The active plasma sheet: definition of ’events’ and statistical analysis

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Abstract: A statistical analysis of the plasma sheet activity is performed from CLUSTER observations (years 2001 to 2004). Different types of ’events’ are defined by using the plasma flow velocity (V-events), the low frequency magnetic fluctuations (B-events), and the spectral density of higher frequency waves (HF-events). They are selected by an automatic procedure from 2 criteria: a lower threshold for the fluctuations and a minimal duration for each events. The V-events correspond to the usual ’BBF’. The three types of ’events’ form an homogenous set, their number (20 to 50 for each Cluster ’tail’ season, depending on the selection criteria) and their total duration (5-10% of the time spent by CLUSTER in the sheet) being comparable. ’Events’ of different types are positively correlated with percentages of common detection reaching 50%. They are also organized in bunches that characterize local active states in the plasma sheet. However, these active states do not present a one-to-one relationship with substorms or auroral activations. Analysing how the number of ’events’ varies with the selection criteria, it is concluded that the B-events saturate at 2-4 nT and have a rather long duration (more than 1-2 minutes) when HF-events are more likely bursty and intense since their number significantly increases for duration smaller than 1 minute. In average, B-events and HF-events begin before V-events. We cannot conclude on a cause-to-effect relationship between ’events’, nevertheless, the study shows that the three types of ’events’ are likely related to the same basic physical phenomena. They could be fundamental elements of the plasma sheet turbulence.

1. Introduction

A significant feature of the Earth’s plasma sheet is the presence of large fluctuations in the magnetic field, in the flow velocity and, in the spectral density of high frequency waves, with timescales ranging from seconds to minutes. This defines a ’turbulence’ that characterizes the ’active’ plasma sheet. Its description and the analysis of its relationships with heating and acceleration processes are of paramount importance for understanding the magnetospheric activity in general, and more specifically the magnetospheric ’substorms’ and their consequences.

The investigation of the plasma sheet turbulence is a vast program. One may concentrate on the analysis of field fluctuations, as it was done using the Geotail and AMPTE/IRM spacecraft by ([11], [8], [7], [4], [5]) and, more recently CLUSTER ([15], [12], [10], [16]). The main objective of these studies is to compare models of the turbulence (intermittency or multi-fractals) and various generation mechanisms of the fluctuations with the observations. Fluctuations in the flow velocity - the bursty bulk flows (BBF) - are other manifestations of ’activity’. They have been studied into details given their possible associations with sporadic magnetic dissipations and their role in the plasma convection (for example: [3], [1], [14]).

These studies demonstrate that the plasma sheet ’activity’ is a multi-form phenomena. As seen locally by a spacecraft, the plasma sheet is not in a permanent ’turbulent’ state for hours. ’Calm’ and ’active’ periods alternate, the durations of active periods ranging from a few minutes to a few 10 minutes. Furthermore, as discussed in the present paper, active periods are often a succession of ’events’ lasting a few 10 s or minutes during which the fluctuations of a given parameter are particularly large. If the active periods corresponds to global energy releases in the plasma sheet then the ’events’ would be the fundamental elements that organize the energetic processes. In many respects, BBF’s are archetypical ’events’ defined from the flow velocity. The notion of ’events’ can also be extended to other physical quantities (magnetic fluctuations, high frequency waves, temperature, pressure...) which will modify the definition of ’activity’. It is then interesting to study the ’activity’ resulting from the choice of different kinds of ’events’, to make the statistical analysis of their occurrence and, to investigate their possible relationships. Surprisingly, this was rarely made in a systematic way.

For the present investigation, we define ’events’ from 4 parameters: (1) the flow velocity (which corresponds to BBF), (2) the amplitude of the low frequency magnetic fluctuations, (3) the spectral density of ’high frequency’ waves (1-10 Hz) and, (4) the thickness of the sheet. This corresponds to 4 different classes of ’events’. We then make statistics on the resulting sets of ’events’: How often are they observed? What is their cumulative duration? What does it mean in terms of proportion of time spent by spacecraft in the plasma sheet? The study of their correlations is also interesting. Do they occur together? Are there classes of ’events’ that statistically occur before other, so that a cause-to-effect relationship could be established between them? In particular, we will investigate the relationship between BBF’s and ’events’ defined from magnetic fluctuations and waves.

The selection of ’events’ is hard from the simple visual inspection of the data. The visual method introduces subjectivity and restricts the analysis to a limited number of criteria for the selection. To solve this methodological difficulty, we use the facilities given by the CDPP (Centre de Données de la Physique des Plasmas, a plasma physics data centre result-

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ing from a French national program) to investigate CLUSTER data. We consider a large data set corresponding to CLUSTER 'tail' seasons, from 2001 to 2004. Each of them lasts ∼3 months and corresponds to orbits with apogee in the magnetotail. We further choose crossings at -10 Re< Y_{gsm} <10 Re. The measurements are performed by 3 different instruments (FGM [2], CIS [13] and STAFF [6]) on the 4 CLUSTER spacecraft.

2. Data and Methods

To illustrate the selection of 'events', the measurements performed during a long crossing of the plasma sheet, with a succession of 'active' and 'calm' periods are presented in Figure 1 (14-15th September 2001, from 2245 UT to 0630 UT). We show the B_x magnetic field measured by the 4 spacecraft (panel 1, from the top), the V_x component of the plasma flow measured by SC1 and 3 (panel 3) and, the spectral density of the magnetic fluctuations in the range 1-10 Hz (panel 5). GSM coordinates are used. From the 4 spacecraft measurements, we compute the magnetic field gradient. We then deduce the typical thickness of the sheet as the ratio between the magnetic field in the lobe - assuming pressure balance - and the magnetic gradient.

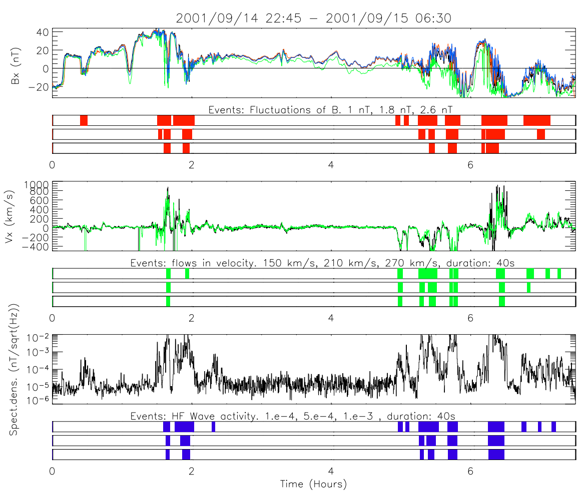

Fig. 1. Example of plasma sheet crossing and selection of events. From top to bottom (panel 1 to 6), B_x magnetic component and selected B-events, V_x flow and selected V-events, high frequency spectral density and HF-events.

Multiple signs of 'activity' are observed in Figure 1: (1) large magnetic fluctuations with periods ranging from a few seconds to several minutes, (2) flows with positive and negative V_x larger than 100 km/s and, (3) time intervals corresponding to large spectral density of waves. These manifestations of 'activity' are also associated with variations of the total pressure, of the thickness, and the current of the sheet (not shown here). The observation of this strong activity is not surprising since two substorms or auroral activations have occurred during this time period, at 2353 UT on day 14/09 (t 1:10, in the Figure) and 0412 UT on day 15/09 (t 5:30) ([9], from IMAGE data). The last case is related to the most active time period.

Using colour bars, we also indicate the selected 'events'. From the amplitude of the low frequency magnetic fluctuations we define 'B-events' (red bars in panel 2), from the plasma flows we define 'V-events' (green bars in panel 4), and from the wave spectral density 'HF-events' (blue bars in panel 6). An 'event' can be defined by two parameters. It corresponds to a time interval of minimal duration (Ta) during which a given parameter - indicated by the subscript 'a' - is larger than a threshold (Sa). For example, by considering Sv=100 km/s and Tv=60 s, we can select 'V-events' as time intervals longer than 60 s during which the flow velocity is permanently larger than 100 km/s. The definition of 'B-events' is more complex. As seen in Figure 1, discrete and variable frequencies seem to dominate the low frequency magnetic fluctuations for given time intervals. This type of signal is better analysed by a wavelet than a Fourier transform. We thus perform a wavelet analysis of the magnetic field and then take into account 3 parameters for defining 'B-events': a threshold for the amplitude of the fluctuations (Sb), a minimal duration for the 'events' (Tb) and a upper value for the periods of the fluctuations (Pb). A 'B-events' is thus a time intervals of minimal duration Tb during which wavelet-like fluctuations with periods smaller than Pb reach amplitude larger than Sb. We choose Pb=30 s for the present study. Of course, this choice must be consistent with the minimal duration of the B-events: Pb must be smaller than Tb. Given their respective frequency ranges and the polarisation, B-events rather correspond to MHD compressional fluctuations when HF-events take into account fluctuations close to the ion gyrofrequency. They are thus related to different types of plasma/wave interactions.

The 'events' shown in Figure 1 have been selected with Ta=40s. We use different thresholds: 1.0, 1.8 and 2.6 nT for the magnetic fluctuations, 150, 210 and 270 km/s for the flows, 0.1, 0.5 and 1 pT/Hz$^{1/2}$ for the spectral density. The selection is made by considering the maximum values seen by any of the 4 spacecraft. For 'V-events', we also impose that the magnetic/total pressure ratio is smaller that 0.5. 'V-events' actually correspond to flows in the central plasma sheet and are equivalent to BBF's.

A detailed analysis of Figure 1 reveals that the procedure adequately selects 'events' from the different data sets. Given the apparent simplicity of the variations of the wave spectral density and of the flow velocity, the identification of 'HF-events' and 'V-events' seem straightforward, the latter clearly corresponding to BBF's. Conversely, the selection of 'B-events' would be impossible from a simple visual inspection. It is interesting to note how accurate is the procedure based on the wavelet analysis. A careful inspection of the period 5:00-6:30 shows that 'B-events' actually correspond to precise time intervals during which, intuitively, the dominant component of the fluctuations has changed in amplitude or period so that fluctuations with periods smaller than 30 s become large.

The procedure of selection leads to comparable sets of 'events'. This concerns the number of events, their individual as well as their total duration. This important point will be more discussed in next sections. It is not as natural as it could look like and indicate that the different type of 'events' are likely related to the same basic physical phenomena.

3. Application to complete 'tail' season

Figure 2 is a general view of 'events' selected during several crossings of the plasma sheet. We consider here the 2002 tail season. The crossings are organized by frames corresponding to 10 hours of observations. For reason of readability, seven over more than thirty recorded crossings are shown. The colour code is the same as in Figure 1 (red: 'B-events', green: 'V-events', blue: 'HF-events'). The minimal duration of events is 40s and the thresholds are: 1.5 nT, 150 km/s and 0.6 pT/Hz$^{1/2}$. The yellow bars indicate the periods during which at least one of the spacecraft measures a thermal/total pressure ratio larger than 0.5, which means that it is located in the internal part of the plasma sheet. By overlying the yellow bar by a dark blue one, we further indicate the periods of 'thin' plasma sheet, with a half thickness smaller than 0.45 Re. We choose examples of 'active' plasma sheet (21/08, 28/08, 18/09), cases with sparse detections of events (13/08,18/08), and examples of 'calm' plasma sheet (25/08, 13/09).

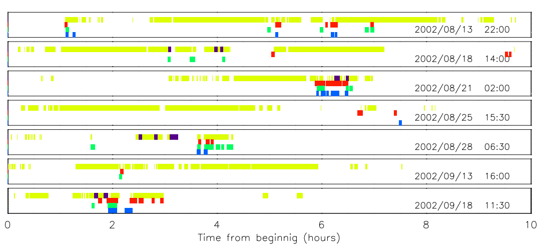

Fig. 2. Global view of selected events during 7 crossing of the plasma sheet. Yellow: presence of CLUSTER in the internal sheet, Red: B-events, Green: V-events and, Blue: HF-events.

As seen in Figure 2, the 'events' generally occur in bunches and present a rather clear positive correlation. This defines periods of 'activity' with typical duration of a few 10 minutes. Nevertheless, none of the periods of 'activity' shown here corresponds to a substorm onset listed by [9]. According to this list, auroral activations or substorms do occur at the days presented in the Figure, in particular on 21/08 or 18/09, by not while CLUSTER was in the plasma sheet. However, when CLUSTER is in the plasma sheet during a recorded substorm, we check that 'events' are actually detected. It is the case of the day 15/09/2001 shown in Figure 1, precisely when a strong activity is observed. Let us also note that there is no clear relationship between the observation of a thin plasma sheet and 'events'. On day 21/08, a thin plasma sheet is observed during the activity, on 18/09 and 28/08, a thin plasma sheet is observed well before the activity.

Table 1 summarizes the statistical study of the different types of 'events' selected during the 2001-2004 'tail' seasons as Cluster was at -10 Re< Y_{gsm} <10 Re. They are selected using the same thresholds as for Figure 2. The cumulated duration for each type of 'events' is indicated in hours. We also indicate the number of selected events('e' in parenthesis). We define common events (B/V, B/HF and V/HF), see next section. The cumulated duration of the common events and the corresponding proportion with respect to the total duration (% in parenthesis) are given.

Table 1. Statistics of events performed from 2001 to 2004. 'sheet' corresponds to magnetic/total pressure ratio smaller than 0.5, and 'thickness' to an observed sheet thinner than 0.45 Re. 'B', 'V', 'HF'... corresponds to the type of 'events'.

	2001	2002	2003	2004
sheet	59.93	59.5	40.72	36.7
thickness	3.45	1.02	1.06	0.71
V	3.34 (38e)	2.9 (35e)	1.72 (21e)	0.84 (13e)
HF	2.95 (37e)	2 (26e)	1.96 (30e)	2.62 (21e)
B	6.41 (57e)	3.27 (40e)	1.74 (18e)	1.54 (18e)
B/V	1.74 (26%)	0.7 (21%)	0.59 (34%)	0.59 (38%)
B/HF	2.3 (35%)	1.1 (34%)	0.55 (31%)	0.63 (41%)
V/HF	1.15 (18%)	0.7 (21%)	0.78 (45%)	0.5 (32%)

The total time spent by CLUSTER in the plasma sheet is ~60 hours in 2001 and 2002 and ~40 hours in 2003 and 2004. We interpret this difference by the fact that the spacecraft are closer each to the others in 2003 and 2004 which decreases the probability to have at least one of them in the sheet. In average, events are detected during ~3-5 % of the total time spent in the plasma sheet, meaning a cumulated duration of ~1.5-3 hours. The number of events varies from 13 (V-events in 2004) to 57 (B-events in 2001). One may consider that B-events are particularly frequent in 2001 and, conversely V-events are rare in 2004. In general, the plasma sheet seems to become less and less active from 2001 to 2004. Note also that the total time spent in a thin current sheet is more than three times longer during 2001 than during the other years. This certainly has to be related to a decrease of the solar activity from 2001.

The common time between different types of events (B/V, B/HF, V/HF) varies from 0.5 to 2 hours, which represent 20 to 35% of the total duration of the events. There are some exceptions (45% for V/HF events in 2003) that will deserve a more careful examination. All these percentages are larger than what would be expected from a random occurrence of the events. This confirms that events of different types generally do not occur independently and are thus likely related to the same underlying physical process.

4. Parametric study of the occurrence of 'events'

The use of an automatic procedure for the selection of 'events' has also the advantage to make easy modifications of their definition and their selection parameters. The contour plots shown in Figure 3 present the total duration of the events as a function of the thresholds (Sa) and of the minimal duration of each events (Ta). In addition of B,V and HF events, we consider 'thickness-events' corresponding to time intervals during which the plasma sheet is thinner than a given threshold. The values of the parameters of selection are chosen in such a way that the total duration of the events varies in the same range, from nearly 0 for severe constraints to typically 5-6 hours.

These plots help to understand how the different events are organized. Considering B-events, one may note that the contour levels are almost perpendicular to the axis representing

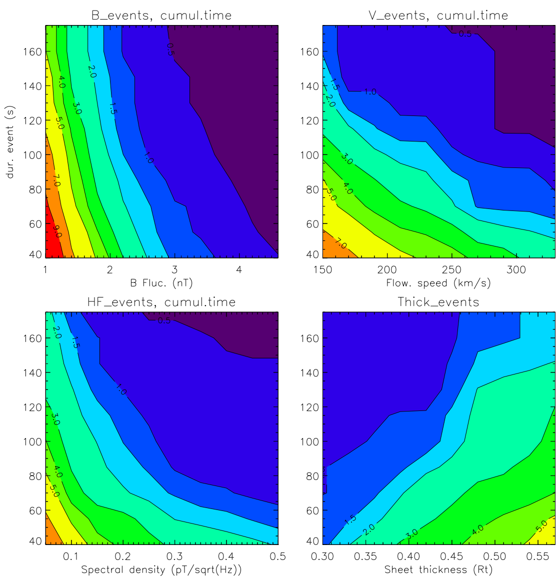

Fig. 3. Parametric study of the total duration of the events. Only 2001 events are considered. Both the minimal duration and the threshold vary.

the amplitude of fluctuations. The important parameter for the selection of B-events is thus the amplitude and not the minimal duration of the events. This means that B-events are rather organized in long time intervals with typical duration of a few minutes. The possible existence of a saturation effect is not excluded: when the thresholds is increased from 1.5 nT to 4 nT, the total duration of B-events decreases by almost one order of magnitude and becomes smaller than 0.5 hour. This demonstrates that the amplitude of the fluctuations with periods smaller than 30s hardly reaches 10-20% of the magnetic field in the lobes. HF-events show an interesting contrasted organisation. For events longer than ∼100 s, the amplitude is again the most efficient criteria of selection. Conversely, when short events are taken into account ($T < 80$s), the minimal duration becomes a strong criteria of selection. The total duration of HF-events decreases by a factor of ∼3 from T=40 s to T=80 s. HF-events thus tend to be organized in short intense bursts. V-events are equally well organized by their minimal duration or the threshold of velocity. Finally, let us note that the minimum duration is a rather efficient discriminating criteria for the selection of ’thickness-events’. This would mean that the thickness of the sheet significantly varies on short time intervals, with typical duration of 40-80 s. A more detailed analysis is needed to understand the causes and the consequences of this variability.

5. Association between events and possible cause-to-effect relationships

After studying separately the different types of ’events’, we now analyse their relationships. Three plots presenting the percentage of common B/V, B/HF and V/HF events are shown in Figure 4. To obtain these percentages, we consider the time intervals corresponding to events of a given type (B-events, for example) and we calculate how often events of another type (V-events or HF-events) are detected during the same time intervals. The results is then normalized to the total number of events.

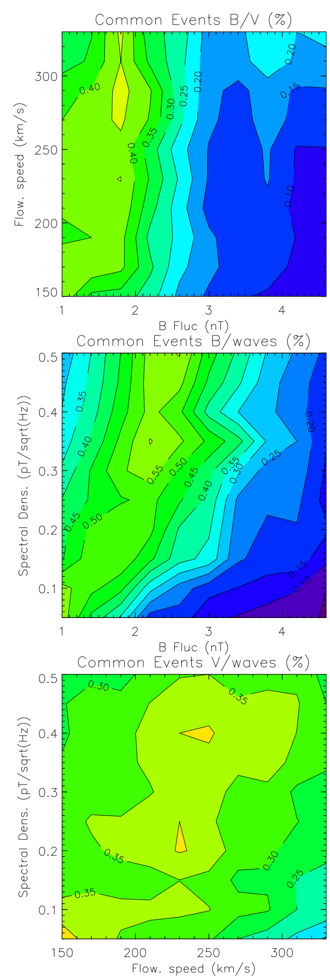

Fig. 4. Analysis of the commonality between the different types of events. It is expressed as the number of common events, normalized to the total number of events. Plot 1 to 3 from top to bottom

Considering B/V-events, the best correlation (∼50%) is obtained for fluctuations with amplitude 2 nT and flows above 250 km/s. The correlation between large fluctuations and slow flows (below 250 km/s) is negligible. However, this correlation seems to increase when larger flow velocities are considered (velocity larger than 300 km/s). It will be interesting to check if the correlation further increases when extreme V and B-events are considered. We note that B-events and HF-events are closely related: as the amplitude of the MHD fluctuations increases, the maximum correlation is obtained for larger spectral density of the high frequency waves. In some way, there is thus a relationship between the level of compressible MHD fluctuations (B-events) and the turbulence at kinetic scale (HF-events). The V/Wave correlation present a maximum for flow speeds in the 200-250 km/s range. One notes that the maximum correlation is obtained for higher spectral density as the flow speed increases. The sharp local maximum that appears on the plots are not significant.

In terms of possible cause-to-effect relationship, we conclude from plot 1 that, if we make the hypothesis that flows trigger magnetic fluctuations, then flows below 300 km/s cannot trigger magnetic fluctuation larger than 2-3 nT. In reverse, if magnetic fluctuations generate flows, then there is no clear relationship between the amplitude of the fluctuations and the velocity of the flows below 250 km/s. Large fluctuations (above 3 nT) could nevertheless generate high speed flows (above 250 km/s). Concerning V/HF wave relationship (plot 3), a positive cause-to-effect may exist: high speed flows could generate a stronger turbulence or, in reverse, large turbulence could more efficiently trigger high speed flows. The good correlation between B and HF-events is likely linked to some continuity in the turbulent spectra, from the low to the high frequencies.

To get a better view of possible cause-to-effect relationships between events, we produce more precise plots that take into account the relative time of detection of the events (Figure 5). To make plot 1, we consider common V/B events. We then identify B-events that start before V-events and calculate the time intervals that separates the start of both events. We add all these time intervals (black line). We do the same for B-events finishing after V-events, and calculated the period that separate the end of the V-events and the end of the B-events (blue line). The plots thus corresponds to the total advanced time of B over V-events (black) and the total retarded time of B over V-events (blue). The same is done for V and HF events in plot 2. The continuous, dotted and dashed lines correspond to increasing thresholds for the selection of events.

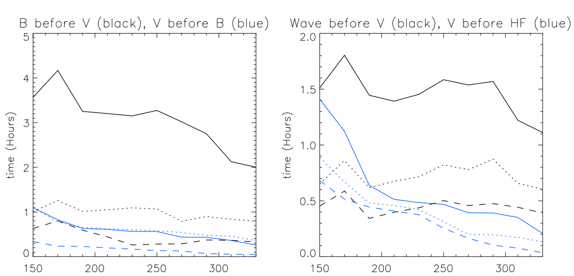

Fig. 5. advanced (black) and retarded (blue) time between B/V-events (plot 1), and HF/V-events (plot 2).

The proportion of B-events and HF-events that start before a V-events is generally much larger than the reverse, by a factor 3. This is especially true for low amplitude fluctuations (continuous line), the difference being less pronounced as the amplitude of the wave increases. This indicates that, in average, low and high frequency fluctuations are seen before the flows. They also do not persist for a long time after the flows. A simple interpretation would be that V-events, HF-events, and B-events are triggered by the same process, the higher velocity of propagation of the magnetic fluctuations (sound or Alfvén speed) allowing to detect B-events or HF-events before V-events. It is nevertheless not excluded that the fluctuations could also have a positive role in the formation of flows: a burst of magnetic turbulence could change the dynamics of the plasma sheet and trigger plasma flows. A more detailed analysis is needed to firmly conclude on these fundamental questions.

6. Conclusion

The prime purpose of this report is to publish a first extended study of the plasma sheet activity from CLUSTER measurements. We perform a statistical analysis of different kinds of 'events' that characterize the plasma sheet activity. They are defined from the flow velocity (V-events, equivalent to BBF), the amplitude of low frequency magnetic fluctuation (B-events), the spectral density of high frequency waves (HF-events) and the thickness of the sheet (thickness-events). We use automatic procedures for the selection of 'events' based on the facilities given by the CDPP.

Depending on quantitative criteria, an 'active' plasma sheet is observed some ∼5-10% of the total time spent by spacecraft in the sheet. We obtain comparable proportions using B-events, V-events and HF-events. If 'activity' is generally identified as a substorm develops when CLUSTER is in the sheet, many examples of active periods are reported without any recorded auroral intensifications or substorms. There is thus certainly not a one-to-one relationship between the development of local active processes and auroral phenomena. We also show that the three types of events present a positive correlation, as large as 50%. This is a strong indication that V, B and HF events are basically related to the same phenomena.

There are different interpretations of the phenomena. One is simply that a localised dissipation process (a reconnection, for example) generates flows and fluctuations. They then propagate independently from the same location and are detected almost simultaneously given the large propagation speeds. However, in such a case, the 'events' cannot be considered as physically related phenomena, they would simply result from a common process. The second interpretation is that a cause-to-effect relationship links the events. For example, magnetic fluctuations generate flows that, in reverse, trigger fluctuations in a large frequency domain. This would create a self-consistent non-linear system that organize the local dissipation. The observed correlation would then be an essential ingredient of turbulence in collisionless plasmas. More detailed analysis are required to answer this dilemma.

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