Multiple-onset substorm case study:
Particle dynamics in the inner magnetosphere

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ABSTRACT

We use data from the CRRES spacecraft to examine the particle dynamics in the inner magnetosphere associated with the multiple-onset substorm of March 12, 1991. At onset the CRRES spacecraft was located near the magnetic equator in the evening sector (~ 21:30 MLT) at L ~ 6.3. The flux of the energetic ions (>30 keV) were observed to increase 2 minutes before the substorm onset during the last growth phase. This increase was registered 20^{o} to the west of the onset position without energy dispersion. During several minutes of gradual magnetic field dipolarization the acceleration of plasma sheet electrons was observed, together with their transformation into trapped energetic electrons due to the betatron-type acceleration. Simultaneous high energy electron variations can be described as an effect of a radial shift of the magnetic drift shells. We analyze also the short substorm activation located near the CRRES meridian and fast energetic electron acceleration. At lower energies (0.5-1 keV), an increase in the field-aligned electrons was registered approximately 40s before the fast increase of the energetic electrons. We conclude that although low-energy electron precipitations which produce active aurora and magnetic field dipolarization with energetic electron acceleration are elements of the same substorm onset scenario, they are separated temporally and/or spatially.

1. INTRODUCTION

There are three populations of charged particles involved in substorm development - plasmasheet particles with energies up to several keV, auroral electrons and ions with typical energy of several tens keV and 'old' trapped particles with energies of ten keV to several MeV. An increase in the flux of the auroral particles during the substorm expansion phase is one of the main substorm signatures. Traditionally referred to as an "injection", this process was thought to be caused by particle acceleration during radial transport from the magnetotail. However, although there are models describing possible dispersionless particle transport by electromagnetic waves [*Li*, 2000], observational results indicate the importance of a local acceleration mechanism [*Kremser et al.*, 1988; *Friedel et al.*, 1994]. There are several acceleration mechanisms which may be involved during substorms in the quasitrapping region, but many open questions remain and there are no accepted and experimentally supported scenaria. We must also consider treating the electrons and ions separately, because with an increase of the temporal resolution, it has become evident that "injections" are simultaneous only in general and that the proton (ion) flux often increases before the electrons and the magnetic field dipolarization [*Lazutin et al.*, 1998].

We initiated the present case study of the substorm of March 12, 1991 to perform a comprehensive study of the particle and substorm dynamics. Ground-based auroral and magnetometer networks were carefully studied in previous papers to create a temporal and spatial picture of the substorm development [*Lazutin et al.*, 2003] and to reconstruct the substorm current systems [*Kozelova et al.*, 2004]. The present paper is devoted to the analysis of the particle measurements. By combining data from the low energy plasma analyzer and the electron and ion angular spectrometer we have the capability of using direct particle measurements over a wide energy range, from 100 eV to hundreds of keV combined with the support of the onboard magnetic field measurements.

2. OBSERVATIONS

The particle data used in this study were provided by instruments on board the CRRES spacecraft, which was launched on July 25, 1990, on geosynchronous transfer orbit with a perigee of 305 km, an apogee of 35,768 km and an inclination of 18^{o}.
The low energy particle data used in this study were provided by the low energy plasma analyzer (LEPA) which measured the complete pitch angle distributions of electrons and ions from 0^{o} to 180^{o} every 30 s with a resolution of 5.625^{o} x 8^{o} in 20 channels in the range 100 eV < E < 30 keV [*Hardy et al.*, 1993]. The medium energy particle data used in this study were provided by the electron proton angular spectrometer (EPAS) which measured electrons in 14 channels in the range 21 keV < E < 285 keV and ions in 12 channels in the range 37 keV < E < 3.2 MeV respectively [*Korth et al.*, 1992]. The

magnetic field data were provided by the AFGL fluxgate magnetometer [*Singer et al.*, 1992].

At 20-21 UT on March 12, 1991 CRRES was near the equatorial plane at 6.5 Re with an estimated magnetic field line projection between the Scandinavia and Great Britain. The local magnetic field and the EPAS energetic particle measurements for this event are presented in Figure 1. The arrows in the top panel indicate the onset

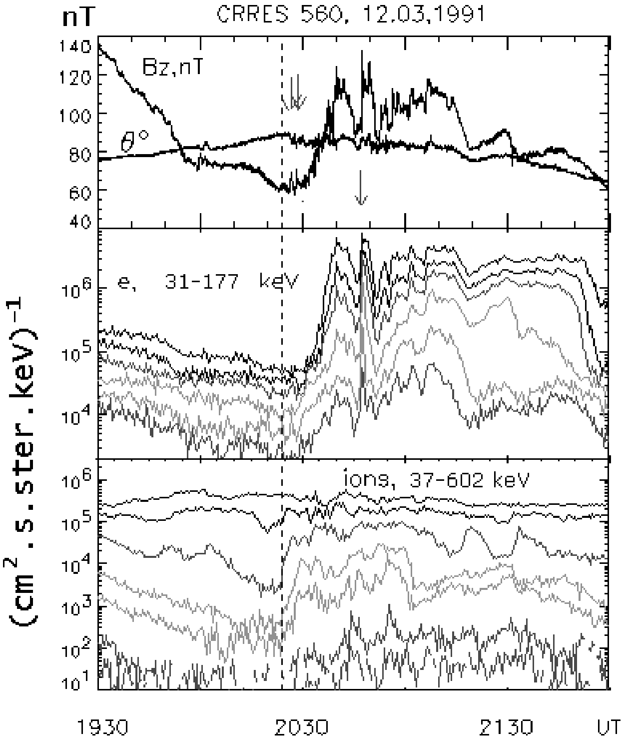

Figure 1. *Top panel: the magnetic field Z-component and inclination (same scale, degrees); middle panel: the energetic electron, channels/(energy, keV) from top to bottom: E2/(31-40) E3/(40-50), E4/(50-60), E9/(112-130) and E11/(151-177). Bottom panel: ion intensities, P1/(37-54), P2/(54-69), P4/(85-113), P6/(147-193), P7/(193-254), P9/(335-447), P10/(447-602) during the multiple onset substorm of March 12 1991.*

of the global substorm expansion phase, which took place 20° eastward of the CRRES footprint, and the beginning of the local substorm intensification.

The gradual increase in the energetic electrons began immediately after global substorm onset and an additional fast increase occurred during the local activation. In contrast, the energetic ion injection (dashed line) began before the substorm onset during the late growth phase and the flux increase was completed before the beginning of the electron increase. These observations suggest that the ion and electron injections are separate and different events. In this paper we concentrate on the behavior of the electrons and defer a discussion of the ion dynamics to a later paper.

The upper panel of Figure 2 shows an extended view of the magnetic field transformation which can be described as several dipolarizations with different increments and durations; shorter dipolarizations are inserted into a longer one. The energetic electron flux displays similar trends. Fast increases occur when the localized activation was close to the satellite while the gradual trends are the result of the integrated large scale dipolarization of the substorm expansion phase. (The

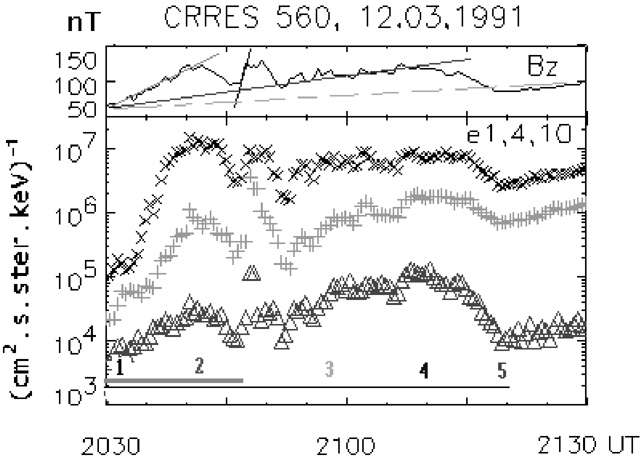

Figure 2. *The magnetic field z-component (top panel), and the energetic electron flux (bottom panel) from 2030UT to 2130 UT. The following electron energy channels/(energy, keV) are shown from top to bottom: E1/(21-31), E4/(50-60),E10/(130-150)*

energetic ions are not magnetized and peak to peak correlation with magnetic field is not observed). Fast localized and gradual electron increases are the two main constituents of the electron dynamics during this substorm. Therefore it is interesting to examine these processes in further detail.

2.1 Auroral electron injection.

The temporal evolution of the electron spectra in medium and low energy regions observed between 2030 and 2040 UT are shown in Figure 3 and Figure 4 respectively. The UT times of

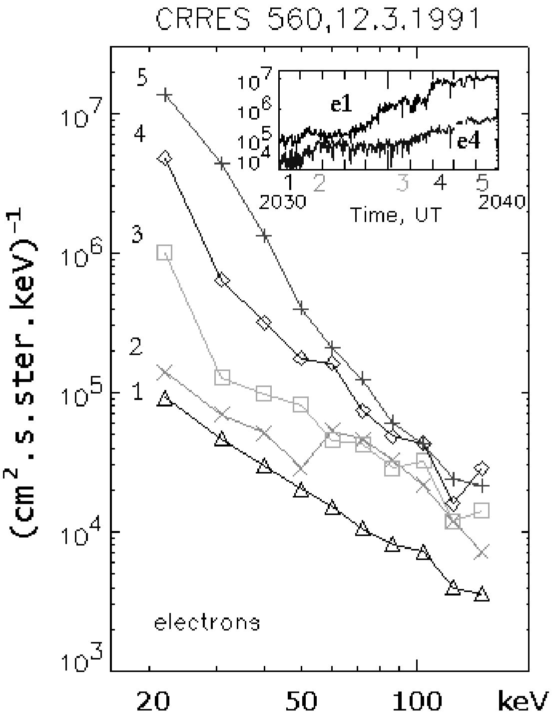

***Figure 3**. EPAS electron energy spectra during the gradual magnetic field dipolarization after the substorm onset. The spectra correspond to the times labelled in the inset panel, where the E1 (21-31 keV) and E4 (50-60 keV) fluxes in $(cm^2.s.ster.keV)^{-1}$ are shown.*

the recording of the five spectra are shown in the inset panel in Figure 3. Before the dipolarization (black trace) two particle populations are present: "old" trapped radiation belt

Particles and plasmasheet electrons with a typical for CPS 1-3 keV average energy [*Weiss et al.*, 1992]. After 6-10 minutes the third population emerges: auroral electrons. The progressive energization of the plasmasheet electrons can be seen in Figure 4 and the resulting increase and softening of the energetic electrons can be seen in Figure 3.

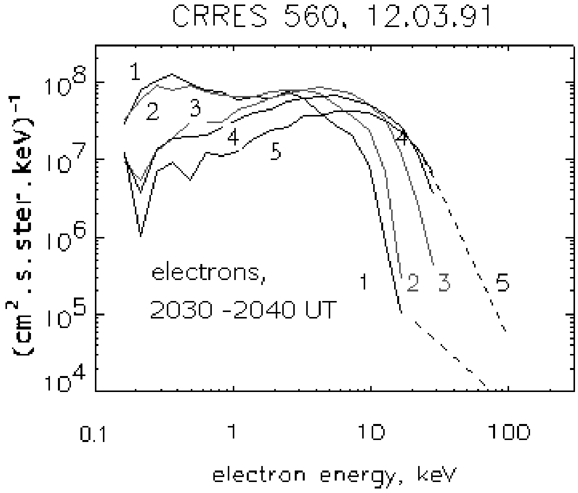

Figure 4. *LEPA electron energy spectra measured at the same times as in Figure 3. The dotted lines indicate the energetic tail measured by EPAS.*

Such well known process as a betatron acceleration can be regarded as the explanation. We will present some details in a discussion section.

2.2 Low and high energy electrons during the local substorm activation

One of the substorm intensifications at 2045-2049 UT took place near the CRRES longitudes and can be studied in further detail. This intensification was described at length by Kozelova et al.[2004] as a third step of the westward substorm expansion. We will not repeat here all the details, for us it is important that it was a substorm activation near the CRRES with short and fast dipolarization and particle enhancement.

The behaviour of the auroral electrons are different in the 0.1-1 keV and 20-100 keV range. The auroral electron pitch-angle distributions during the onset of CRRES intensification are shown in Figure 5. The upper six lines correspond to 0.16 - 1 keV and the bottom five lines to 16 - 30 keV electrons. The first arrival of the field aligned electron flux was registered at 2045:20 - 2047:00 UT and after interruption at 2048:45-2049 UT. Exactly during interruption a high-energy electron burst and a magnetic field dipolarization were registered.

Some of the electron pitch angle distributions (PADs) shown in Figure 5 display symmetric up-going and down-going field-aligned electrons so that the summary FAC will be close to zero. In other distributions field-aligned fluxes are asymmetric and may be regarded as an indication of the substorm current wedge development.
The auroral electron energy spectrum transformation during the local substorm activation differs from the gradual adiabatic

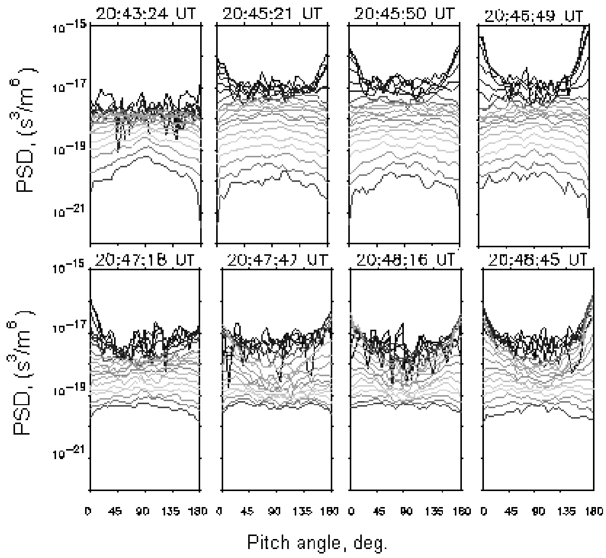

Figure 5. *Auroral electron pitch-angle distributions during the onset of CRRES local intensification. Upper seven lines correspond to 0.16 - 1 keV and bottom three lines to 16 - 30 keV electrons.*

acceleration by the preferential acceleration of the electrons in 50-100keV energy ranges As seen from the comparison of Figure 6 with Figure 3.
It was shown by *Pellinen and Heikilla* [1998] by simple model of the induced acceleration in restricted spatially current meander that the resulting acceleration is strongly related on the electron entry point and energy. This can explain the observed shape of the electron energy spectrum.

3. Discussion

There are two basic processes which can explain the relation between the gradual change of the magnetic field and the particle flux described above. The first process is a radial shift of the magnetic drift shells, earthward during growth phase and tailward during dipolarization. The resulting decrease and increase of the particle flux recorded by the satellite detectors are caused by the radial gradient of the particle distribution. The energy of the individual particles does not change during this process.
The second process is a betatron acceleration. The perpendicular component of individual particle energy is changing proportional to the change of the magnetic field intensity from the starting to the final point of particle trajectory, $W1/W2 = B1/B2$. From 2032 to 2037 UT the particle energy increased by factor of 2 (Figure 4) while Bz at the CRRES position changed from 65 to 110 nT. To receive necessary B1/B2 ratio one can take into account the existence of the cross-tail electric field and electron ExB drift from 55 nT level, which is about 0.5 Re tailward from the CRRES. Therefore, in this injection event, electrons are injected, but from a short distance and injection plays a minor role compared to local betatron acceleration.
If the dipolarization region is small, only low energy particles will stay there all the time, while high energy particles will drift through unaffected by the betatron acceleration and their flux increase will be controlled only by drift shell motion. With the recovery of the magnetic field the measured particle flux will return to the previous value.

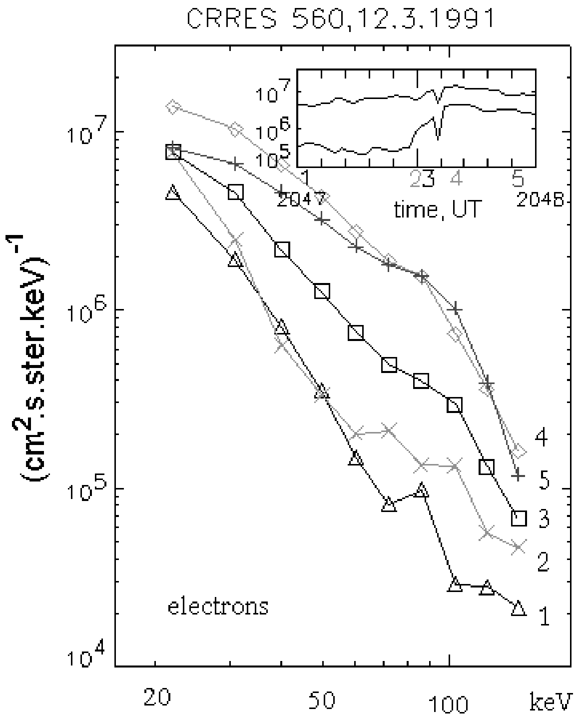

Figure 6. *EPAS electron energy spectra during the local activation. The spectra correspond to the times labelled in the inset panel, where the E1(21-31 keV) and E4(50-60 keV) fluxes in (cm^2.s.ster.keV)$^{-1}$ are plotted.*

Betatron deceleration also will reduce electron flux with the magnetic field decrease, but the acceleration effect will not be compensated because some accelerated particles will drift out of the deceleration region and also acceleration due to the combined ExB and magnetic drift will remain.

There are two intervals of the magnetic field decrease as shown by the Figure 2, the first after 2030-2040 UT trend and the second after the long trend 2030-2110 UT where we can examine effect of flux recovery and the relative importance of these two processes. Figure 7 shows the electron flux versus Bz for the long trend, small and large signs corresponds to the increasing and decreasing magnetic field intervals.

Although the electron flux is decreasing in all energy channels with Bz decrease, the positive acceleration effect is obvious at the energies up to 90 keV, while in high energies total recovery was registered, suggesting that drift shell radial displacement is the main effect for high energy electrons. For the short trend at 2030-2040 UT the effect was the same - high energy flux plots has no hysteresis while low energy ones reveal net flux increase after deceleration, although not so large as during the long trend.

We can therefore conclude that the observed electron flux increase during the substorm is a mixture of recoverable drift shell motion and true particle acceleration. The bigger the electron energy the smaller is the net acceleration. But if substorm activations follow each other in a short time, which is not a rare occasion, then the upper limit of the energy of accelerated electrons might be as large as hundreds of keV and more.

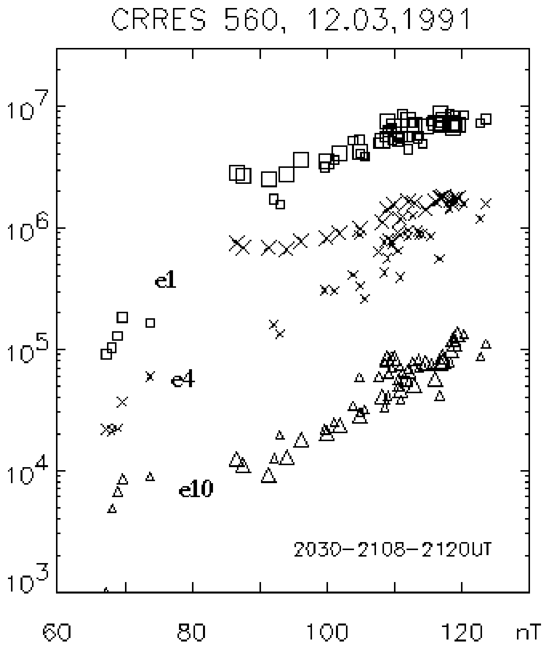

Figure 7. The electron flux versus Bz from 2030 to 2120 UT. Small signs correspond to the interval of the flux increase, while the large ones correspond to last minutes when Bz and particle flux were temporarily decreasing. Energy channels the same as on Figure 2.

Another important remark must be made: the described process does not correspond to the accepted name "particle injection" and moreover "injection from the magnetotail". In-situ magnetic field dipolarization with small radial displacement is sufficient source for the auroral electron acceleration.

The picture of the particle dynamics during the local acceleration is not as clear as the global process accompanying magnetic field dipolarization. Field-aligned electron acceleration has been measured during substorms previously and was considered as an important part of the substorm onset. But it is for the first time that field-aligned electron events were registered exactly at the beginning of the activation and with some delay with energetic electron increase.

However, single point measurements are not sufficient for the understanding of the process, because geometry and fast dynamics of the activation is rather complicated. That we can conclude for example from the active auroral records. The geometry of the active region is very important. Simulation of the particle energization in the induction field during the substorm discussed by Pellinen and Heikilla, [1978] shows that during substorm transient magnetic changes typical traectories of low, middle and more energetic particles differ significantly. Also CRRES spin period allows to obtain PAD only with 30s resolution, which is comparable with the increment of the substorm instability.

We cannot for sure choose the acceleration mechanism because the induced field is not the only one possible source. For example, *Abel et al*, [2002] found that after field-aligned electron events often occurs pitch-angle scattering accompanied by electron acceleration, possibly due to wave-particle interactions. They suggest that this process provides hot plasmasheet particles from the ionosphere to the equatorial region.

4. Summary

We have used data from the CRRES satellite to study the particle dynamics in the inner magnetosphere associated with the multiple-onset substorm event of March 12 1991. Our main conclusions are as follows:

1. Ion and electron substorm injections have different origins. The electron increase closely correlated with magnetic field dipolarization, whereas the energetic proton increase started about 2 minutes before the onset and before the magnetic field dipolarization.

2. The increase in the auroral electron flux during the substorm expansion, known as an injection, is a composition of field-aligned, inductive and betatron acceleration and magnetic drift shell radial displacement. The latter prevails for the high energy electrons, the pure acceleration effects for the soft particles, and a combination of betatron acceleration and drift shell displacement for the middle-energy auroral electrons. We were able to trace transformation of the central plasmasheet 0.1-1 keV electrons into 10 - 50 keV auroral electrons which creates most of known precipitation effects and supplies the radiation belts with fresh particle flux.

3. We investigated the fine structure of the local onset in the vicinity of the CRRES at 2046-2048UT. For the first time we show that keV field-aligned electrons (and upward current) arrived in front of energetic electron increase and dipolarization. The transformation of energy spectrum of the middle-energy electrons differs from the accelerated by betatron mechanism and suggest induced electric field or other types of acceleration.

4. In this event both ion and electron substorm injections are the result of local acceleration in the quasi-trapping region without transport from the magnetotail region. Several steps can be assumed in this case, with the ionosphere as one of the initial source of low energy inner plasmasheet population later transformed into auroral and trapped radiation.

Further studies will be undertaken to see if the results of this study are true in more general terms.

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