristic of $E_y$ in GSM coordinates is a persistent negative bias in the median value that lasts for at least four days. Although not demonstrated here this bias is a consequence of the Russell-McPherron effect discussed in the introduction. During solar cycle #22 virtually all high-speed streams that occurred near equinox were geo-effective according to the Russell-McPherron rule “spring to fall away”.

The foregoing result does not imply that the IMF was unidirectional as is demonstrated in the fifth panel. This panel shows the spiral angle of the IMF in a coordinate system rotated 45° counter clockwise about the GSE z-axis. In this system an IMF pointing sunward makes an angle of $-90^\circ$ relative to the rotated x-axis. Note, however, that for fall data we have reversed the sign of the spiral angle so that the spiral angle has the same sign as in spring data. In addition this panel was constructed using only geo-effective events which in this case was 22 out of 26 events.

It is apparent that before the stream interface the selected events were geo-ineffective, i.e. an IMF in the ecliptic plane projects onto the GSM-z axis with a positive projection. ($+90^\circ$ implies an away sector which is ineffective in spring). However, the Earth passed through the heliospheric current

Figure 5. A quartile plot similar to Figure 4 for IMF variables as function of time relative to stream interfaces. From the top down the panels include: azimuthal flow angle, magnetic field magnitude, $B_z$ in GSE, $E_y$ in GSM and the spiral angle of the IMF in the ecliptic plane. The IMF field magnitude and hence $B_z$ and $E_y$ are smaller in 2004 than in 1995.
sheet before the stream interface reversing the polarity of the IMF so that the IMF was geo-effective during the high-speed stream. Usually this passage occurred about 6 hours before the interface, however, some transitions occurred earlier. The preponderance of geo-effective orientation of the IMF during the high-speed stream is the cause of the persistent bias in GSM $E_y$ shown in the fourth panel.

The right hand panels of Figure 5 show the IMF variations during 2004. The qualitative behavior is similar to what has already been presented but all median values are weaker. However, a more important difference is that $B_z$ fluctuations were weaker at the interface and there was no bias in the GSM $E_y$ after the interface. The spiral angle for geo-effective events is plotted in the bottom panel. During 2004 the polarity of the IMF in the high-speed stream was almost equally distributed between geo-effective and ineffective orientations. In this panel we show only the 16 of 42 events that were geo-effective in the high-speed stream.

3.3. Variations of Magnetospheric Activity

The relation of geomagnetic activity to stream interfaces is summarized in Figure 6. Panel 1 repeats the flow angle used to define the interface. Panel 2 shows solar wind dynamic pressure. In 1995 the dynamic pressure variation is slightly asymmetric relative to the interface. The median curve begins to increase about one day before the interface; it peaks at 6 nPa just before the interface; and it returns to normal values of 2 nPa by 12 hours after the interface. Panel 3 shows the GSM $E_y$ component described earlier. Panel 4 illustrates the behavior of the 3-hr $ap$ index. For this analysis we used nearest neighbor interpolation to change the time resolution to one minute. The constant nature of $ap$ for three-hour intervals is not apparent because the time of epoch zero for each data segment is randomly phased relative to the time the $ap$ index changes value. The median $ap$ obtains its lowest value of about 5 nT one day before the interface. Subsequently it

![Figure 6](image_url)

Figure 6. The bottom two panels show quartiles of the 3-hr $ap$ index and 1-min Sym-H index produced by various solar wind drivers in the upper panels. Both auroral activity ($ap$) and ring current activity (Sym-H) are distinctly weaker in the 2004 solar minimum than they were in 1995.
increases rapidly reaching a peak value of 40 nT at the time of the interface. It then decays exponentially reaching quiet values again in about five days. The bottom panel presents the Sym-H index. Sym-H is a 1-minute approximation of the Dst index and hence monitors the behavior of the ring current. Median Sym-H begins a very gradual increase two days before the stream interface. By the time of the interface it has increased only 5-6 nT. This increase corresponds to the initial phase of a magnetic storm, but in a single event would be undetectable. About 4 hours before the interface Sym-H begins a rapid drop into a storm main phase. The median storm minimum occurs about 6 hours after the interface. Subsequently Sym-H recovers slowly and more or less linearly reaching quiet levels within about a week.

The behavior of the various drivers and response variables during 2004 are summarized in the right hand panels of Figure 6. Qualitatively the behavior is the same as in the year 1995, but quantitatively activity is much weaker. It is clear that this is because both the solar wind velocity and IMF field strength are weaker in this solar cycle than they were in the previous cycle. In 2004 peak values of ap and Sym-H were roughly half of what they were in the year 1995. Clearly an event in which minimum Sym-H is no less than 20 nT would not be classified as a magnetic storm. Despite this the quartiles show that geomagnetic activity is organized by the stream interfaces even if most of these events are too weak to detect in single traces.

Two additional magnetospheric response parameters are available for 1995 and are shown for a 20-day interval in Figure 7. The top four panels present velocity, E_y, ap, and Sym-H and have already been described. The fifth panel shows an index of ULF power in the Pc 5 frequency band (150-500 seconds period). A description of this index can be found in the paper by O’Brien et al. [2001]. These waves have been shown to be correlated with the appearance of relativistic electrons at synchronous orbit. Since the period of these waves is comparable to the drift period of relativistic electrons around the Earth it is likely that they are an important cause of inward radial diffusion of lower energy electrons from further out in the magnetosphere.

Prior to the arrival of the CIR magnetic activity is very low and electrons accelerated previously are gradually lost from the radiation belts. About one day before the arrival of the stream interface the azimuthal flow and dynamic pressure begin to increase while at synchronous orbit fluxes of relativistic electron fluxes begin to decrease more rapidly. Twelve hours before the interface the solar wind electric field begins to become more negative, geomagnetic activity picks up, and electron fluxes are dropping most rapidly. Four hours before the interface the main phase of a magnetic storm begins and Pc5 ULF wave activity begins to increase. At the interface the E_y fluctuations are at their largest, and geomagnetic activity and ULF wave power reach peaks. Finally, four hours after the interface the main phase ends and electron fluxes reach their lowest value. For the next four days solar wind electric field and geomagnetic activity gradually decrease in strength with ULF power dropping somewhat more slowly. Throughout this time the ring current recovers slowly while the flux of relativistic electrons continues to increase to a peak 100 times higher than they were at the end of the main phase. Subsequently all parameters decay slowly with the electron fluxes still high ten days after the end of the main phase.
4. DISCUSSION

In the Introduction we summarized current understanding of the formation of a corotating interaction region (CIR). This description is based on analysis of solar wind observations similar to those presented here. For example Gosling et al. [1978] performed superposed epoch analysis of many different plasma variables obtaining results some of which we have duplicated. However, our work differs from the previous work in several respects. First, Gosling et al. [1978] used speed, density, and temperature to identify stream interfaces as compared to our use of speed, density, magnetic field magnitude, and azimuthal flow angle. Second, these authors selected only events for which there was a discontinuous change in the parameters during a 1-3 minute interval whereas we used the zero crossing of the azimuthal flow angle as the fiducial time. Because of these differences Gosling et al. [1978] identified only 28 events in three years of data while we found about this many events per year. A more important difference between the two studies is that we have included the components of the magnetic field and several magnetic indices in our analysis. These additional variables make it easier to understand the manner in which the stream interfaces organize magnetospheric activity.

4.1. Recurrent Magnetic Storms

About 1-2 days before the stream interface, fluctuations in GSE \( B_z \) reach a minimum as does the solar wind velocity. Transformed to GSM coordinates these produce a weak electric field, which if \( B_z \) is southward, will drive weak activity. About 12 hours before the interface the magnetic field magnitude begins to increase due to compression of the slow stream by the fast stream so \( B_z \) increases as well. The field magnitude peaks at the interface with a value 2-3 times the value in the normal solar wind. Consequently \( B_z \) is largest at this time. In addition the velocity of the solar wind has increased above its value in the slow stream so that the electric field fluctuations reach their maximum amplitude at the interface. We therefore expect geomagnetic activity to be a maximum at this time as well. The profile of the perturbation in magnetic field magnitude is asymmetric with respect to the interface taking only 12 hours to rise to a peak but 48 hours to decay. The velocity profile is also asymmetric being low before the interface and high for more than five days afterward. Because of these asymmetries the amplitude of the electric field fluctuations decays rather slowly after the interface. Consequently we expect magnetic activity to persist for some time.

The behavior of two indices of magnetospheric magnetic activity was summarized in the description of Figure 6. The \( ap \) index in the fourth panel is a measure of auroral electrojet activity. The Sym-H index in the fifth panel measures the strength of the ring current. Both indices are clearly organized by the solar wind stream interfaces in the manner expected based on the variations of solar wind variables described above.

Auroral zone activity begins to increase about 12 hours before the interface, peaks at the interface, and then decays slowly for several days after the interface. The strongest auroral zone activity is limited to a 1-12 hour interval centered on the interface where the fluctuations in \( E_y \) are largest.

The ring current index increases gradually for nearly two days before the interface. This is a consequence of a combination of ring current decay during very quiet times and the increase in dynamic pressure beginning a day before the interface. A few hours before the interface ions begin to be injected into the ring current by the enhanced electric field and their magnetic effects overcome the effect of dynamic pressure so that Sym-H decreases. As long as the electric field fluctuations are large the ring current continues to grow causing Sym-H to decrease further. This growth produces the main phase of a weak magnetic storm that ends 6-12 hours after the interface. Subsequently the ring current recovers very slowly with time. The apparent recovery is much slower than expected from charge exchange. Most likely this is a consequence of a slowly changing equilibrium between frequent injections into the ring current by progressively weakening intervals of southward \( B_z \) and charge exchange of ring current ions with atmospheric neutrals.

4.2. Acceleration of Relativistic Electrons

As we showed in the discussion of Figure 7 relativistic electron fluxes decay slowly during the quiet times produced by the slow-speed stream. As the leading edge of a CIR arrives they begin to decrease more rapidly, and during the main phase of the CIR storm they drop to very low values. It is in the first four days of the recovery phase of these storms that electrons are accelerated most efficiently. During this time substorms occur frequently and ULF power is high. Other data not shown here indicate that during the storm recovery phase whistler mode chorus is very strong outside the plasmapause between midnight and dawn [Meredith et al., 2003; Meredith et al., 2001]. These observations support a complex theory explaining how electrons are energized to relativistic energies.

This theory [Horne et al., 2006; Horne et al., 2005] suggests that the first step in the process is an increase in dynamic pressure in the compression region of the CIR which moves the magnetopause closer to the Earth. This converts closed electron drift paths outside of synchronous orbit to open paths allowing electrons to be lost to the magneto-sheath. The second step occurs as the main phase develops...
while dynamic pressure is still elevated. The “Dst effect” [Kim and Chan, 1997] of the growing ring current causes a decrease in magnetic flux in the inner magnetosphere. To conserve their third adiabatic invariant relativistic electrons must move outward to maintain constant magnetic flux through their drift shells. As these particles encounter the magnetopause they are also lost. During this time the power in Pc 5 waves is increasing rapidly. These waves may play a role in the rapid loss of relativistic electrons during the main phase. If the peak in phase space density of relativistic electrons is near synchronous orbit ULF waves may actually drive outward diffusion placing relativistic electrons on open drift paths. This process continues until the ring current stops growing at the end of the main phase and the dynamic pressure relaxes to its normal value. At this time the electron fluxes reach their lowest values.

Meanwhile, during the 8-10 hours of the main phase several substorms have taken place each injecting lower energy electrons ~100 keV into the magnetosphere beyond synchronous orbit. During this interval Pc 5 waves are generated at the magnetopause by the Kelvin-Helmholtz instability and inside the magnetosphere by the substorms [Nose et al., 1995; Vennerstrom, 1999]. These waves drive inward radial diffusion of the lower energy electrons increasing their energies by conservation of the first two invariants as they drift closer to the Earth [Elkington et al., 2003]. The radial diffusion creates an electron pitch angle distribution peaked at 90° that is unstable to the electron cyclotron instability for low energy electrons near the loss cone. Because of the instability these electrons lose energy and are scattered into the loss cone in the region outside the plasmapause between midnight and dawn. The waves generated in this manner also interact with higher energy electrons over a broad range of pitch angles scattering them to larger pitch angles and higher energy. Each time these electrons drift around the Earth they encounter the chorus and are pumped to even higher energies. Eventually a peak in phase space density of relativistic electrons is produced inside of synchronous orbit. Radial diffusion driven by fluctuations moves these electrons both inward and outward with those electrons that move inward gaining still more energy.

As the stream interface passes the Earth and the main phase ends the Earth is immersed in the high-speed stream. This stream contains large amplitude Alfvén waves of several hour period that quasi periodically turn the IMF southward at the magnetopause. Each time this happens another substorm is driven by magnetic reconnection. More electrons are injected in the outer magnetosphere and are radially diffused inward by the Pc 5 waves created by the K-H instability at the magnetopause. As the electrons move inward radial diffusion becomes less important and the cyclotron instability takes over producing chorus that scatters higher energy electrons over a wide range of pitch angles to larger pitch angles and higher energies.

This process lasts for many days as the velocity of the solar wind slowly decreases, the Alfvén waves become less dominant in the stream, substorms occur less frequently, and fewer electrons are accelerated to relativistic energies. After four days the electron fluxes reach their maximum values and then slowly begin to decay as loss processes begin to dominate over injection and acceleration.

4.3. Probabilistic Forecasting

The systematic behavior of the solar wind relative to stream interfaces provides a possible means for forecasting space weather [McPherron and Siscoe, 2004; McPherron et al., 2004a; McPherron et al., 2004b]. If the arrival time of a stream interface can be predicted in advance then one can use the quartiles of various magnetic indices relative to this time to predict activity indices. One forecasting method would specify the range of values within which activity would fall 50% of the time. This range is given by the upper and lower quartiles shown in our plots by the shaded patches. An alternative would be to calculate the cumulative probability distribution at each time and specify the probability that an activity index will exceed some specified threshold.

A serious obstacle to the success of these prediction schemes is change in the probability distributions between cycles. It is apparent from our comparison of the stream structure in 1995 and 2004 that the two cycles differ by nearly a factor of two in the magnitude of changes in different parameters. In 2004 flow deflections, velocity change, density enhancement, temperature increase, and fluctuations in GSE-B_z are all smaller than they were in 1995.

An additional difference between the two solar cycles is apparent in the traces of median GSE-B_z and the spiral angle of the IMF. In 1995 almost all high-speed streams that occurred near the equinoxes were geo-effective according to the Russell-McPherron rule “spring to fall away” [Russell and McPherron, 1973]. Thus the heliospheric current sheet crossing that typically occurs before the stream interface converted an ineffective radial IMF orientation to an effective orientation after the interface. This is apparent from the negative bias of the median GSM E_y that lasted for several days after the interface (see Figure 5). In contrast in 2004 the IMF orientations before and after the interfaces were almost equally distributed between effective and ineffective orientations. An even more perplexing fact is that in 1995 GSM E_y was strongly negative for several hours around the interface, but not so in 2004.

One possible explanation for differences between the plots for 1995 and 2004 is the phase of these years in the solar cycle. The year 1995 ends only 6 months before the minimum
of cycle #22 while 2004 ends at least two years before the projected minimum of cycle #23. Although not shown here, analysis of the years 1994 and 1996 produced results very similar to those shown for 1995. Thus it seems likely that our results are explained by true differences in the Sun and solar wind between the two cycles and not by slight differences in phase.

A more likely explanation for the differences is the 22-year double solar cycle exhibited by the Sun’s magnetic field [Chernosky, 1966; Hale et al., 1919]. In each 11-year cycle of sunspot activity the polar magnetic field of the Sun reverses about two years after solar maximum. Consequently it takes 22 years for the Sun’s magnetic dipole moment to repeat its orientation relative to the rotation axis. But the rotation axis of the Sun is tilted 7° with respect to the ecliptic plane such that the Earth is furthest below the solar equator on March 6, and furthest above on September 6. Thus near fall equinox the Earth is likely to be immersed in magnetic field lines connected to the north magnetic pole of the Sun.

Observations of the solar magnetic field have established that the phase of the 22-year cycle is such that the Sun’s north magnetic pole becomes positive (outward field) just after the maximum of even numbered solar cycles. The last even cycle was #22 which reached its maximum in August 1989. Thus from about 1991 to 2002 the north pole of the Sun was positive. Consequently the interplanetary magnetic field (IMF) at the Earth was away from the Sun at fall equinox. Six months later near spring equinox the Earth was on the opposite side of the Sun and the IMF was toward the Sun.

This particular orientation of the IMF is geo-effective at the Earth because of the Russell-McPherron effect [Russell and McPherron, 1973] described in the Introduction. However, in the second half of the 22-year cycle the solar field reverses creating an away sector in spring and a toward sector in fall. These orientations of the IMF have positive projections on the GSM-z axis that suppress geomagnetic activity.

A second factor affecting the level of activity in a given cycle may be the Rosenberg-Coleman effect [Rosenberg and Coleman, 1969] also described in the Introduction. The dipole axis of the Sun is usually tilted at some angle to the rotation axis. Thus as the Sun rotates every 27 days the Sun’s magnetic equator and its extension, the heliospheric current sheet, wobbles up and down at the Earth. Usually the Earth crosses the current sheet two or more times per solar rotation. Depending on the tilt of the dipole axis the Earth will spend more time on one side of the sheet than the other. If it spends more time on the side with a geo-effective orientation geomagnetic activity is enhanced.

The foregoing explanation is discussed at some length in a paper by Cliver et al. [1996], and found by these authors to be incomplete. The authors argue that “… an intrinsic solar variation (other than polarity reversal) … is the dominant cause of the 22-year cycle in geomagnetic activity.” This variation leads to more coronal mass ejections in the first half of odd-numbered cycles and longer-duration 27-day recurrent streams in the second half of even-numbered cycles.

Our results support the Cliver et al. [1996] conjecture that there are intrinsic variations on the Sun responsible for strong recurrent streams in even-numbered cycles and weak streams in odd-numbered cycles. Figure 4 demonstrates this behavior. For the year 2004 of the odd-numbered cycle #23 the velocity contrast is smaller; the flow deflections are weaker; there is a smaller density enhancement; and the temperature change is weaker than in the preceding even-numbered cycle. The weaker streams lead to less compression of the IMF at the stream interface and hence to smaller fluctuations in Bz.

While we can not rule out the possibility that stronger high-speed streams will be observed in the next two years it seems unlikely because the strongest streams in the last cycle were seen in 1994 – two years before the end of the cycle, at basically the same phase in the cycle as the year 2004. Results for 1994 (not shown) are similar to those for 1995 and contrast sharply with those for 2004 so that we feel the differences between the two cycles are real. The implication of this difference is that the climatology derived from a single solar cycle can not be applied to the next cycle. For space weather forecasting it will be necessary to develop separate climatology’s for odd and even solar cycles.

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