Highest Fluxes of Suprathermal Electrons; Cluster Observations in the Earth Magnetotail

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Abstract

Acceleration of electrons to suprathermal energies can be seen in many circumstances, but Earths magnetotail allows the possibility to observe such phenomena directly. Special cases have been studied, and possible mechanisms have been suggested by numerical simulations, but thus far no statistical study of observations have been made to determine what mechanism is the most efficient.

Here an algorithm to extract the events with the highest electron fluxes for different energy channels and spatial regions is devised to analyze the extensive magnetotail observations performed by the Cluster spacecrafts.

It is seen that many of the events found by the analysis are characteristic dipolarisation events, i.e. that the electrons are accelerated by magnetic reconnection in the magnetotail, but also that there are many events that does not share that same characteristic.

1 Introduction

One topic of high importance is the acceleration of electrons to suprathermal energies, energies much larger than the local thermal energy, in the Earth magnetotail. X-ray emissions from such suprathermal electrons can be seen elsewhere, for example in the Suns corona, but the Earth magnetotail is significant because its close proximity allows in situ observations. The occurrences in the magnetotail are believed to be created by magnetic reconnection and related physical processes.

There have been detailed studies of specific events and numerical simulations have suggested different possible acceleration mechanisms, but so far no statistical study of observations have resolved which mechanism is the most efficient. The aim of this project is to devise a program that runs through electron energy observations to isolate and compile the largest viable cases of high energy fluxes. Data for this is provided by Cluster, four spacecraft orbiting the Earth in formation, that has been observing the magnetotail in the changing conditions of more than a decade, thus providing plenty of data for a statistical analysis.

1.1 Cluster

The Cluster mission consists of four spacecraft moving in a tetrahedron formation in orbit around the Earth, investigating Earth's magnetic environment and its interaction with the solar wind in three dimensions. The four spacecraft are depicted in fig. (1).

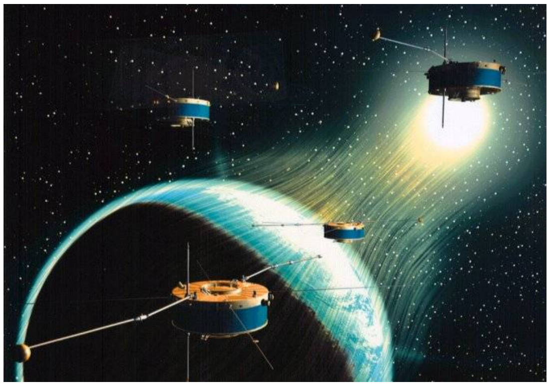

Figure 1: Artists impression of the four Cluster spacecraft in tetrahedron formation above the Earth. Image source [3].

Cluster is a European Space Agency mission launched in the summer of 2000. The simultaneous measurements from four identical spacecraft in formation makes it possible to distinguish spatial variations from temporal evolution, allowing the most detailed three dimensional data on the small-scale structure of the near Earth environment. The Cluster formation moves around the Earth in an elliptical polar orbit (see fig. (2)) with an orbital period of 57 hours, perigee 3 Earth radii and apogee 18.6 Earth radii. The orbit follows the Earth but its orientation is always the same with respect to the Sun, so the apogee will be in the tail on the opposite side of the Sun in autumn, and in closest to the Sun in spring, moving through the solar wind.

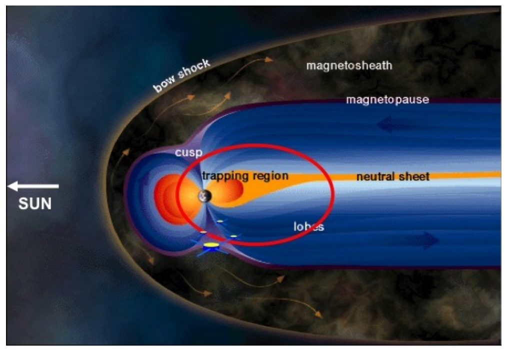

Figure 2: Earth's magnetosphere immersed in the solar wind, with Cluster's orbit marked in red. Image source [4].

Fig. (3) shows some of the instruments on Cluster. The most relevant instrument for this project is RAPID, Research with Adaptive Particle Imaging Detectors. RAPID measures the flux of energetic electrons above 30 keV, that is, electrons in the higher energy range. It has many detectors that measure the flux from certain angle intervals, thus measuring how the flux varies in three dimensions. The flux is also divided over several energy ranges, giving values for the flux in different energy intervals. Other instruments are PEACE, that measures the electron flux for lower energies, CIS which measures the ion flux as well as ion velocity, and FGM that measures the components of the magnetic field.

1.2 Suprathermal Electrons

The occurrence of suprathermal electrons in this context means that the normalized velocity distribution of the electrons detected in some region at some time has much higher densities than what is found in the "fast-tail" of an ordinary Maxwell-Boltzmann distribution. This means that the electrons are significantly accelerated by some other mechanism than the brief elastic electromagnetic "collisions" between electrons.

1.3 Magnetic Reconnection

One property of low density space plasma, that arise when a magnetic field through the plasma varies over much larger distances than the Larmor radius

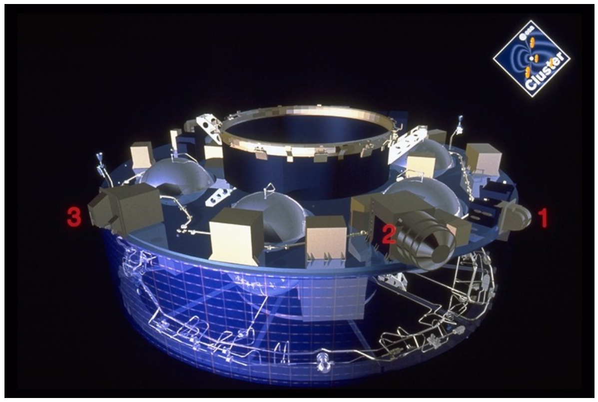

Figure 3: Cutaway of Cluster spacecraft main equipment platform, showing the PEACE (1), CIS (2) and RAPID (3) instruments. Image source [5].

(the radius with which a moving particle rotate in a constant magnetic field), is that the magnetic field lines are "frozen" into the plasma and follow the motion of the plasma.

When two frozen magnetic fields end up parallel to each other but in opposite directions as in fig. (4.a), and the magnetic energy density increases, a diffusion region might form where the magnetic field lines unfreeze and reconnect as in fig. (4.b). When this happens the magnetic energy density decrease and the energy in transfered to the plasma particles that gain kinetic energy and carries the newly reconnected magnetic field lines away in jets to the left and right.

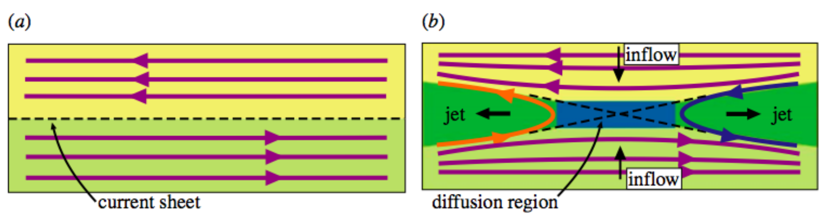

Figure 4: (a) A current sheet directed out of the picture is formed when two oppositely directed frozen in magnetic field lines end up close to each other. (b) When reconnection starts, plasma moves in from the top and the bottom, the fields unfreeze and reconnect in a new configuration with lower magnetic energy density. That same energy is transfered to the plasma as kinetic energy in the jets that move out to the left and right carrying the new frozen-in field configuration with them. Image from [2].

1.4 Magnetotail

In absence of the Sun, the Earth's magnetic field would have roughly the shape of an electric dipole but the plasma in the Sun's solar wind carries a frozen-in magnetic field with it, and in particular when the field direction of the wind is directed to ecliptic south, that is, opposite the direction of the Sunward side of the Earth magnetic field, the two fields will form a magnetopause as seen in fig. (5). In the magnetopause magnetic reconnection will occur, forming open field lines that are folded around the Earth's magnetic field by the solar wind, extending Earth's field away from the Sun and forming a magnetic tail region, the magnetotail. Here there will be regions of near parallel and oppositely directed field lines where magnetic reconnection occurs.

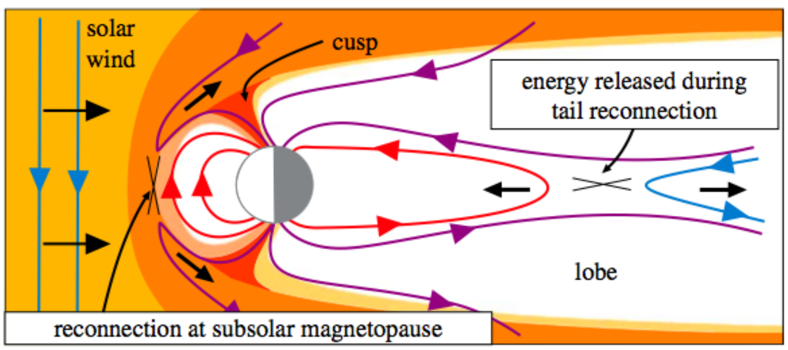

Figure 5: Then the magnetic field of the solar wind and Earth's sunward magnetic field are oppositely directed, magnetic reconnection occurs, and the now open field lines are pushed back, forming the magnetotail. When the field strength in the tail builds up, reconnection releases the energy.

2 Data Analysis

The RAPID-instrument provides measurements of electron flux in the higher energy ranges, and we are going to look at the data set ESPCT6 which contains electron flux(summed over all incoming directions) for each energy channel. To investigate the occurrences of suprathermal electrons, we want to divide the magnetotail into different regions, and for each region create toplists of the ten highest fluxes, one list for each channel we look at. When finally these toplists have been finished, we want to create a plot for each event on those lists, including magnetic field components, ion velocities, ion flux, and electron flux from both RAPID and PEACE, all plotted for ten minutes before and after the listed event.

The finished matlab code is available at [6].

2.1 Data Selection

Electron flux data is available between the years 2001 and 2011, and is thus the time period to be considered. Data from all four Cluster spacecraft is used for the analysis.

When the electrons are detected, the exact energies aren't measured, instead they are grouped into different energy intervals, or channels. This study is limited to RAPID channels 3, 4, 5, i.e. the interval 68.1 keV to 244.1 keV. Details in table (1).

Table 1: Some of the RAPID energy channels, where the energy values are the lowest thresholds for that channel and given in keV.

channel	energy
3	68.1
4	94.5
5	127.5
6	244.1

The regions to be considered was decided to be constrained on the Geocentric Solar Ecliptic(GSE) x-axis only. The GSE coordinate system has its origin at the Earth with the x-axis pointing toward the Sun and the z-axis points toward ecliptic north. In these coordinates the negative x-axis is always behind the Earth with respect to the Sun, and thus inside the magnetotail. Twelve subsequent regions were chosen; $-8 > x \geq -9$ to $-19 > x \geq -20$ with x measured in Earth radii.

To avoid each list being crowded by the same event but a few seconds apart, it was decided that two data points have to be separated by at least eight minutes.

In our final plots there will be data from five different data sets, but data is not available at all times in all data sets. The analysis works with the RAPID data, but for an event to be included it was decided that there has to be magnetic field data available at that time. No criteria is imposed on the other three data sets.

In the RAPID data, false flux peaks can occur, usually in conjunction with gaps in the data, where some can be attributed to activation and deactivation of the instrument. To filter out these, a valid data point have to have the closest data points on either side no more than a certain time apart, chosen to be about three times the ordinary time separation between points, and the two closest data points on either side is not allowed to have Not-a-Number values.

2.2 Algorithm Structure

The algorithm takes one year and one spacecraft at a time and does as follows. The data set containing spacecraft coordinates for that time interval is loaded, and and the program runs through it and makes a list where each contains the time of entry, the time of exit, and the region concerned.

In the part of the year when the spacecraft orbit intersects the relevant regions at all, passage through the of relevant regions will alternate with passage outside the those regions when the spacecraft is near perigee. Since the RAPID data-sets are loaded in blocks of about a day at a time, it is good for efficiency to load electron flux and magnetic field data for all the relevant regions once per orbit, and then pick out the part pertaining to a particular region when that one is to be analyzed further. For each region, one energy channel is treated at a time.

The code is design to move forward sequentially in time and update the toplist as it goes along. However, the criteria that an entry has to be separated to the others by at least eight minutes complicates this a little. Say, for example, that we move through the data points forwards in time and we know that there are not any potential points within eight minutes before the current one. We then encounter a data point that is larger than the smallest entry currently on the list, and if it is not filtered out as a false peak, and it has a magnetic field data point at a time within the set limit, we have a valid data point. We now have to check all points within eight minutes after this point, and if the first one was the largest one, we can add it to the list. On the other hand, if there are one or more valid data points larger than the lowest one currently on the list ahead of the first one, we have to step up to the largest one, and then look ahead if there is are any points larger than that one within eight minutes later. This have to continue in steps until we have a largest data point with respect to all points within eight minutes ahead and before, and we can add it to the list. Problem is, we may very well have passed several points on the way that may yet qualify for the updated top list. So we start to move backwards from the highest point, doing the same checks and possible updates to the list, until we reach the first data point that triggered this process. Then we can jump forward and continue from eight minutes after the highest point we found.

The dependence on surrounding data points that caused the need to move forward and backward as described above does complicate things when the data from another spacecraft is to be treated. This is solved by going though the toplist, and in case there are any entries that lie within the time interval about to be analyzed, they are removed from the list and inserted at the right time among the new data. This way the comparisons will be correct.

3 Results and Discussion

Looking through the 360 plots produced, one can see that hardly any obvious false peaks have survived, and that the RAPID results generally look valid. Magnetic field plots are indeed available at the time of the events in all plots. PEACE data is present in almost all plots. Ion velocity and ion flux is unfortunately lacking in quite a few plots. Not surprisingly, the same events seems to appear in the plots of more than one energy channel, though not necessarily at exactly the same time.

It is most likely that there are more efficient ways to construct the algorithm, but as written it does seem to do what it is supposed to do well enough.

A full analysis of the physical meaning of the results is beyond the scope of this project, but here we will take a look at a few examples. Figs. (6), (7), and (8) all share the same typical characteristics of a dipolarization. Around the time of the event, the plot of the magnetic field components in the the top panel of each graph show that the x-component decreases in absolute value while the z-component increases to a larger value. Imagine the observing spacecraft between the Earth and the reconnection region in fig. (5). The spacecraft changes its spatial location much slower than a change in the magnetic field structure, and can thus be seen as practically fixed in relation to the fields. Before a reconnection event the magnetic fields in the magnetotail are close to parallel with the x-axis, with small components in the other directions. After reconnection the plasma jet will move the closed field lines toward the Earth, which obtains a more dipole-like structure, with a larger z-component at the location of the spacecraft. Looking though the plots reveals that variations on these plots are quite abundant. Fig. (9) on the other hand, is an example of an event that doesn't have the dipolarization features, in this case rather the opposite since the z-component decreases at the event.

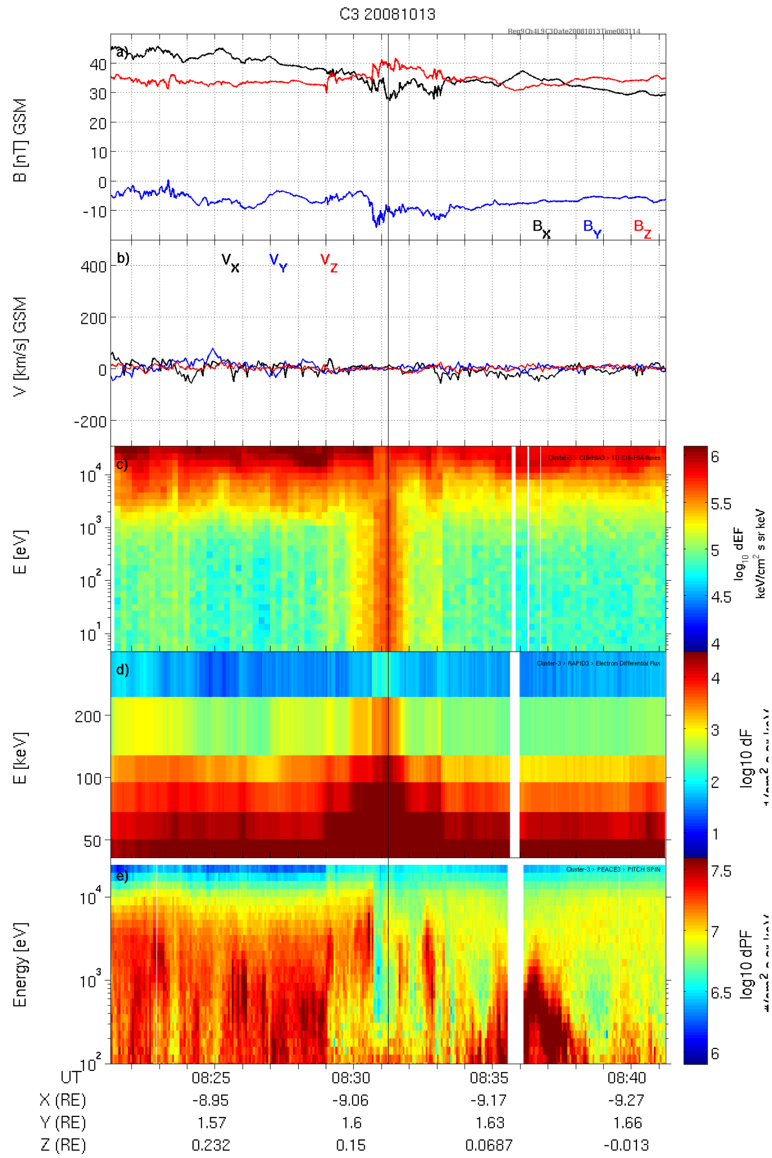

Figure 6: Second highest event for energy channel 3 in $-9 > x \geq -10 R_E$ in GSE, observed on the 13th of October 2008 at the time 083114.

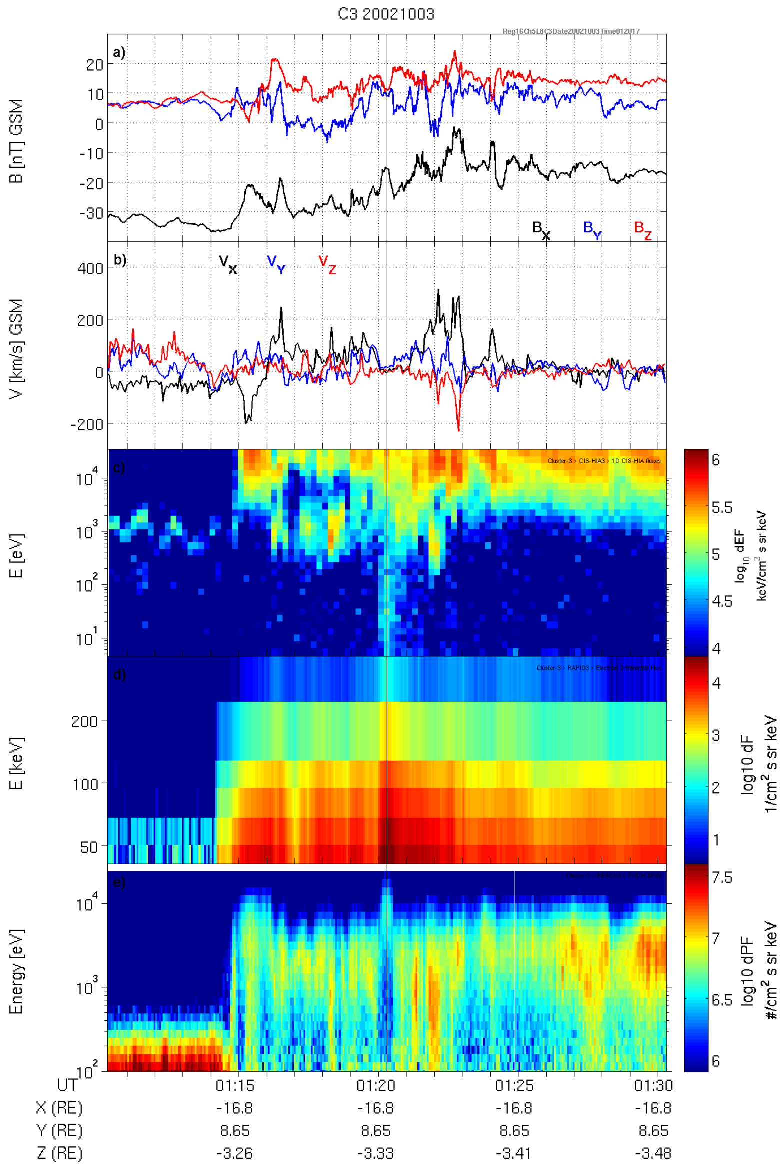

Figure 7: Third largest event for energy channel 5 in $-16 > x \geq -17 R_E$ in GSE, observed on the 3rd of October 2002 at the time 012017.

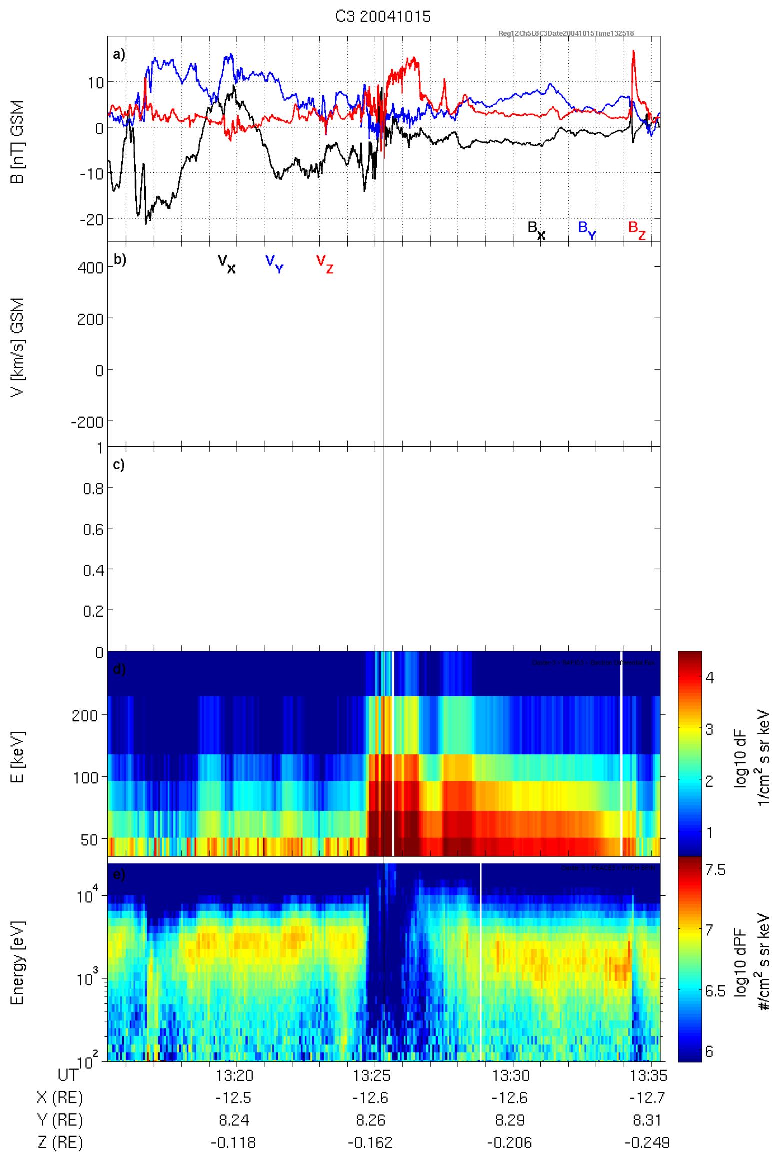

Figure 8: Third highest event for energy channel 3 in $-12 > x \geq -13R_E$ GSE, observed on the 15th of October 2004 at the time 132518.

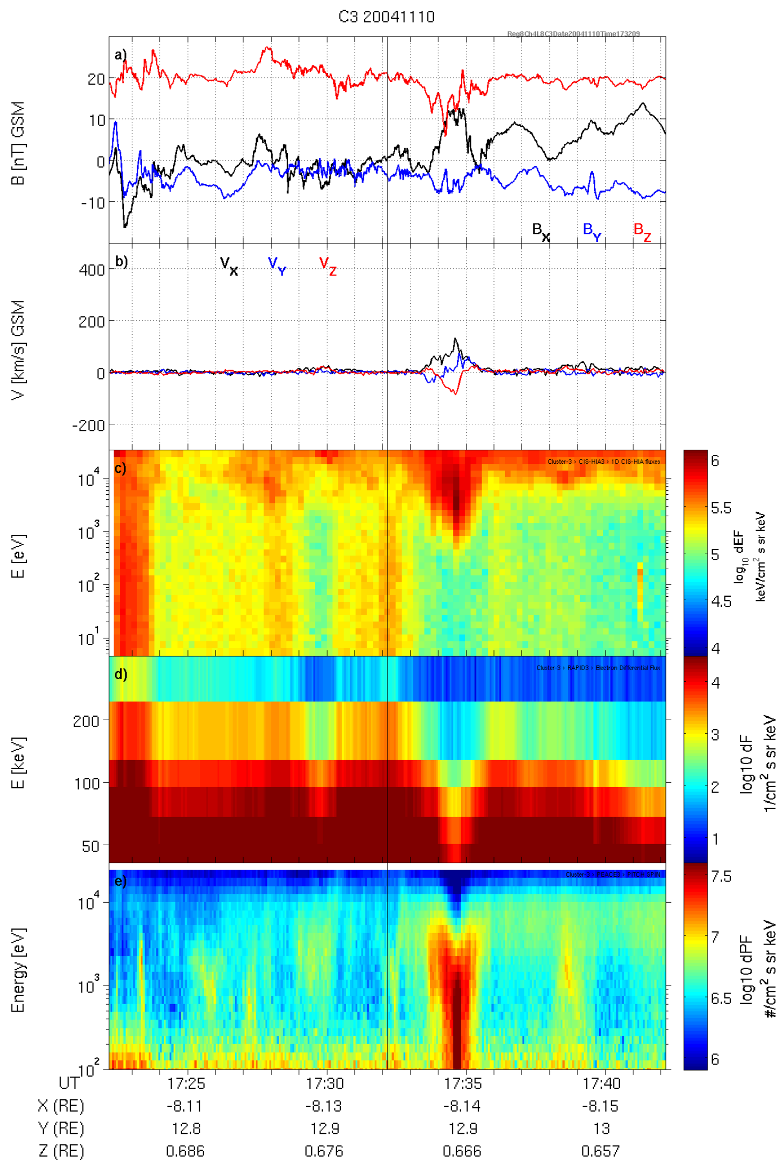

Figure 9: Third highest event for energy channel 4 in $-8 > x \geq -9R_E$ GSE, observed on the 10th of November 2004 at the time 173209.

References

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[6] Matlab code produced for this project,
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