Energetic electron flux enhancements during geospace magnetic storms associated with earthward penetration of Pc 4 and 5 waves?

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Abstract

ULF waves with frequencies of a few millihertz (mHz) have been associated with changes in the flux levels among relativistic electrons comprising the outer zone of the radiation belts. In particular, the fluxes of electrons with energies > 1 MeV in the outer radiation belt increase and decrease during geospace magnetic storms. For all storms studied by Reeves et al. [2003], only about half of them led to increased electron fluxes, one quarter led to decreased the fluxes, and one quarter produced little or no change in the fluxes.

We focus on the increase of relativistic electrons observed during a number of magnetic storms by GOES satellites at geosynchronous orbit. To minimise the effects caused by the Earth's magnetic field asymmetries, we apply a statistical reconstruction of the fluxes to a common local time, which is chosen to be noon, a technique proposed by O'Brien et al. [2001].

Next, we look into multipoint observations from ground-based magnetometer arrays and the characteristics of Pc 4 and 5 waves during the different phases of the magnetic storms with particular emphasis on the distribution of Pc 4 and 5 wave power over the L shells that correspond to the radiation belts.

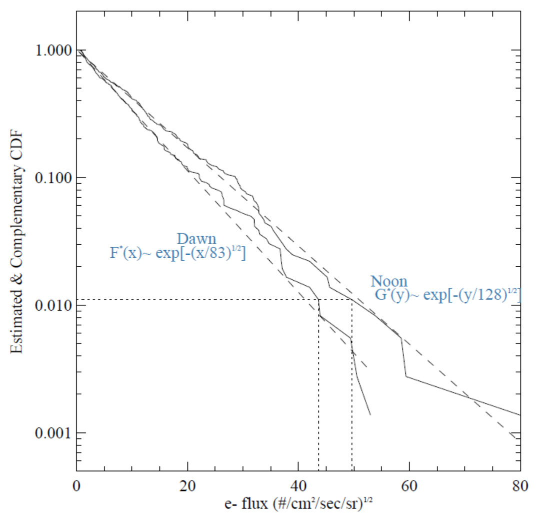
With these observations as a starting point, we investigate whether Pc 4 and 5 wave power penetrates to lower L shells during periods of enhanced relativistic electron fluxes. We discuss, lastly, the implications to wave-particle interaction.

Data and their analysis

We focused on geospace magnetic storms that occurred between 2000 and 2006, a period that covers the main and declining phase of solar cycle 23. Each storm was defined by a minimum in the hourly Dst index, falling below -50 nT. Available measurements of relativistic (>2 MeV) electron fluxes from the GOES-10 satellite at geosynchronous orbit have been obtained from CDAWeb to investigate the radiation belt electron population flux level.

Using the Statistical Asynchrounous regression (SAR), a method proposed by O'Brien et al. (2001) to determine the relationship between two quantities without simultaneous measurements, the electron flux measurements have been reconstructed to local noon in order to distinguish temporal variations from the consequences of the orbital motion of the satellite. Specifically, owing to the asymmetry of the Earth's magnetic field between the dayside and nightside, as the satellite passes through different local times, it measures slightly different parts of the radiation belts.

In this step of the analysis, we calculated monotonically increasing functions relating energetic electron fluxes measured at one local time with fluxes measured at local noon through the complementary cumulative distribution functions (CDF). The functions used to map fluxes from different local times to noon were defined as the change of variables that converts one distribution into the other while conserving probability.



The GOES-10 geosynchronous satellite measures the flux of electrons with energies above 2 MeV. As the satellite passes through regions of different local time, it measures electron fluxes from different parts of the radiation belts. This plot shows the complementary CDF for regions at the local noon and dawn, on which along with functions from every local time we have based the reconstruction of electron measurements. The level of geomagnetic activity as this is expressed by the Kp index has also been considered.

The characteristics of enhanced and sustained ultra-low frequency wave activity coinciding with the onset of storms were examined based on data from different magnetometer station arrays. These include time series of magnetic field measurements from the CARISMA array [Mann et al., 2008] covering the northernmost region of the American continent and IMAGE in Northern Europe [Viljanen and Hakkinen, 1997]. The geomagnetic field measurements have a temporal resolution of 10 s and 5s, respectively, and a continuous wavelet transform with the Morlet wavelet as the basis function has been applied to analyse them in the time-frequency domain. Magnetometer data from other networks are also being surveyed for this study.

Discussion

During the course of the five in total magnetic storms that we have studied, enhancements in the wavelet power at Pc 4 and Pc 5 frequencies, on the order of a few millihertz, have been observed simultaneously at all different magnetic latitudes and longitudes examined. This is clearly seen in filtered time series and wavelet power spectra of the X-component of the geomagnetic field measured at 10 IMAGE and 7 CARISMA stations covering L shells from 3.34 to 6.81 (*please see upper and lower panels on the right*).

Summary of the main parameters for the five magnetic storms we present here, which include the strength of each storm defined as the minimum of the Dst index, the maximum mean wave amplitude (MWA) and the L shell where this was observed.

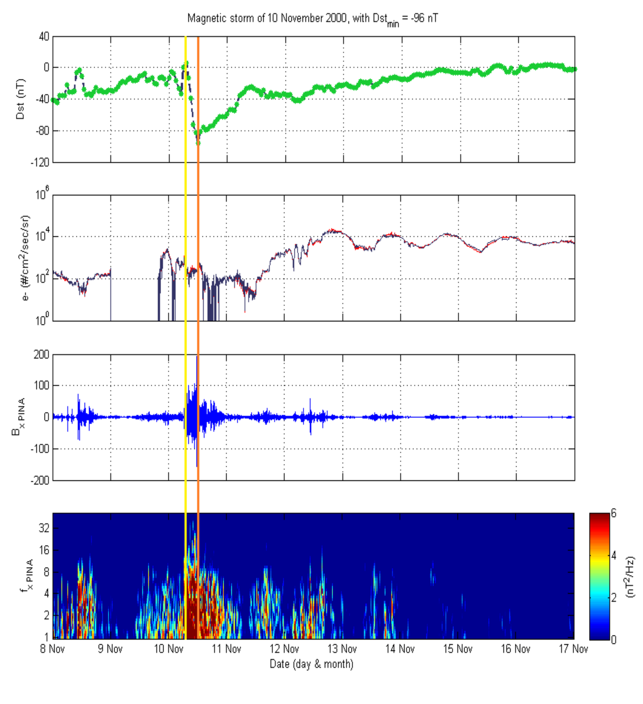
Date	Time	Dst_{min} (nT)	MWA (nT)	L shell
17 July 2004	03:00 UT	-76	~ 38.0	6.15
10 November 2000	13:00 UT	-96	~ 59.0	6.09
23 July 2004	03.00 UT	-101	~ 62.0	6.09
24 July 2004	17.00 UT	-148	~ 134.0	6.09
26 July 2004	14.00 UT	-197	~ 167.0	5.35

Despite the existence of geomagnetic pulsations before and throughout the course of the five magnetic storms, more pronounced Pc 4 and Pc 5 wave packets are observed during the main phase of each magnetic storm. Furthermore, stronger magnetic storms are accompanied by greater enhancements in the power spectral density and Pc 4 and Pc 5 waves of larger mean wave amplitude (MWA). The MWA is defined as the square root of the sum of the power spectrum density over the frequency range from 1 mHz to 50 mHz. It is worth noting the timing of mean wave amplitude increase coincides with the storm commencement.

When looking at the filtered time series of measurements from the IMAGE and CARISMA, it is interesting to note that, in the main phase of each storm, the amplitude of waves is decreasing with decreasing L shell. On the other hand, the maximum WMA seems to have moved towards lower values of the L shell in the case of magnetic storms of greater intensity. In particular, Pc 4 and Pc 5 waves of significant WMA are being observed at the northern stations of IMAGE and CARISMA during the strongest magnetic storms.

These findings are forming the basis for a statistical analysis of Pc 4 and Pc 5 waves observed during magnetic storms and mapping of their occurrence at different latitudes and longitudes, with the aim to investigate radial diffusion which can arise from resonant ULF wave-particle interactions against local resonant acceleration of radiation belt electrons upon interaction with high-frequency chorus emissions.

Case study of the November 2000 magnetic storm

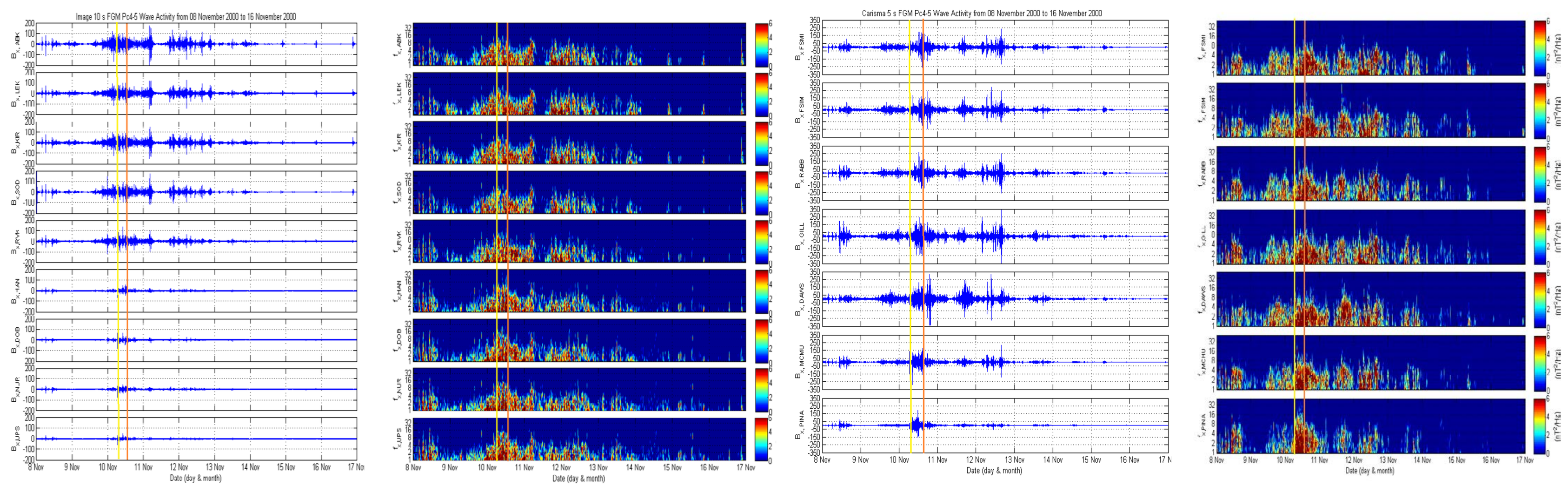


The 10 November 2000 magnetic storm: From top to bottom, the Dst index time series, the >2 MeV electron fluxes from the GOES -10 satellite (black line) and the reconstructed time series (red line), the filtered time series of geomagnetic fields' x-component measured at the CARISMA PINA station and the corresponding wavelet power spectrum are shown.

Interplanetary driver: Each geomagnetic storm is the consequence of a chain of causative events originating from the Sun, evolving into the solar wind flow and ultimately reaching the near-Earth space. The storm of 10 November 2000 was characterised by a minimum value of the Dst=-96 nT. The interplanetary driver of the storm was an extended interval of southward magnetic field that started on 8 November and lasted for several hours. The Dst index recovered in response to a northward turning of the interplanetary magnetic field. The passage of a fast forward interplanetary shock was identified in measurements of the ACE spacecraft. The shock was followed by a sheath of plasma of enhanced fluctuating field strength, speed, density and temperature, indicating the passage of a magnetic cloud.

Response of the radiation belts electron population: The plot on the left shows the relativistic electron response to the magnetic storm of 10 November 2000. During the storm, a decrease in the flux of electrons with energies higher than 2 MeV, as measured by GOES-10, was observed during the ring current growth. The initial electron flux decrease was followed by a continuous increase during the recovery phase, when the electron flux reached values approximately two orders of magnitude higher than the pre-storm electron flux. The drop and subsequent recovery of energetic electrons at geosynchronous orbit can be explained in terms of an adiabatic response to magnetic field changes (Kim & Chan, 1997) or, alternatively, in terms of an interaction with ULF waves (Elkington et al., 2003). The latter scenario is currently being examined.

Wave activity in the Pc 4 and Pc 5 frequency range: The lower panels shows Pc 4 and Pc 5 waves, which have been identified by inspection of time series of geomagnetic field measurements collected by the IMAGE (*lower left panels*) and CARISMA *(lower right panels*) magnetometer arrays, to which a high-pass filter with a cut-off frequency of 0.8 mHz was applied. Furthermore, in the power spectrum produced by means of wavelet analysis covering the nine days interval around the magnetic storm, Pc 5 waves are observed throughout the course of storms, with the most pronounced wave observed during the main phase of the storm.



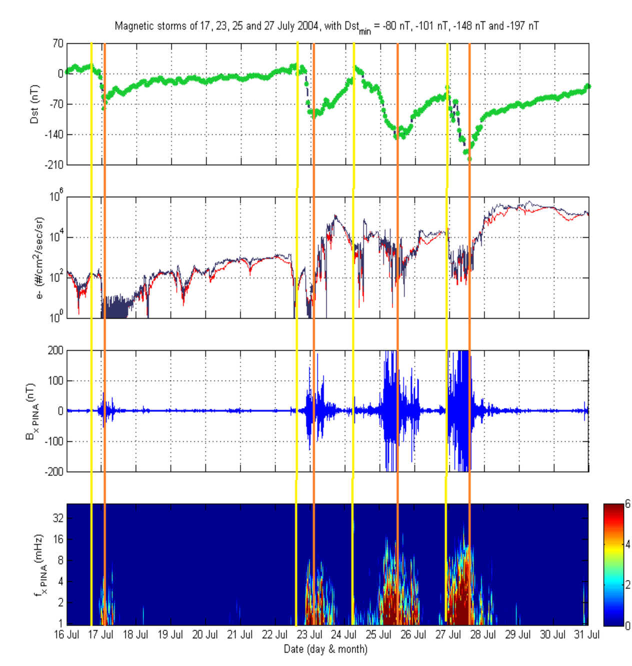
Pc 4 and Pc 5 waves observed during the 10 November 2000 magnetic storm: From left to right, the filtered time series of the geomagnetic field's x-component measured at 9 IMAGE stations (ABK, LEK, KIR, SOD, RVK, HAN, DOB, NUR, UPS) , covering L shell values from 5.82 to 3.34, and 7 CARISMA stations (FSMI, FSIM, RABB, GILL, DAWS, MCMU, PINA), covering L shell values from 6.8 to 4.1 and the corresponding wavelet power spectrum are shown.

Case study of the July 2004 magnetic storms

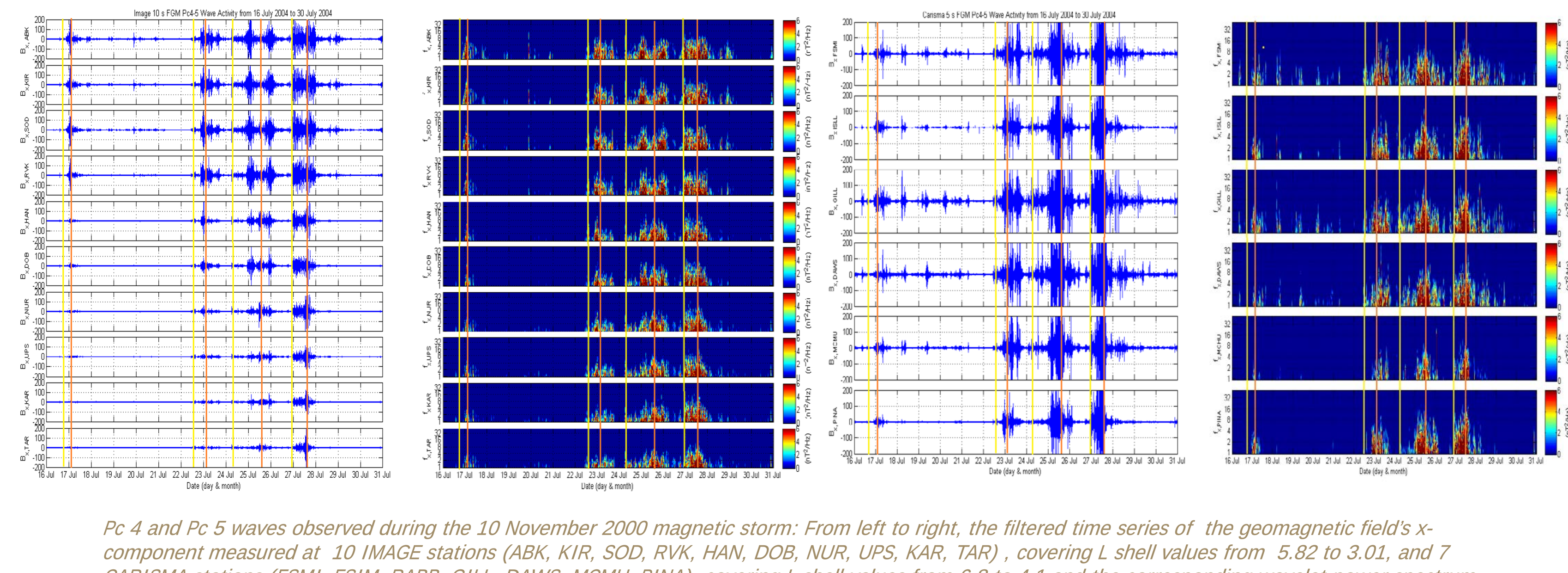
Interplanetary driver: The four successive storms which occurred in July 2004 were characterised by a successively decreasing minimum value of the Dst index, which was equal to -76 nT, -101 nT, -148 nT, and -197 nT. The interplanetary driver of the main phase of each storm did not differ among the four storms. Specifically, there was an interval of southward field from 22:00 UT on 26 July to 02:00 UT on 27 July that depressed the Dst index just below -100 nT at 02:00 UT. An extended interval of southward magnetic field reaching values of approximately -20 nT that started at 05:00 UT on 27 July and lasted for about 10 hours was associated with the passage of a magnetic cloud. The short period of southward field producing the initial phase was associated with a sheath of shocked plasma ahead of the magnetic cloud. The Dst index recovered in response to a northward turning of the interplanetary magnetic field.

Response of the radiation belts electron population: The plot on the right shows the relativistic electron response to the four magnetic storms that occurred in July 2004. It is worth noting that, except for the magnetic storm on 25 July 2000, the three magnetic storms on 17 , 23 and 27 July 2004 were characterised by a significant increase in the flux of electrons at geosynchronous orbit with energies higher than 2 MeV, as this was measured by GOES-10 during the recovery phase of the storm. Specifically, the electro flux increase ranged from one to approximately two orders of magnitude.

Wave activity in the Pc 4 and Pc 5 frequency range: Pc 4 and Pc 5 waves have been identified in both filtered magnetograms of ground-based magnetometer measurements as well as in the corresponding power spectrum produced by means of wavelet analysis. In all components (the x component has been selected to be shown *in the lower panels*), they were observed simultaneously in all stations of the IMAGE and CARISMA magnetometer arrays throughout the course of storms.



The 10 November 2000 magnetic storm: From top to bottom, the Dst index time series, the >2 MeV electron fluxes from the GOES -10 satellite (black line) and the reconstructed time series (red line), the filtered time series of geomagnetic fields' x-component measured at the CARISMA PINA station and the corresponding wavelet power spectrum are shown.



Pc 4 and Pc 5 waves observed during the 10 November 2000 magnetic storm: From left to right, the filtered time series of the geomagnetic field's x-component measured at 10 IMAGE stations (ABK, KIR, SOD, RVK, HAN, DOB, NUR, UPS, KAR, TAR) , covering L shell values from 5.82 to 3.01, and 7 CARISMA stations (FSMI, FSIM, RABB, GILL, DAWS, MCMU, PINA), covering L shell values from 6.8 to 4.1 and the corresponding wavelet power spectrum are shown.

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