Proton Injections into the Ring Current Associated with B_z Variations During HILDCAA Events

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The variation of Earth's magnetic field at the equator, as monitored by the *Dst* index, can stay below its quiet day value for days. This can happen after storms resulting in a very slow recovery of the *Dst* index, or it can happen in the absence of a storm. Such "anomalous" behaviour is observed during periods with continuous auroral activity called High-Intensity Long-Duration Continuous AE Activity—HILDCAA. NOAA satellite data is used to investigate the radial depth of particle injections into the ring current and its dependence on fluctuations in the interplanetary magnetic field. It is found that the particle injections are sufficient to delay the recovery of the *Dst* during HILDCAA events. It is further found that the particle injections during HILDCAA events are closely connected with Alfvén fluctuations in the interplanetary magnetic field B_z component.

1. INTRODUCTION

The HILDCAA phase of the storm is characterized by fluctuations in the solar wind magnetic field B_z component simultaneous with continuous high *AE* activity through the recovery phase of the storm or during no storm periods with reduced *Dst*. During HILDCAA events the *Dst* index does not exhibit the "normal" recovery back to its quiet-day zero-level value. A working definition of a HILDCAA event is; a maximum of $AE > 600$ nT, continuous $AE > 200$ nT, duration > 2 days, and the event is not associated with the storm main phase [*Tsurutani and Gonzalez,* 1987].

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Variations of Earth's magnetic field at the equator, is measured with the *Dst* index, which can stay negative for several days. The depression is mostly attributed to the ring current, but it also depends on other current systems in the magnetosphere such as magnetopause, tail and auroral currents. It is well established that the magnetic effect of the ring current is proportional to the energy content of the charged particles generating it [*Dessler and Parker,* 1959; *Sckopke,* 1966]. *Søraas et al.* [2002] have developed a ring current index based on the precipitation of protons into the evening side upper atmosphere. The precipitating protons give a good estimate of the ring current injection rate. By comparing the newly developed ring current index with the pressure corrected *Dst** index, *Søraas et al.* [2004] determined that the depressed *Dst** index during HILDCAAs could to a large degree be accounted for by the ring current alone, not influenced by other current systems.

In this paper we will use NOAA (National Oceanic and Atmospheric Administration) satellite data to determine the depth of the particle injections into the RC and its relation to B_z variations during three HILDCAA events.

2. DATA SOURCES

We will use solar wind data from the ACE satellite, geomagnetic activity indices provided by the World Data Center in Kyoto, and proton data from the low-altitude satellite NOAA-12. The polar satellite NOAA-12 is orbiting Earth at an altitude of 815 km. The orbital plane of NOAA-12 is in the local evening/morning sector (see Figure 1). The orbital period is around 103 minutes. We are using data from the MEPED (Medium Energy Proton and Electron Detector) instrument. MEPED measures protons and electrons at angles of 0° and 90° with the local vertical. We are concentrating the analysis on precipitating protons as observed by the 0° detector. A full description of the NOAA spacecraft and the MEPED instrument is given by *Raben et al.* [1995].

The precipitating protons observed at low altitude reflect the proton intensities at higher altitude at various locations in the radiation belt. The precipitating protons that the 0° proton detector observe at high geomagnetic latitudes, originate from the inner part of the ring current. In both cases the intensity of the precipitating protons mirrors the proton population in the magnetosphere, and their variations reflect injections of protons into the ring current.

3. THREE HILDCAA-EVENTS IN 1998

Figure 2 displays observations during two geomagnetic storms from April 1998, Figure 3 displays a storm from August 1998, and Figure 4 shows a storm in October 1998. All these storms exhibit HILDCAA activity. The three Figures all have four panels. The first panel gives the B_z component of the solar wind magnetic field measured by the ACE spacecraft. The second and third panels give the *AE* and *Dst* indices. The last panel exhibit the precipitating proton data from the NOAA-12 satellite. Each satellite pass is plotted versus L and time, and the observed proton flux is plotted with a logarithmic gray scale code. The proton flux from channel 1 (30-80 keV) illustrate the depth and intensity of proton penetration in the $L = 3$ to $L = 9$ range.

3.1. HILDCAA Event in April 1998

The period covers the days 113 to 120 in year 1998 (April 23 to April 30). The *Dst* index has two minima during this period, one on day 114 and the other on day 116. The *Dst* index reaches −70 nT on day 114 and −60 nT on day 116. The main phase of the first magnetic storm is at the beginning of day 114. The recovery phase starts at the end of day 114, but the *Dst* index shows a very slow recovery and stays almost constant at −40 nT for about two days. After the second storm at the end of day 116, the *Dst* index requires almost three days to recover to the quiet day value.

The *AE* index is high and variable through the recovery phase of both storms and these periods are marked 'HILDCAA' at the top panel of Figure 2. The interplanetary magnetic field B_z component fluctuates around zero with several intervals as low as −7 nT throughout the first HILDCAA period. Through the second HILDCAA period, B_z is also fluctuating but with −3 nT as the lowest value.

During the main phase of the two storms the protons are injected deep into the evening side magnetosphere as evident from the intensity observed inside $L = 4$. It is only during

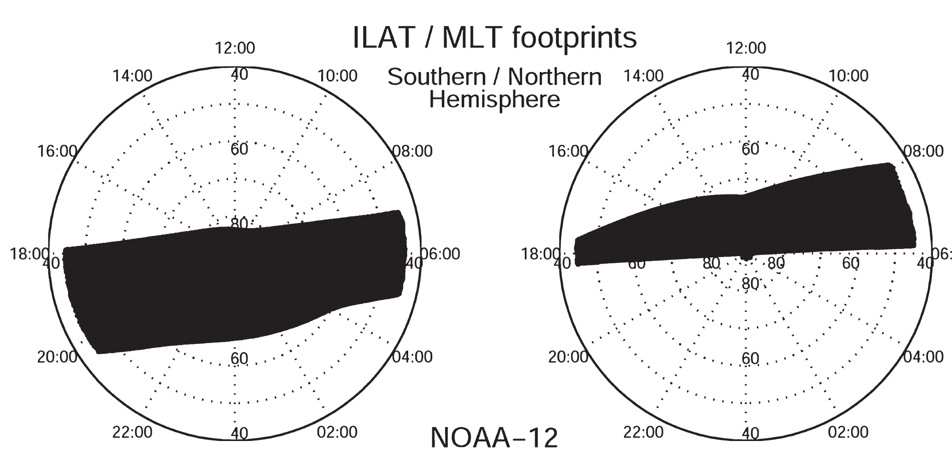

Figure 1. ILAT/MLAT footprint of the NOAA-12 spacecraft. Southern Hemisphere to the left, and Northern Hemisphere to the right.

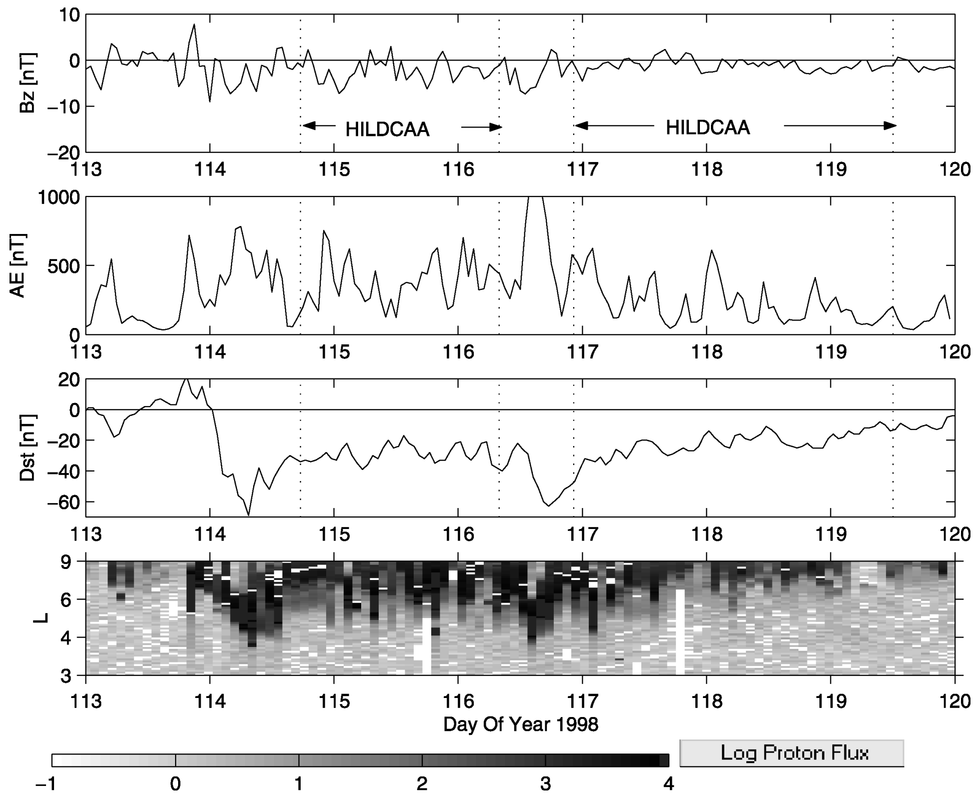

Figure 2. The B_z component of the solar wind, *AE* and *Dst* indices are given in the first three panels. Given in the last panel are NOAA-12 proton fluxes measured in the evening side of the Northern Hemisphere, for April 23-30, 1998. The proton fluxes, shown with a logarithmic grayscale, are plotted versus *L* and time. The intensity variations through the different *L*-values reflects the depth and intensity of proton penetration into the radiation belt.

the main phase of the storms that protons are injected to those low *L*-values. In the outer region of the ring current there is a continuous particle injection, both in the main phase and during the HILDCAA period of the storms.

3.2. HILDCAA Event in August 1998

The period in Figure 3 is from day 237 to day 248 in year 1998 (August 25 to September 5). On day 239 there is a large geomagnetic storm and the *Dst* reaches −150 nT. The recovery phase of the storm shows a *Dst* index that slowly returns to quiet day values. The HILDCAA period with high *AE* index through the recovery phase is marked in the first panel. The main phase of the storm is coincident with two intervals of B_z negative that last for almost one day. The largest negative B_z value is −15 nT. In the HILDCAA phase of the storm, B_z is fluctuating around zero with an amplitude of a couple of nT and a characteristic period of about 12 hours.

The lowest panel of Figure 3 show proton injections to below $L = 3$ during the main phase of the storm. The injection penetrates from the outer part, through the middle part reaching the inner part of the ring current. Throughout the HILDCAA period, the proton injections are concentrated in the outer part of the ring current with small injections into its central part.

3.3. HILDCAA Event in October 1998

In Figure 4 we show data from day 291 to day 304 (October 19 to November 1) in year 1998. The storm starts with the B_z component reaching down to −18 nT and staying at that value for almost half the day 292. The *Dst* index goes down to −120 nT during the main phase, and requires six days to recover to the quiet day value. The *AE* indices are high throughout the recovery phase of the storm, and the HILDCAA period, as shown in the upper panel. During the main phase we observe proton injections into the inner part of the ring current. During the storm main phase the polar caps widens as the poleward boundary of the proton precipitation resides down to lower ILAT values. Throughout the HILDCAA period, proton injections are observed only into the outer region of the ring current.

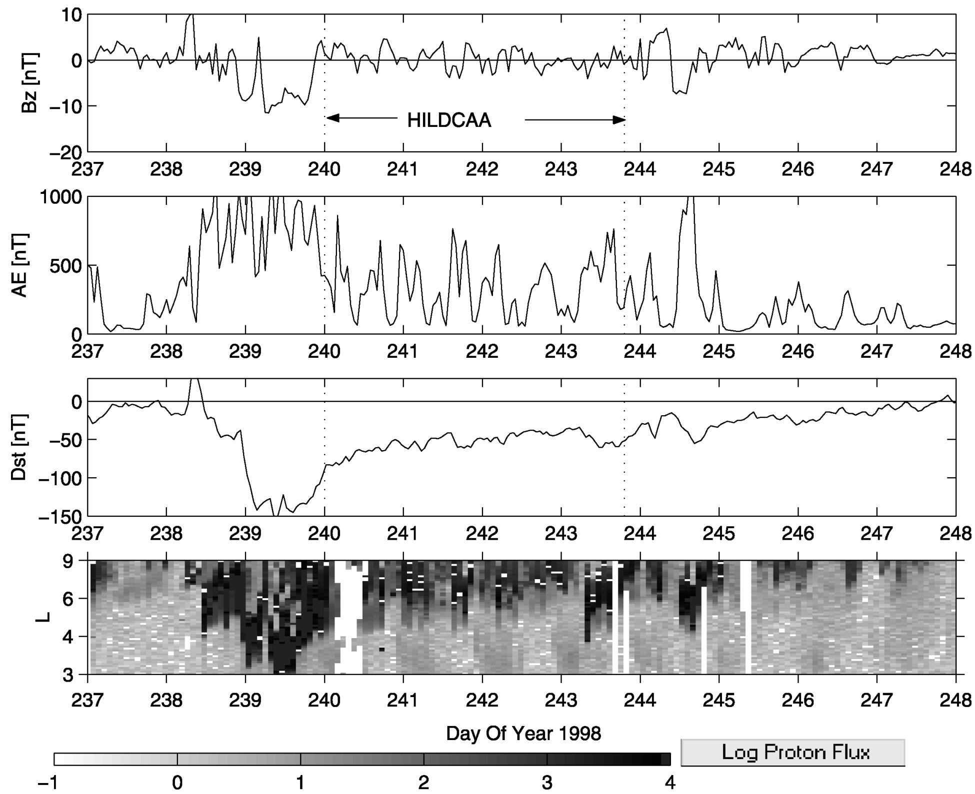

Figure 3. The B_z component of the solar wind, *AE* and *Dst* indices are given in the first three panels. Given in the last panel are NOAA-12 proton fluxes measured in the evening side of the Northern Hemisphere, for August 25-September 5, 1998. The proton fluxes, shown with a logarithmic gray scale, are plotted versus *L* and time. The intensity variations through the different *L*-values reflects the depth and intensity of proton penetration into the radiation belt.

Søraas et al. [2002] use observations of proton precipitation measured by low-altitude polar-orbiting NOAA satellites to derive a space-based *Dst* index in near real time. A parameter Q(t) is used to estimate the energy injection rate into the ring current based on the total power of precipitating 30 to 800 keV protons in the midnight/evening local time sector. Figure 5 demonstrates the good correspondence between the calculated RC index [*Søraas et al.,* 2004] and the *Dst* index for the October 1998 event. We conclude, therefore, that the reduced *Dst* index during HILDCAA is, to a large degree, accounted for by the ring current alone and not influenced by other current systems.

4. B_Z FLUCTUATIONS IN THE SOLAR WIND AND PARTICLE INJECTIONS INTO THE RING CURRENT

A Fourier analysis of B_z for the August 1998 HILDCAA interval shows a clear 12-15 hour periodicity. *Bruno et al.* [1985] have investigated the Alfvénic character of the solar wind fluctuations and found evidence for the existence of Alfvén waves with periods up to 15 hours in the trailing edge of the high speed solar wind streams.

The origin of the Alfvén waves is unknown. *Hollweg* [1978] has concluded that the waves are remnants from heating processes occurring in the solar corona. Large amplitude nonlinear Alfvén waves are always found to be present in high speed streams emanating from coronal holes [*Tsurutani et al.,* 1994]. *Tsurutani and Gonzalez* [1987] observed wave trains following high-speed streams and density enhancements during two HILDCAA events in August 1978 and May 1979.

Tsurutani et al. [2004] have shown that auroral expansion phases are present during HILDCAA events. However, by using UVI images from the Polar spacecraft, they found that there is a lack of an one-to-one correspondence between substorm expansion phases and *AE*/-*AL* enhancements. They advocate that a likely explanation for this is that the southward component of the interplanetary magnetic field (of Alfvén waves) cause magnetic reconnection and drive enhanced westward auroral electrojets. *Søraas et al.* [2004] put forward the hypothesis that the plasma injection into

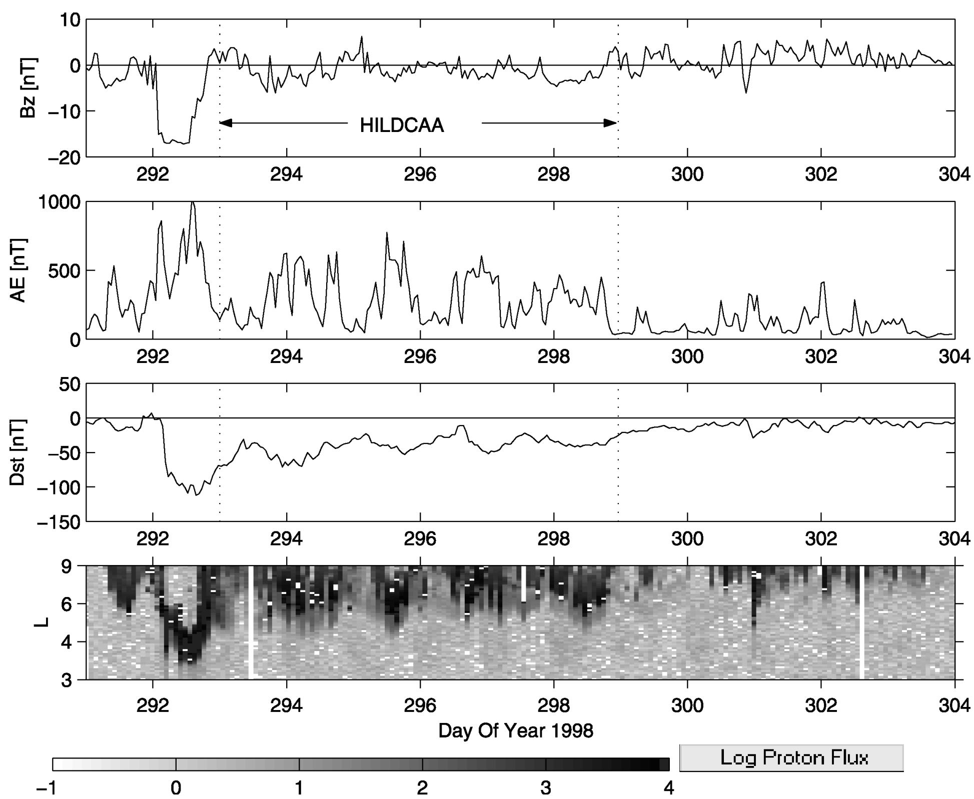

Figure 4. The B_z component of the solar wind, *AE* and *Dst* indices are given in the first three panels. Given in the last panel are NOAA-12 proton fluxes measured in the evening side of the Northern Hemisphere, for October 18-31, 1998. The proton fluxes, shown with a logarithmic gray scale, are plotted versus *L* and time. The intensity variations through the different *L*-values reflects the depth and intensity of proton penetration into the radiation belt.

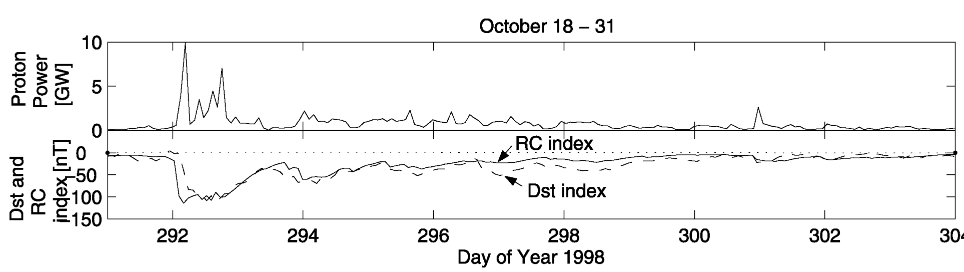

Figure 5. Proton power, Q(t), calculated from NOAA-12 measurements at the evening side of the Southern Hemisphere, the *Dst* index and the calculated RC index for the October 1998 event.

the magnetosphere during HILDCAA is due to magnetic reconnection between the Alfvén waves and the magnetopause field.

In order to test this hypothesis we have done a comparison between fluctuations in the B_z component of the solar wind magnetic field and the Q(t) parameter. *Søraas et al.* [2002] have shown that Q(t) is a good proxy for the proton injection rate into the ring current. The results of this exercise are shown in Figure 6. The figure consist of three panels one for each HILDCAA period considered. The injected power into the outer part of the ring current (the black filled area) are compared with the negative B_z component (the gray filled area). In all cases there is a clear correspondence of particle injections and negative excursions in the B_z component. There seems to be a slight delay between the negative B_z excursion and the injected particles. This is as expected both because of the time delay between the ACE observation and the magnetopause, and also the additional time delay

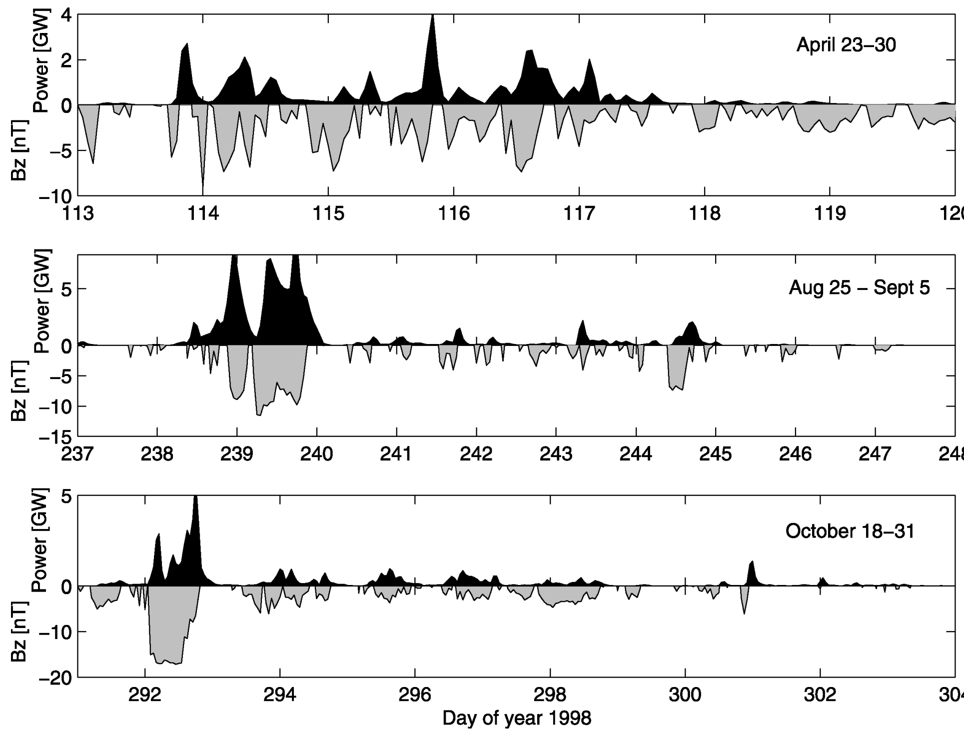

Figure 6. Proton power, Q(t), calculated from NOAA-12 measurements at the evening side of the Northern Hemisphere, together with the negative values of IMF's B_z component for the three storms presented in figure 2, 3 and 4.

between dayside merging and the particle injections from the nightside plasmasheet. The time delay reflects processes that could be of importance for the geoeffectiveness.

5. CONCLUSIONS

The calculated ring current index, a proxy for the ring current energy content, fits well with the *Dst** index. From this it is concluded that the reduced geomagnetic field and slow recovery during HILDCAA events are mainly due to particle injection into the ring current from the nightside plasmasheet.

It is shown that there is a direct correspondence between negative fluctuations in the B_z component of the interplanetary magnetic field and particle injections into the nightside ring current. Fluctuations in the B_z component of the interplanetary magnetic field give rise to field line merging at the front side of the magnetosphere and a convective electric field at the night side, driving the plasma sheet particles into the ring current. The duration of the B_z negative phases are not long enough to drive a magnetic storm.

The interplanetary magnetic field fluctuations have been examined [*Tsurutani and Gonzalez,* 1987] and shown to be Alfvén waves propagating outward from the Sun. The fluctuations are more or less continuous, and the southward components of the long period waves cause HILDCAAs [*Tsurutani and Gonzalez,* 1987; *Tsurutani et al.,* 1990; *Tsurutani et al.,* 2004].

The proton injections as seen in the bottom panel for all the cases are well correlated with the *AE*-index. These panels further show that HILDCAA events are associated with particles injected into the outer part of the ring current. The injected protons penetrate deep enough into the ring current to have an influence on the *Dst* index, but their energy content and their depth of penetration is not large enough to cause a magnetic storm.

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