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A study on the main periodicities in interplanetary magnetic field Bz component and geomagnetic AE index during HILDCAA events using wavelet analysis

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ABSTRACT

The interplanetary and geomagnetic characteristics of High-Intensity Long-Duration Continuous AE Activity (HILDCAA) events are studied using wavelet analysis technique. The Morlet wavelet transform was applied to the 1 min interplanetary magnetic field (IMF) Bz component and the geomagnetic AE index during HILDCAA events. We have analyzed the AE data for the events occurring between 1975 and 2011, and the IMF Bz data (both in GSE and GSM) for the events between 1995 and 2011. We analyzed the scalograms and the global wavelet spectrum of the parameters. For 50% of all HILDCAA events, the main periodicities of the AE index are generally between 4 and 12 h. For the Bz component, the main periodicities were found to be less than 8 h for ~56% of times in GSM system and for ~54% of times in GSE system. It is conjectured that the periodicities might be associated with the Alfvén waves which have typical periods between 1 and 10 h. The results are discussed in the light of self organized criticality theory where the physical events have the capacity of releasing a considerable amount of energy in a short interval of time.

1. Introduction

The study of the events which disturb the geomagnetic field/ magnetosphere is an interesting subject owing to the worldwide sensibility of the technology systems to the geomagnetic disturbances, which is called space weather. The electrodynamic processes that occur in the space environment between the Sun and the Earth (called geospace) may affect our technologies such as spaceships, telecommunications, power lines, navigation, etc. The understanding of the theoretical and practical aspects of these processes is important in order to facilitate the procedures for technological and human activities became safer (Baker, 1998; Siscoe, 2000; Echer et al., 2005).

Several studies were done on the geomagnetic storms since 1808 and on substorms since 1960 s (Gonzalez et al., 1994, and references therein). Tsurutani and Gonzalez (1987), while studying geomagnetic storms with a long-duration recovery phase, discovered a new type of geomagnetic/auroral activity called High-Intensity Long-Duration Continuous AE Activity (HILDCAA). The HILDCAAs are defined by four stringent criteria. First, the AE index must be 1000 nT or more at least once during the event; second, the event must be at least two days long; third, the AE index must not be less than 200 nT for longer than two hours at a time; and finally, the event must occur outside of the main phase of the geomagnetic storms. Tsurutani et al. (2004) suggested that HILDCAAs are not merely substorms, and there is much more happening in the magnetosphere/ionosphere system. Several papers that studied HILDCAAs have been done recently (Tsurutani et al., 1995; Soraas et al., 2004; Hajra et al., 2013, 2014a, 2014b, 2014c, 2015a , 2015b).

The Bz component of the interplanetary magnetic field (IMF) is highly fluctuating during the high-speed solar wind stream (HSS) interval following the corotating interaction regions (CIRs). This is highly correlated with the AE variation during HILDCAA events. The magnetic reconnection between the southward component of IMF and the geomagnetic field (Dungey, 1961; Gonzalez and Mozer, 1974) leads to intense substorm/convection events that comprise the HILDCAA intervals. HILDCAA events may occur after geomagnetic storm main phases caused by CIRs or interplanetary coronal mass ejections (ICMEs). They may even occur without a preceding geomagnetic storm (Guarnieri et al., 2006; Hajra et al., 2013). However, the overwhelmingly majority of the HILDCAAs were reported to occur after CIRs followed by HSS events (Hajra et al., 2013) when Alfvén waves are most common (Belcher and Davis, 1971; Tsurutani et al., 1994). The

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Alfvén waves are considered to play the major role for the occurrence of HILDCAA events (Tsurutani and Gonzalez, 1987; Hajra et al., 2013).

While the HILDCAA events may occur at any phase of the solar cycle, Hajra et al. (2013) reported that these events are three times more frequent during the descending phase compared to other phases. This is because the HSSs accompanied by the Alfvén waves emanate from the solar coronal holes which are most frequent and geoeffective in the declining phase (McPherron, 1995; Tsurutani et al., 1995).

Soraas et al. (2004) attributed the long storm (Dst) recovery during the HILDCAA events to the injection of protons into the ring current. This injection prevents the natural decay process of the ring current, thereby delaying the Dst recovery. Recent studies (Hajra et al., 2014b, 2015a, 2015b) showed acceleration of the energetic electrons to relativistic MeV energies by electromagnetic chorus waves (Kennel and Petschek, 1966; Tsurutani and Smith, 1974, 1977) during the HILDCAA events.

Another important impact of the HILDCAAs on the magnetosphere/ionosphere system is that a large amount (~6.3×10^{16} J) of solar wind energy is transferred to the magnetosphere/ionosphere system during these events (Hajra et al., 2014a). Ionospheric Joule heating was suggested to be the major HILDCAA energy dissipation process, spending ~67% of the solar wind energy input. On the other hand, only ~11% of the solar wind energy goes into the ring current during HILDCAAs (Hajra et al., 2014a).

Although several works have been done recently on HILDCAAs, the main periodicities in the interplanetary and geomagnetic parameters during these events are still not well understood. In the original paper by Tsurutani and Gonzalez (1987), HILDCAA events were suggested to be one-to-one correlated with Alfvén waves. The Alfvén waves are high frequency waves where IMF components are highly correlated with solar wind speed components. Thus understanding the main periodicities in the interplanetary and geomagnetic parameters during HILDCAA events are very important to understand the geophysical phenomena. This is the main aim of the present study. In order to conduct this study, the global wavelet spectrum was used to determine the main periods related to the HILDCAA events for the period between 1975 and 2011. The 1 min IMF Bz and the AE index were used to characterize the interplanetary and geomagnetic conditions, respectively. This study may be important for deeper insights into better understanding of the magnetosphere/ionosphere energy coupling processes. Further, it can give information about HILDCAA periodicities that can be useful for modeling studies of solar wind-magnetosphere coupling.

2. Database and methodology

For the present work, we have used a list of 133 HILDCAA events occurring between 1975 and 2011, compiled by Hajra et al. (2013). The HILDCAAs were identified using four criteria suggested by Tsurutani and Gonzalez (1987) as mentioned in Section 1. First, from the AE time series, the AE > 1000 nT events were sought. The data were scanned both forward and backward in time to determine where the AE value decreased below 200 nT for 2 h or more. If this interval was outside of a storm main phase (Dst≤−50 nT: Gonzalez et al., 1994) and the event was longer than 2 days, this was categorized as a HILDCAA event. The AE indices at 1 min time resolution were obtained from the World Data Center for Geomagnetism, Kyoto, Japan (http://wdc.kugi.kyoto-u.ac.jp/). The IMF Bz data (1 min) for 52 HILDCAA events occurring in the 1995–2011 interval were also analyzed. The earlier data were not considered due to poor interplanetary data coverage. The IMF data were obtained from the OMNI web (http://omniweb.gsfc.nasa.gov/). The interplanetary data are already propagated from observation points up to the position of the "nose" of the shock front (bow shock) of the Earth.

As mentioned in Section 1, the Wavelet Transform (WT) technique was applied to the HILDCAA related AE and IMF Bz datasets studied in this work. A simple description of this robust mathematical tool is given below.

The WT is a mathematical tool developed on the 80's decade and is based on the simple mathematical functions, called *wavelet-mother* functions represented as $\psi(t)$. These are mathematical functions with compact support as they are located on time and scale (Meyer, 1990). The functions are generated by the expansion: $\psi(t)\rightarrow\psi(2t)$, and the translation: $\psi(t)\rightarrow\psi(t+1)$, from a simple generating wavelet-mother function given by the following equation:

$$\psi_{a,b}(t)=\frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right), \quad (1)$$

where a is the scale associated with expansion and contraction from wavelet, and b is the time localization. For each values of the a and b coefficients, we obtain a set of wavelet functions, called *daughter wavelets* (Daubechies, 1992). In this work we used the Morlet wavelet (Torrence and Compo, 1998) given by:

$$\psi(t)=e^{i\xi_0 t}e^{\frac{-t^2}{2}}, \quad (2)$$

where ξ_0 is a dimensionless frequency. The Morlet wavelet function is a function suitable for the geophysical data because it presents a good location in frequency (Bolzan, 2004). We use this technique to obtain the main periodicities in the interplanetary and geomagnetic parameters during the HILDCAAs events.

The WT applied to the time series $f(t)$ is presented as:

$$TW(a,\ b)=\int f(t)\psi_{a,b}(t)^{*}dt, \quad (3)$$

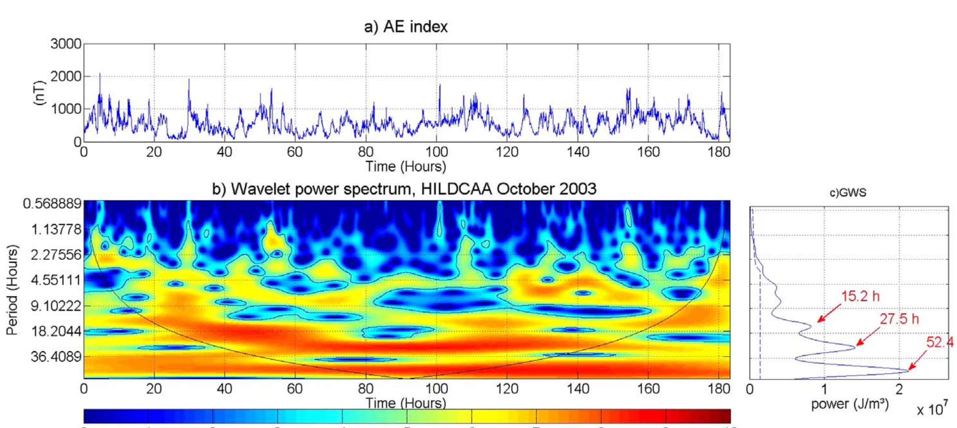

Fig. 1. (a) The AE index time series during a HILDCAA event starting at 0328 UT on 15 October and continuing till 1835 UT on 22 October 2003. (b) The wavelet transform (WT) periodogram of the AE time series. (c) The Global Wavelet Spectrum (GWS) showing the main periods in AE.

where $\psi_{a,b}(t)^*$ represents the complex conjugate of the wavelet function $\psi_{a,b}(t)$.

Due to the presence of discontinuities at the edges of the wavelet spectrum caused by filling of the end of the time series with zeroes to approach the data to the next power of two (since the Fourier Transform assumes that the data is cyclic), a cone of influence (COI) is introduced (black line in the plots of this paper). The COI is the region where the edge effects caused by zeros inserted in the data become relevant (Torrence and Compo, 1998). So what is observed in the region out of the COI should be not considered in the analysis.

Finally, we used the Global Wavelet Spectrum (GWS) to identify the most energetic periods present in the time series. The GWS is given by:

$$GWS=\int |TW(a,\ b)|^2 db, \tag{4}$$

3. Results

3.1. The main periods during HILDCAA events

In order to obtain the main periods in the AE index and the IMF Bz component during the HILDCAAS events, the WT was applied. Where the peaks of periods that appears in the global wavelet spectrum was used. Fig. 1 shows an example of the WT applied to the AE index variation during a HILDCAA event that occurred between 0328 UT on 15 October and 1835 UT on 22 October 2003. The HILDCAA event was preceded by a geomagnetic storm caused by a CIR (not shown). The event lasted for ~183 h (7 days and 15 h) and had the AE peak intensity of ~2090 nT. Three main periodicities, namely, ~15, 27 and 53 h are noted in the AE index (Fig. 1c). The energies for each of the periods are: 3.3×10^{12} J/m^3, 5.7×10^{12} J/m^3, and 8.5×10^{12} J/m^3, respectively. The unit that is obtained from the equation of the global wavelet spectrum is nT². To obtain the energy unit ($\frac{J}{m^3}$), was used the equation of magnetic energy:

$$U_b = \frac{B^2}{2\mu_0}. \tag{5}$$

The above procedure was carried on for the AE time series during all 133 HILDCAA intervals in order to obtain the statistical main periods. Fig. 2 shows the histogram with the results for these events. The most energetic periods are found to occur between 4 and 8 h, representing ~32% of the cases. If we consider the periods between 4 and 12 h, it is noted that 50% of all the cases have the AE periodicity within this range. This result coincides with periods of substorms found in the literature (e.g., Tsurutani et al., 1990; Borovsky et al., 1993), that present scales of 2–5 h..

We use the same procedure in order to identify the main periods in the IMF Bz component. As mentioned in Section 2, we considered the 52 HILDCAA events occurring during 1995–2011 period for this part. This analysis was performed for IMF data obtained in two coordinate systems, GSM and GSE. For brevity, we will show the results only for the GSM system.

Fig. 3 shows the WT analysis results of the IMF Bz (GSM) for the same event (occurring between 0328 UT on 15 October and 1835 UT on 22 October 2003) of Fig. 1. The main (most energetic) periodicities in the IMF Bz are: ~5, 21 and 52 h, with energies of 1.1×10^8 J/m³, 5.9×10^8 J/m³, and 5.7×10^8 J/m³, respectively (Fig. 3c).

Fig. 4 shows the results of the most energetic periods observed in the IMF Bz, in GSM coordinate system, during the 52 HILDCAA events between 1995 and 2011. It is observed that ~56% of the most energetic periods are in the range of 0–8 h. For IMF Bz in the GSE system, ~54% of the most energetic periods are found to be in the same range, between 0 and 8 h (not shown). Thus, we conclude that the characteristic periods of the IMF Bz during the HILDCAA intervals in both GSE and GSM coordinates are the same. This result corroborates with the typical periods of 1–10 h observed in the Alfvén waves (Smith et al., 1995). This is consistent with the fact that HILDCAAs occur most frequently during the descending phase of the solar cycle (Tsurutani and Gonzalez, 1987; Hajra et al., 2013), when the HSSs are dominant and are emitted from solar coronal holes. The HSSs are embedded by Alfvén wave trains (Belcher and Davis, 1971)..

3.2. Classification of the main periods during the HILDCAA events

In this section we will study the types of the energy distribution for HILDCAA AE index periodicities. From the WT periodogram of the AE index, the temporal variability of the energy distribution is classified into four types: Intermittent, Continuous, Quasi-Continuous and Local. The intermittent classification is given when we observe in the signal small regions of strong energy distributed over the entire time period. The continuous classification is given when we observe the signal as a

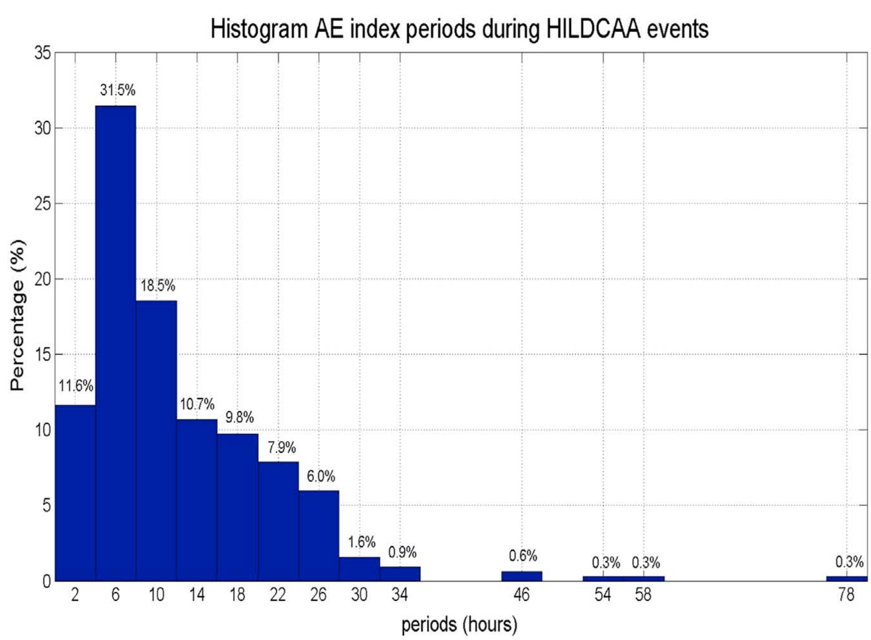

Fig. 2. Histogram of the percentage of the most energetic periods of AE index during the HILDCAA events.

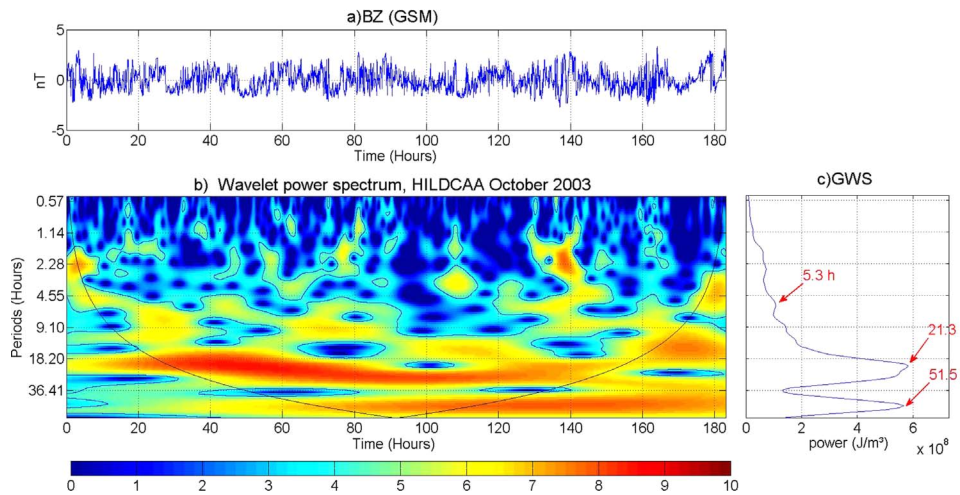

Fig. 3. (a) The IMF Bz time series in GSM coordinates for the HILDCAA event shown in Fig. 1. (b) The WT periodogram of the IMF Bz, and (c) The GWS showing the main periods in Bz.

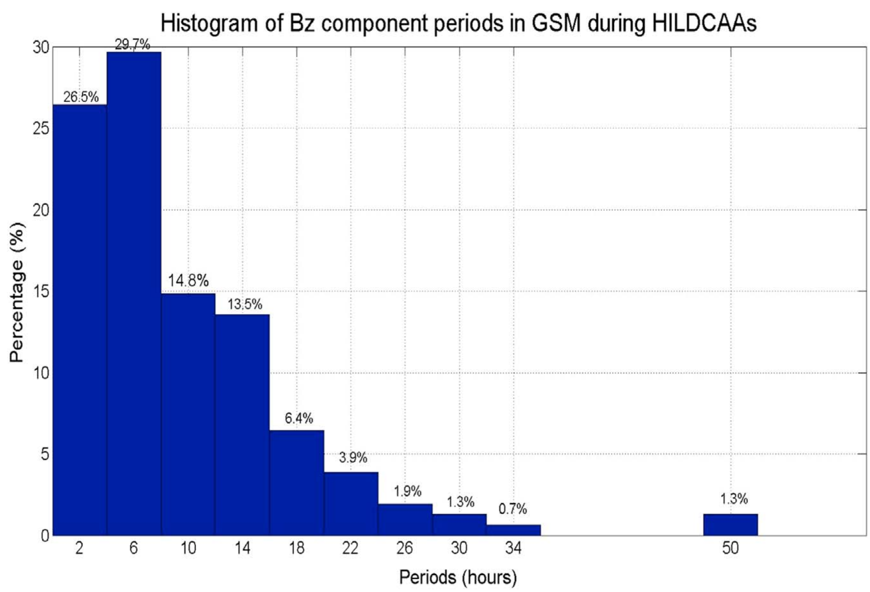

Fig. 4. Histogram with the percentage of the most energetic periods for IMF Bz component (GSM) during the HILDCAAs events.

continuous energy spread over the entire interval. The quasi-continuous classification is used when we observe the same characteristics mentioned above, but they do not occur for the entire interval. Finally, the local classification is given when we observe a energetic periodic signal which occurred for a very limited time range.

Fig. 5 shows the WT periodogram for the AE index during two HILDCAA events. The panel (b) presents a WT periodogram during a HILDCAA event occurring in May of 1986 (between 1734 UT on 30 May and 0934 UT on 2 June 1986), and the panel (d) during a HILDCAA event occurring in December 1986 (between 1314 UT on 22 December and 1442 UT on 24 December 1986). In both panels, it is possible to observe bands that correspond to the most energetic periods (marked by bold red curves). In panel (b), it is possible to see three bands, which the first is classified as intermittent distribution, the second as local distribution and the last one as a continuous distribution. In panel (d), two bands were observed. The first one is classified as local distribution, and the second one is classified as quasi-continuous. Fig. 6 shows the WT periodogram for the AE index during a HILDCAA event occurring in March 1975. It is possible to note intermittent signals occurring during the entire event.

For the 133 HILDCAAs events, we applied the above methodology and counted the number of the most energetic periods which occurred in each particular classification during each event. Fig. 7 shows a histogram of the results. About 47% of the most energetic AE periods during HILDCAA events are found to show an intermittent signal. This result is very interesting because it shows that for almost 50% of the events the energy release occurs quickly and in short periods in time.

This property, where a particular physical phenomenon has the capacity of releasing a considerable amount of energy during a short period, is known as the Self Organized Criticality (SOC) (Bak et al., 1987). The SOC was observed in several kinds of the physical systems (Chang et al., 2006, and references therein). Although this concept was introduced in the plasma physics and the space physics since the 1990 s, this subject is relatively little explored, mainly in interplanetary medium/magnetosphere physics. Sitnov et al. (2001) used the SOC approach to model the terrestrial magnetosphere dynamics. It was suggested that the terrestrial magnetosphere is always in the phase transition out of equilibrium, where small perturbations can lead the system to release strong energies during short periods of time. Recently, Sharma et al. (2016) did an excellent review about this topic and they mentioned many studies characterizing substorms as SOC (Chapman et al., 1998; Uritsky et al., 2001a, 2001b). Since turbulence plays a critical role in the transport of the plasma in the space environment, some phenomena such as magnetic clouds, presents

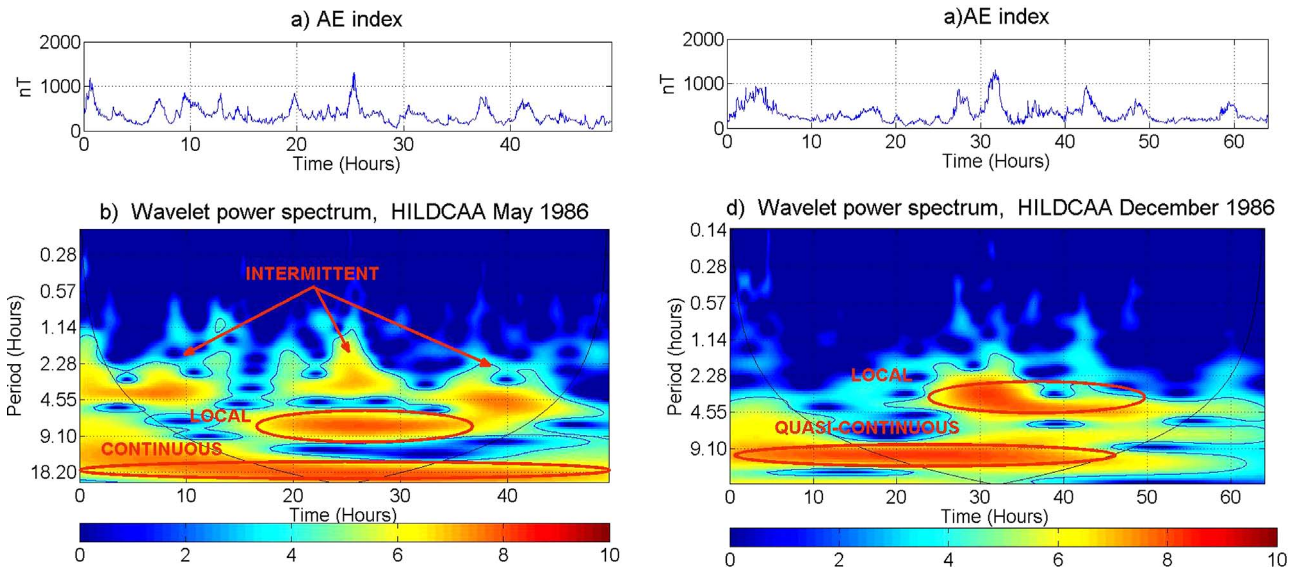

Fig. 5. (a) The AE time series for a HILDCAA event occurring between 1734 UT on 30 May and 0934 UT on 2 June 1986. (b) The WT periodogram for AE index of item (a). (c) The AE time series for a HILDCAA event occurring between 1314 UT on 22 December and 1442 UT on 24 December 1986. (d) The WT periodogram for AE index of item (c).

the tendency for self-organization, such as SOC, in order to promote the minimum energy states. Thus, it may be inferred that the terrestrial magnetosphere acts like a physical system which is out of equilibrium owing to the constantly incoming radiation and ion fluxes. Those fluxes play an important role for the magnetosphere store energy until a certain threshold. When this threshold is reached, the total energy would be released energetically during a short period of time, and intermittently, as revealed in the present work.

4. Summary and conclusions

In this paper we identified the main periodicities of the AE index and IMF Bz during HILDCAA events using the WT technique. The main results may be summarized as follows:

1. The most significant periods of the AE index during HILDCAA events are localized between 4 and 12 h. More than 50% of the most energetic periods from the 133 events studied are within this time range.
2. In the interplanetary medium, independent of the coordinate system used (GSE or GSM), the periods most commonly found in the IMF Bz component were ≤8 h. The periods may be associated with Alfvén waves that have periods between 1 and 10 h (Smith et al., 1995).
3. About half (47%) of the most energetic AE periods during the HILDCAA events exhibit intermittent characteristics. These may be associated with the Self Organized Criticality (SOC) (Bak et al., 1987), since the release of energy occurs during short, isolated and very energetic events.

In conclusion, we have for the first time characterized the major frequencies/ periods observed during HILDCAAs. These seems to be in the range of Alfvén wave periods. Further, about half of the main periods are intermittent, possibly due to SOC.

Acknowledgments

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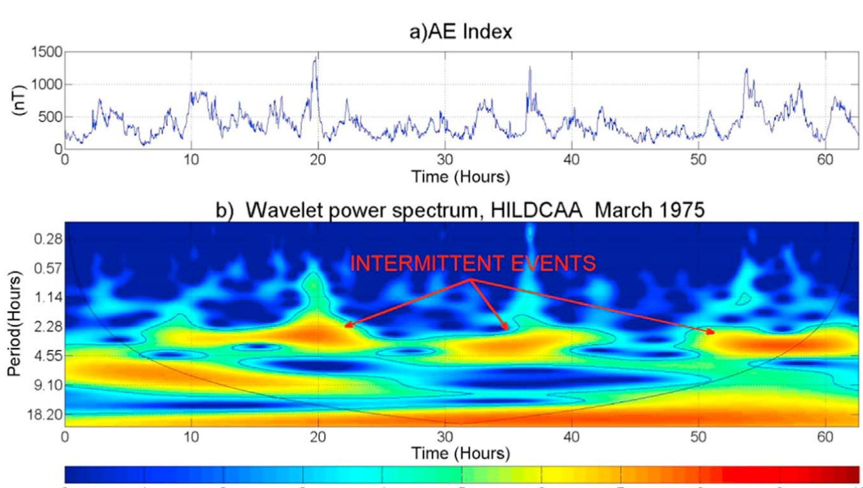

Fig. 6. (a) The AE time series for a HILDCAA event occurring between 0307 UT on 14 March and 1744 UT on 16 March 1975. (b) The WT periodogram for AE index.

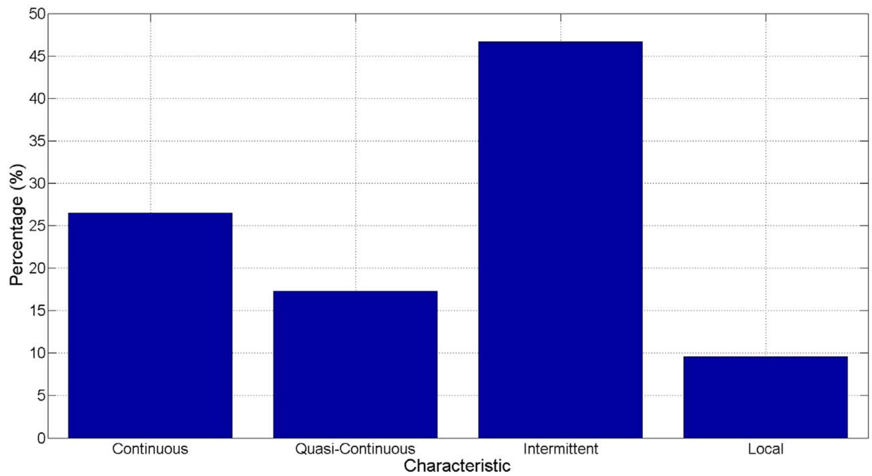

Fig. 7. Histogram of the types of energy distribution for the AE index during HILDCAAs events.

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