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Evidence for particle injection as the cause of D_{st} reduction during HILDCAA events

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Abstract

The Earth's magnetic field at the equator, as monitored by the D_{st} index, can stay below its quiet day value for days. This can happen after storms resulting in a very slow recovery of the D_{st} index, or it can happen in the absence of a storm. Such "anomalous" behavior of the D_{st} recovery is observed during times showing continuous auroral activity called High Intensity Long Duration Continuous AE Activity (HILDCAA) (Planet. Space Sci. 35 (1987) 405). The D_{st} is mostly attributed to the ring current (RC), 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 RC is proportional to the energy content of the charged particles generating it (J. Geophys. Res. 64 (1959) 2239; 71 (1966) 3125). It is thus of interest to determine if the reduction of the D_{st} during HILDCAAs is due to an increased RC or/and can be accounted for by an increase or a relocation of other current systems.

This paper considers the injection of electrons and protons into the auroral and subauroral zone for four cases exhibiting HILDCAA activity. The total energy flux of the ions into the midnight/evening quadrant gives a good estimate of the energy injection into the RC (J. Geophys. Res. 107 (2002) 149). This injection, if it occurs during the recovery phase of a storm, prolongs the final decay of the D_{st} to quiet day values, and if it occurs during times without storms the injection can maintain D_{st} at more or less constant negative values for days. The ion injection into the RC is sufficient to account for the reduced D_{st} index during HILDCAAs. It is determined that the HILDCAA events are associated with a low-level injection of protons into the outer portion of the RC above L equal 4. The HILDCAA events are thus not due to plasma sheet current intensifications or earthward motion of this current. The prolonged low-level ion injection is associated with fluctuations in the B_z component of the solar wind magnetic field giving rise to magnetic field line merging on the front side of the magnetosphere (Planet. Space Sci. 35 (1987) 405). The duration of the B_z negative phases are not long enough to drive a magnetic storm.

Keywords: HILDCAA; Ring current; D_{st}; Energetic protons

1. Introduction

Stormy weather in the near-Earth environment is mostly caused by large solar eruptions, which eject clouds of charged particles at high speeds into interplanetary space. Depending on the type of the solar disturbance, the speed of the plasma flow, the associated interplanetary field structure, and the state of the magnetosphere, the storm signatures in the near-Earth environment can be highly variable. Geomagnetic disturbances are manifested by increased auroral ionospheric currents at high and mid-latitudes and by enhancements in the ring current (RC) at lower latitudes (for a review see, Tsurutani and Gonzalez, 1997).

It is the purpose of this paper to discuss how magnetospheric activity, as manifested both in the auroral zone (substorms) and at subauroral latitudes (the build up of the ring

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current) is revealed by precipitating energetic electrons and ions. Historically, geomagnetic activity has been characterized by magnetic indices based on ground measurements of the magnetic field. Magnetic observations are, however, influenced by current systems far away from the point where the measurements are being made. Furthermore, the ionospheric currents depend both on the conductivity and on the electric field and cannot give direct information on the particle injection.

However, using satellite observations the particle environment can be determined both in space and time. In the present study observations from a low-altitude polar orbiting NOAA satellite are used to determine the precipitation of protons and electrons into the upper atmosphere. These precipitating particles are a direct measure of the energy into the auroral/high-latitude regions and are proportional to the energy injection into the RC (O'Brien, 1964; Søraas et al., 2002).

In particular the buildup and decay of the RC will be considered in our study. It is essential to know what is causing the RC buildup in order to reveal if the depressed D_{st} is due to particle injection or something else. It is well known that the initial phase of a geomagnetic storm is caused by the increase in plasma ram pressure associated with an increase in density and speed of the solar wind (SW). The storm main phase is due to a prolonged southward interplanetary magnetic field (IMF) convecting ions from the tail into the RC.

The storm recovery phase begins when the IMF turns less southward. This reduces the convection electric field, the injection of particles to L-values below 5–6 stops, and the RC starts to decay. The decay of the RC is due to a combination of several different particle loss processes (scattering by Coulomb collisions, charge exchange, wave-particle interactions, and convection transporting the ions across the magnetopause).

The decay/recovery phase of the RC is not completely understood. In larger storms there is usually a fast initial decay, attributed to a collapse of the tail current (Turner et al., 2000), and/or a fast decay of oxygen ions through charge exchange, and/or large-scale convection losses in the main phase of the storm (Kozyra et al., 1998; Liemohn et al., 1999). After this abrupt reduction in the RC, the decay is more gradual depending on charge exchange of the RC ions with the geocorona and wave-particle interaction at or near the plasmapause forcing the RC ions into the loss cone (Cornwall et al., 1971; Søraas et al., 1999). These processes result in an average decay time of the RC at about 7–10 h. The initial asymmetric and the symmetric recovery phases of the RC can be followed in local time by looking at the Storm Time Equatorial Belt (STEB) development (Søraas et al., 2003).

Not all storms, however, appear to follow this scheme. Some storms have a very prolonged decay, which can last for many days to weeks. During such prolonged decays, the magnetic field in the high-speed SW streams can be described as an Alfvén wave, where the varying B_z component causes intermittent reconnection, intermittent substorm activity, and sporadic injection of plasma sheet energy into the outer portion of the RC prolonging its final decay to quiet day values, or when occurring without a storm, depresses the D_{st} to a more or less constant value lasting for days (Tsurutani and Gonzalez, 1987, 1997). This continuous auroral activity is the signature of HILDCAAs.

2. Data sources

In the following four HILDCAA events will be studied in order to see if they can be associated with prolonged injection of RC particles from the tail plasma sheet. The RC injection is revealed by particle observations from a low-altitude satellite. The aim of the study is to identify the causes of the prolonged recovery phase observed in some geomagnetic storms, and the sometime observed reduced D_{st} over a period not related to storms.

A working definition of HILDCAA is: a maximum of AE > 600 nT, average AE > 200 nT, a duration > 2 d, and not associated with the storm main phase.

In order to do such an investigation, a number of HILDCAA events occurring in 1998 were identified (Gonzalez, private communication, 2002). The selected events are associated with varying interplanetary conditions. HILDCAA events occurring during four types of IMF conditions are studied: (1) events immediately following magnetic storms; (2) events related to coronal mass ejections (CMEs); (3) events related to high-speed SW streams without close association to a storm, and (4) events related to high-speed SW streams subsequent to a magnetic storm. The results reported here are appropriate to all of the four types of IMF conditions.

Our strategy is to follow the chain of events beginning with the SW encounter with the Earth's magnetosphere, its interaction with the magnetosphere, the effects on the RC as revealed by the D_{st} index, and the depth of the proton injection into the RC. This was accomplished by combining SW data, geomagnetic activity indices (AE, D_{st}, and K_p), and low-altitude satellite particle observations.

The SW and magnetic activity data are for the large part available through public data bases. As a source for the satellite data we will use data from the low-altitude polar orbiting NOAA 12 satellite. It is thus pertinent to give a description of the relevant instrumentation on this satellite. The instrument description given is however pertinent to all of the newer NOAA satellites.

3. Instrumentation

The present study examines observations of protons and electrons from the medium energy proton and electron detector (MEPED) on board the satellites. The MEPED instrument measures protons and electrons at angles of 10° and 90° with the local vertical. The MEPED detectors have an opening angle of 30° full angle, that is ±15° about the pitch angle that is given. The MEPED is sensitive to all energetic ions. The most abundant ions in the RC are hydrogen and oxygen. The relation between these ions varies throughout the storm as discussed by Daglis et al. (1996). As MEPED cannot distinguish between different ion species we will use the term protons throughout this paper. The instrument will also respond to energetic neutral atoms (ENAs). For a discussion of the instrument response to heavier ions see Søraas et al. (2002). A full description of the NOAA spacecraft and the MEPED instrument is given by Raben et al. (1995).

The NOAA satellite orbits are sun-synchronous circular at an altitude of about 850 km. The orbital plane of the NOAA 12 satellite is in the local evening/morning sector. The orbital period is around 103 min.

4. Data analysis

From the NOAA satellite data it is possible to calculate a RC-index (Søraas et al., 2002). The RC-index is a measure of the energy content in the RC and is directly related to the energy injection rate into the RC. Thus by examining this index during HILDCAA events it is possible to determine if the energy content in the RC is sufficient to account for the observed D_{st}. If this is the case one can conclude that the RC is the main contributor to the D_{st} during HILDCAA events.

As the RC-index is crucial for the present work, a short description on how the index is obtained is pertinent. From the NOAA data the power loss, $Q^*(t)$, due to the precipitation of protons over the energy range 30–800 keV into the evening/midnight quadrant of the magnetosphere is estimated. The time resolution of $Q^*(t)$ is around 100 min, that is one orbital period of the satellite.

From the Burton formula (Burton et al., 1975):

$$dK/dt = Q(t) - K/T$$

the energy content K in the RC due to energetic particles can be estimated. $Q(t)$ is the RC energy injection rate and T is the RC decay constant.

Several loss mechanisms like charge exchange, convection losses at the front of the magnetosphere, wave/particle interaction, etc. are lumped into the decay constant T. The mechanisms for the decay of the storm time RC are still a matter of debate. Jordanova et al. (1996) have shown that charge exchange is the most important collisional loss mechanism. Kozyra et al. (1998) found that in addition to charge exchange loss, convection loss through the dayside magnetopause, and Coulomb collision loss, other loss processes must be operating. Liemohn et al. (1999) demonstrated that the convective loss through the dayside magnetopause is dominant during the storm main phase.

Burton et al. (1975) used a value of $T = 7.7$ h for the RC decay constant. This value is pertinent to storm events, where the proton injection reach below $L=4$. In Section 7, it is shown that the particle injection during HILDCAA events only reaches into the outer part of the RC. At these larger L-values the charge exchange loss time is increased due to the reduced geocorona density. Taking this into account a value of $T = 10$ h seems to be pertinent for HILDCAA events.

Assuming now that $Q^*(t)$, determined from the NOAA satellite data, is proportional to the real RC injection rate $Q(t)$. A value K^* proportional to the RC-energy content can be calculated from the Burton equation with $Q^*(t)$ as the injection rate. The Dessler–Parker–Sckopke relationship (Dessler and Parker, 1959; Sckopke, 1966) describes that the magnetic perturbation at the center of the Earth, ΔB, caused by the RC is proportional to the RC-energy content. Thus our estimate of the RC-energy can be converted to a RC-index. As this index only depends on the RC and is not influenced by other current systems in the magnetosphere it is a space-based equivalent to D^*_{st}. D^*_{st} is the so-called pressure-corrected D_{st}, correct for SW dynamic effects using a relationship suggested by Burton et al. (1975) and developed further by Gonzalez et al. (1989). Our RC-index is normalized for the whole year of 1998 to have the same average value as the D^*_{st}.

5. The HILDCAA events

The observations related to the several HILDCAA events will now be presented. Using the NOAA satellite data, the power into the upper atmosphere carried by electrons and protons with energies above 30 keV in both the dawn/noon and the evening/midnight MLT sectors is determined.

Figs. 1–4 display the results for each of the events studied in identical format. The panels on the left of each figure display (from top to bottom), the IMF strength B, the B_z component of IMF, the SW velocity, and the SW density. The panels on the right side of each figure display (from top to bottom), the AE-index, the power deposited by electrons into the morning/noon quadrant of the auroral oval, the power deposited by protons into the evening/midnight quadrant of the auroral oval, and the D^*_{st} index (dashed line) and the RC-index (solid line).

6. Observations

6.1. Type 1. Event following a storm. The April 24 HILDCAA

The observations cover days 113–119 (April 23–April 29) in 1998. During that period the D_{st} exhibited two decreases (the first on day 114 going down to −70 nT, and the second

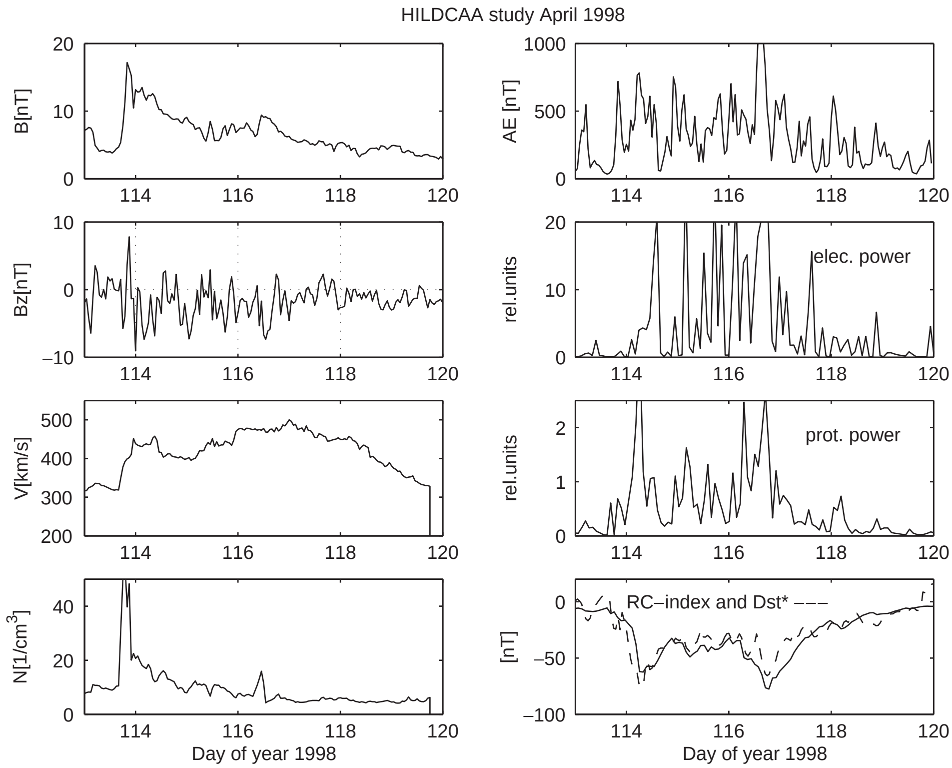

Fig. 1. Left panels: Solar wind parameters(B, B_z, V, N). Right panels:AE-index, electron power into the noon/morning sector, proton power into the evening/midnight sector, RC-index (solid line) and D_{st}^{*} (dashed line).

on day 116 reaching down to −60 nT). The D_{st} recovery after each decrease was very slow, with hardly any recovery at all after the decrease on day 114 when D_{st} remained almost constant at −40 nT for about 2 days. The AE-index was elevated during the whole period, having an average value of 360 nT and reaching as high as 1130 nT. By our definition this event thus qualified as a HILDCAA event.

From the four panels on the left of Fig. 1 one sees that the IMF magnitude increased abruptly in connection with the first D_{st} decrease, and then exhibited an almost exponential decrease for the rest of the period. The B_z component of IMF exhibited large amplitude variations during the whole period having an average value of around zero and a rms value of 3.1 nT. The SW velocity increased from around 350 km/s to around 450 km/s and stayed fairly constant until day 117 when it showed a slow decay. The density exhibited a pulse-like increase from 10 to 50 particles/cm^3 that lasted for about 6 h followed by an exponential decrease for the rest of the period considered.

The second and third panel on the right-hand side of Fig. 1 shows the precipitating power into the morning/noon sector from electrons with energies above 30 keV, and the second panel exhibits precipitating protons into the evening/midnight sector. Both the electrons and the protons exhibited variations similar to the variations found in the AE-index. It should however be noted that at the onset of the two D_{st} decreases the proton power into the upper atmosphere is relatively much more intense than the electron power.

The fourth panel shows the comparison between the D_{st}^{*} and the RC-index. The RC-index is a proxy for the D_{st}^{*} but depends only on the RC and not on other current systems. There is a good correspondence between the D_{st}^{*} and the RC-index during the whole period considered. The linear correlation coefficient between these parameters is 0.87. This indicates that the depressed D_{st}^{*} during the prolonged period of auroral activity is due in large part to protons injected into the RC.

6.2. *Type 2. Event before and after a coronal mass ejection (CME). The August 22 HILDCAAs*

The second type of IMF conditions covers days 234–245 (August 22–September 2) in 1998. The data related to HILDCAAs in this period is shown in Fig. 2. This time period contains two HILDCAA events. The first took place

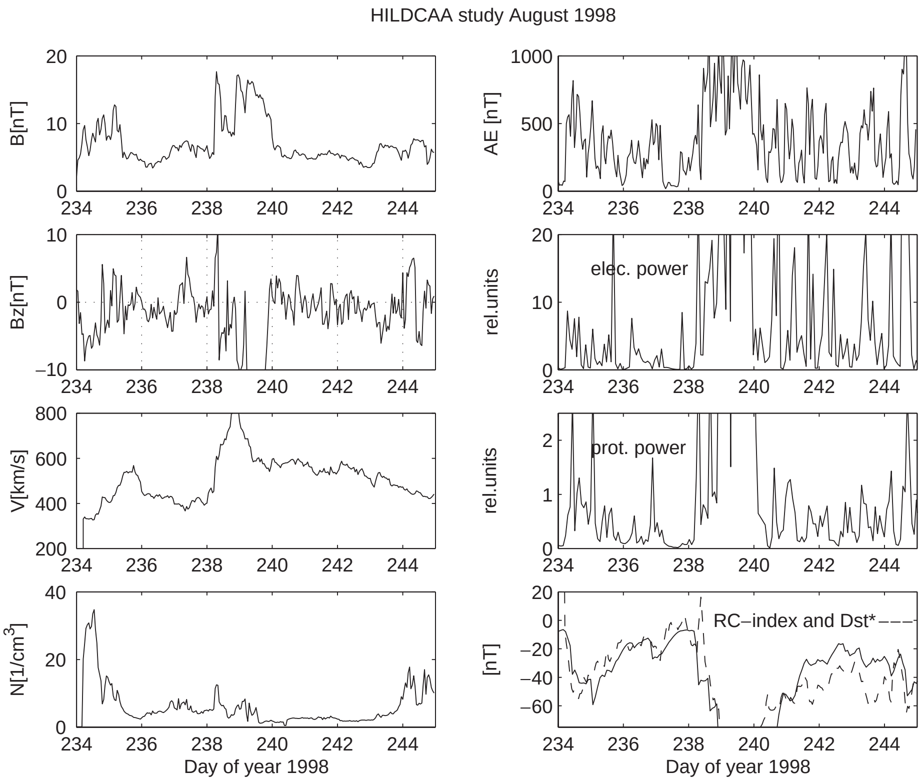

Fig. 2. Left panels: Solar wind parameters(B, B_z, V, N). Right panels:AE-index, electron power into the noon/morning sector, proton power into the evening/midnight sector, RC-index (solid line) and D^*_{st} (dashed line).

during the days 235–238 that is before a −150 nT storm, while the second event commenced on day 240 and continuing several days into the recovery phase of the storm. The before storm HILDCAA is associated with a small −40 nT storm on day 234. This storm has a slow recovery containing oscillations in the D_{st} associated with large B_z positive and negative excursions.

The magnitude of the IMF was fairly constant during the two HILDCAAs having an average value of around 5 nT. The B_z component exhibited large amplitude variations during the whole period having an average value of around zero. During the pre-storm HILDCAA the SW velocity had a short increase reaching a velocity of 550 km/s and then levelled off at around 400 km/s. During the large storm between days 238 and 240 the SW velocity reached above 800 km/s. The SW density was generally low, with an average value of about 5 particles/cm^3. This applies to both HILDCAAs.

The top panel on the right-hand side of Fig. 2 shows the AE-index. Both the electron and the proton power, panel 2 and 3, exhibit variations similar to the variations found in the AE-index.

The comparison between D^*_{st} and the RC-index, shown in the bottom panel on the right-hand side of Fig. 2, exhibits a correlation coefficient of 0.81 again indicating that the depressed D_{st} during the HILDCAAs is due in large part to protons injected into the RC.

6.3. *Type 3. Event related to streams, no storm. The June* 3 *HILDCAA*

The third study covers days 153–160 (June 3–June 9) in 1998, an event almost identical to the April event discussed above. During this period the D_{st} had an average value of −20 nT, and exhibited two decreases (the first on day 155 going down to −30 nT, and the second on day 157 decreasing to −50 nT). The D_{st} recovery after each decrease was slow, and after the decrease on day 157 D_{st} remained almost constant at around −30 nT for several days. The AE-index was elevated during the whole period, having an average value of 260 nT and reaching as high as 770 nT. By our definition, this event also qualified as a HILDCAA event.

As seen from the upper panel on the left of Fig. 3 the magnitude of the IMF was fairly constant during the period, but exhibited a few variations that had an average amplitude of 7 nT and reached a maximum of 13 nT. The B_z

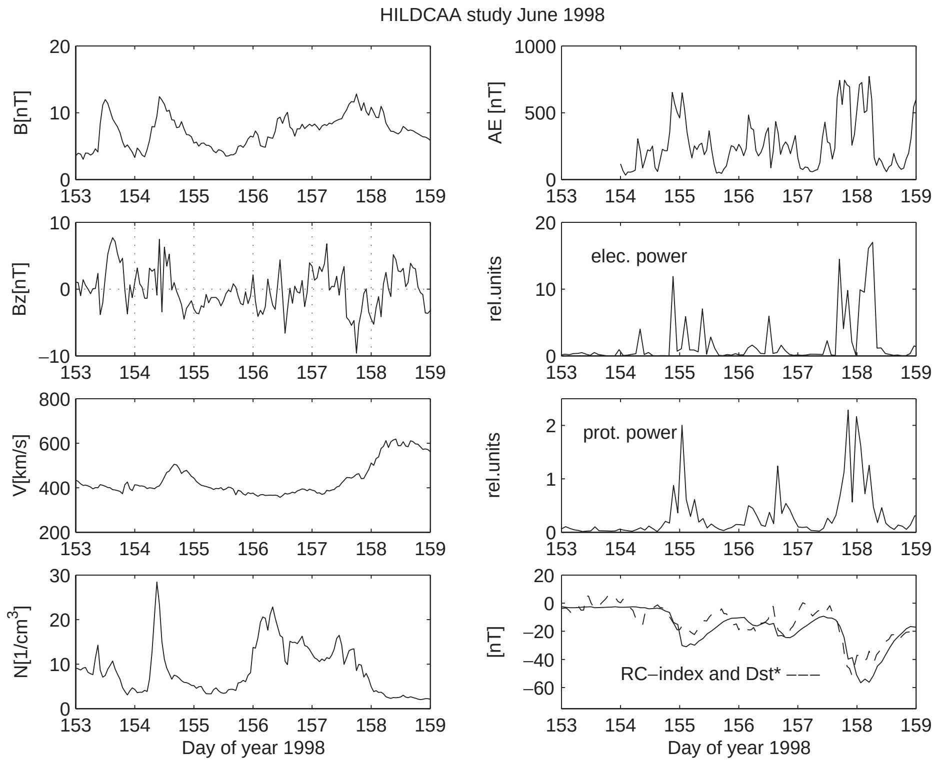

Fig. 3. Left panels: Solar wind parameters(B, B_z, V, N). Right panels:AE-index, electron power into the noon/morning sector, proton power into the evening/midnight sector, RC-index (solid line) and D^*_{st} (dashed line).

component exhibited large amplitude variations during the whole period having an average value of around zero and a rms amplitude of 2.8 nT. During the early part of the period the SW velocity was fairly constant with a value slightly above 400 km/s. At the end of day 157 the SW velocity increased and reached around 600 km/s near noon on day 158. This increase in SW velocity was associated with the second decrease in D_{st}. The SW density was generally low, with an average value of about 5 particles/cm^3, but with periods of somewhat increased densities on day 154 and throughout days 156–157.

The second panel on the right-hand side of the Fig. 3 shows precipitating power into the morning/noon sector from electrons with energies above 30 keV, and the third panel exhibits the power loss from precipitating protons into the evening/midnight sector. Both the electron and the proton power losses exhibit variations similar to the variations found in the AE-index.

The bottom panel show a comparison between the D^*_{st} and the RC-index. As before, there is a good correspondence between the D^*_{st} and the RC-index during the entire period studied. The linear correlation coefficient is 0.77. This again indicates that the depressed D^*_{st} during the prolonged period of auroral activity is due in large part to protons injected into the RC.

6.4. *Type 4. Event related to high-speed solar wind streams subsequent to a magnetic storm. The October* 20 *HILDCAA*

This HILDCAA event took place in the recovery phase of a −120 nT D_{st} main phase storm and, thus differs from the two discussed above. The storm started on day 292 October 19 with an abrupt increase in the total IMF. The B_z component went negative to −18 nT and remained strongly negative for around 12 h. There was only a gradual increase in the SW velocity, but there was a short intense increase in the density to 60 particles/cm^3. The HILDCAA event started late on day 293.

The second panel on the right-hand side of Fig. 4 shows the power loss into the morning/noon sector from electrons with energies above 30 keV, and the third panel exhibits the proton power loss into the evening/midnight sector. Once again both the electron and the proton power losses exhibited variations similar to the variations found in the AE-index, but it should be noticed that during the storm main phase the proton injection (as estimated from the power loss) totally dominates over the electrons.

In the recovery phase of the storm a number of individual particle injections are evident in both the particle power and the AE-index. The proton injection is very high during the

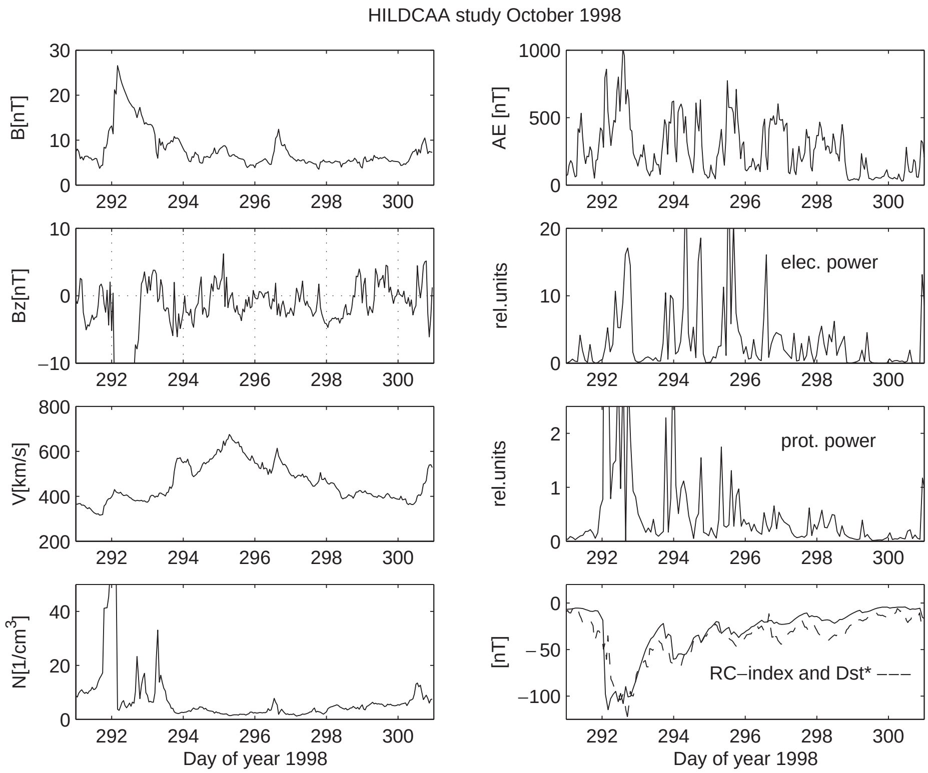

Fig. 4. Left panels: Solar wind parameters(B, B_z, V, N). Right panels:AE-index, electron power into the noon/morning sector, proton power into the evening/midnight sector, RC-index (solid line) and D^*_{st} (dashed line).

initial and main phases of the storm, but there was also proton injection into the RC during the recovery phase of the storm. The RC-index has been calculated from the proton injection. It is seen that there is good similarity between the RC-index and D^*_{st}. The linear correlation coefficient is 0.89. This, once again, indicates that the prolonged recovery phase of the storm is due in large part to protons injected into the RC.

7. The depth of proton injection during HILDCAA events

A fundamental aspect of the physics of magnetic storms is the injection of the trapped RC particles that are responsible for the depression of D_{st}. It has been shown that the majority of the enhancement in RC energy during the main phase of storms occurs at $L < 4$ (Smith and Hoffman, 1973; Lui et al., 1987; Hamilton et al., 1988).

In Fig. 5 the depth of the proton injection into the RC during two of the HILDCAA events considered earlier are shown.

The left-hand panel shows data related to the October storm. This HILDCAA takes place in the recovery of a -120 nT magnetic storm. During the main phase of the storm the proton injection penetrates to below $L = 4$ causing RC enhancement over a large L range. Note that the particle injection above $L = 5.6$ during the main phase of the storm is less then it is during the HILDCAA events taking place in the recovery phase of the storm. In the recovery phase of the storm there is no injection below $L = 4$, but there is an appreciable injection into the outer part of the RC in particular above $L = 5.6$ as shown in panel three from the top. This injection is large enough to prolong the decay of the RC as evident from the D_{st} index.

The right-hand panel shows data related to the April storm. This HILDCAA is following a -60 nT storm, and as seen from the top panel there is a proton injection to below $L = 4$ in connection with the storm. For the rest of the period considered there is no particle injection below $L = 4$. The D_{st}, however, exhibits an almost constant depressed value of around -40 nT for almost 4 days, that is during the HILDCAA event. During this period there is a continuous injection of protons in the L range above 4. It is interesting to note that the particle injection in this outer part of the RC is large enough to keep the D_{st} at a constant value. The source and loss processes for the RC are equal. In the October HILDCAA the proton injection above $L = 4$

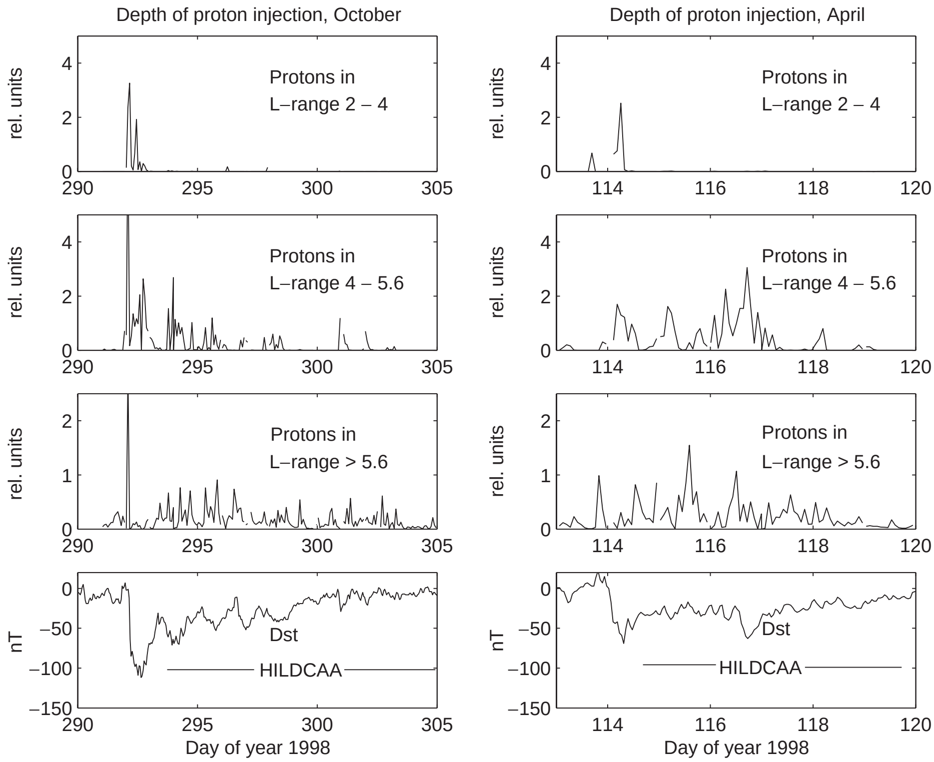

Fig. 5. The left panels relate to the October and the right panels to the April HILDCAA events. The three top panels show the amount of protons penetrating into the different L regions, 2–4, 4–5.6, and above 5.6. The bottom panel show the D_{st} index.

was less than in the April HILDCAA, and the injection during the October HILDCAA was not sufficient to balance the loss processes. The injection was only able to delay the recovery phase of the storm.

We thus find in accord with Lyons and Williams (1975) that the particle injections to $L < 4$ are unique to storms. They further state that the particle injections to L values above 4 are about the same in intensity during storms as during non-storm-time substorms. Our findings in this respect are that the proton injection can be larger during HILDCAA events than during storms in the outer parts of the RC.

8. Summary and discussion

In all cases considered in our study there are good correspondences between the D_{st} and the RC-index. This is true not only in the main phase of the storm, but also during the recovery phase. These findings strongly support the view that the reduced D_{st} in HILDCAA events is due to protons injected into the RC. During HILDCAA events ions/protons are continuously injected into the outer part of the RC, delaying its recovery towards quiet conditions. The slow D_{st} decay is thus not due to other current systems in the magnetosphere, such as tail or electrojet currents, or to a slower decay rate of the ions in the RC. The measurements show that the long recovery phase of the D_{st} in HILDCAA storms is due to a persistent injection of ions into the RC. This recovery phase injection prolongs the RCs normal decay due to charge exchange and wave/particle processes. The particle injection is strongly correlated with increased AE activity (the defining parameter for HILDCAA events).

The prolonged low-level injection of particles into the RC is not associated with a long period of negative B_z. It is, however, associated with fluctuations in the B_z component of the SW magnetic field. These fluctuations possibly give rise to magnetic field line merging over the front side of the magnetosphere. A convection electric field is associated with reconnection, the electric field convect particles into the nightside magnetosphere. Substantial particle injection is thus taking place during the recovery phase of some storms and during periods of depressed D_{st} not associated with storms. In both cases, fluctuations in the SW magnetic field possibly result in continuous injection of protons into the RC thus maintaining a depressed D_{st} and inhibiting the decay of the RC. In the four events studied there is a good correspondence between the fluctuations in B_z, AE, and the particle power into the upper atmosphere.

The cause of continuous substorms are the large amplitude B_z fluctuations in the IMF. Although the average B_z value is near zero, the large amplitude fluctuations provide very large B_z (B-south component) intervals and concomitant substorms through the reconnection process. The IMF fluctuations have been examined and have been 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).

9. Conclusion

The injection of electrons and protons into the auroral and subauroral zone has been studied for four cases exhibiting HILDCAA activity. The total energy flux of the protons into the midnight/evening quadrant gives a good estimate of the energy injection into the ring current. It is concluded that the HILDCAA events are associated with a low-level injection of protons into the outer portion of the ring current. This injection, if during the recovery phase of a storm, will prolong the final decay of the D_{st} to quiet day values, and if occurring during times without storms, the injection can keep the D_{st} at nearly constant negative values for days. The ion injection into the RC is sufficient to account for the reduced D_{st} index during HILDCAAs. The HILDCAA events are thus not due to plasma sheet current intensifications or earthward motion of that current. The prolonged low-level ion injection is associated with fluctuations in the B_z component of the solar wind magnetic field giving rise to magnetic field line merging on the front side of the magnetosphere. This process can occur even though the B_z negative period is not long enough to drive a magnetic storm. Further work has to be done in order to characterize the HILDCAA events in relation to the general SW conditions.

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