Towards evidences of a threshold system as the source for magnetic storms detected on Earth's surface

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Abstract

In this work we present evidences that point to a threshold system as the source for magnetic storms detected on the Earth. We based our analysis on series of data acquired during many years in the network of magnetic observatories of the National Observatory (Brazil). In particular we focused our attention on October 2000 month of the Vassouras Observatory, which have been active since 1915. The data was appropriately processed using classical Fourier formalisms. The analysis of statistical distribution of amplitudes, periods of calm and storms was implemented on the difference resulting from the processed and unprocessed data.

Introduction

One of the more typical examples of interdisciplinarity (which is a consequence of modern science where the addressed problems are so complex that scarcely we could say that they are contained in a single classical science realm) is the theory of non-linear dynamical systems and, more particularly, self-organized criticality. Bak, Tang and Wiesendfeld (from now on referred as BTW) (Bak et al., 1987) introduced, in 1987, the new concept of self-organized criticality to explain the behavior of large interactive systems. Many systems that at a first glance could appear totally different, share the tendency to a stationary state without a typical length scale and without a typical time scale. Avalanches, the name that bursts of activity in those systems receive, of all sizes are observed. According to the BTW theory the mechanisms that lead to minor events are the same that lead to major ones.

Self-organized criticality appears to underlie the global behavior of systems very unlike at a first look. Experimental evidence has been found in superconductor's vortex avalanches (Field et al., 1995), sand piles (Held et al., 1990), the brain (Papa et al., 1997), ^{4}He (Moeur et al., 1997) and earthquakes (Bak et al., 1987).

There are some general characteristics common to systems that self-organize critically: their single components are able to store potential energy in a more or less local way and just to a more or less well defined threshold. There are some self-organized systems in which it is not obvious what kind of magnitude is stored. An example is the stock market. But we will refer always to it as potential energy. The systems are continuously supplied with energy not necessarily in a local way. When the accumulated energy in a single element surpasses the threshold it is released in part to other single elements related to the former and in part out of the system. Eventually some of the related elements will be close enough to the threshold in such a way that the energy supplied by the neighbor is sufficient for this element to surpass the threshold. In this way, a single element can initialize a chain reaction that will stop only when all the elements are below the threshold. This chain reaction is what receives the name of avalanche in clear reference to sand piles and snow barriers.

The continuous supply of energy has to be small if compared with the maximum power that the system can support because if not there would be no sense in speaking about avalanches. A simple example that can help to understand this is a sand pile. When we throw sand on the pile it has to be done grain by grain. If we try to put a quantity of sand similar to the greater avalanche that we observe when the sand is thrown grain by grain, we will not observe avalanches because the external perturbation is not more a slight one, instead we observe sand falling off the pile in approximately the same rate at which it is thrown on the pile.

There are two normal procedures to study systems that present this type of behavior: the frequency distribution of duration/intensity of great activity periods (avalanches) and the frequency distribution of periods between two consecutive avalanches (first return time). It is also a normal procedure to establish a cut-off above which it is considered a stormy or avalanche period and below which it is considered a calm period. To the best of our knowledge, there is no way to previously determine the value of the cut-off and the choice obeys to the apparition of power laws.

In this work we show that magnetic storms should be added to the long list of threshold-driven phenomena.

Theory

It is well known that any of the components of the magnetic field measured on the Earth's surface presents characteristic frequencies (corresponding to time periods of 24 hours and harmonics) owing to the rotation of Earth. There are also present other factors (for example ionospheric influences). However, in this first approach we were concerned just with the elimination of well-known frequencies letting a more detailed study (main field removal, tidal corrections, electrojets corrections, for instance) for future works.

In Figure 1 we show the temporal dependence of the *H* component of the magnetic field measured on the ground during a day. There are superimposed several patterns coming from diverse factors. We have used the *H* component because, due to Vassouras Observatory low geomagnetic latitude, it is almost equal to the total field F. The data corresponds to the INTERMAGNET international network that in Brazil is placed at the Vassouras Observatory and whose registers with a sample rate of 1 point per minute.

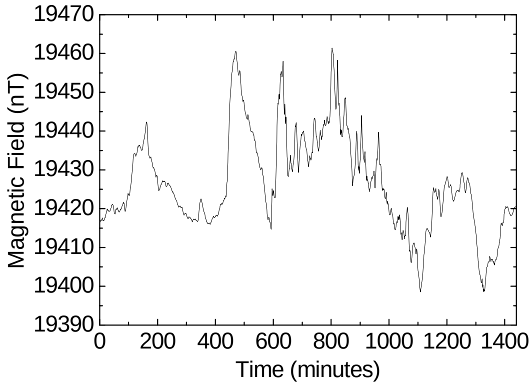

Figure 1 – Typical time dependence of the H component of the magnetic field measured on the Earth's surface during one day.

To extract a signal independent of daily influence we closely followed a method developed in previous works (Seixas et al., 1994 and Fontes et al., 1995). There was proposed a computational procedure for the automatic determination of the K-index (that varies between 0 and 9), instead of the classical hand-made one. It is based on the application of a Butterworth's low-pass filter (see Figure 2) to the daily registered data of geomagnetic activity. After many tests it was verified that the gradient giving the best final results was of 12 dB/octave. The variable cut-off frequency of the filter is adjusted depending on two parameters: the latitude and longitude of the observatory and the peak-to-peak amplitude of the registered day. Its value is determined by the expression:

$$f_c = \frac{\delta_{OBS}}{A_{pp}} \quad (1)$$

where δ_{OBS} is a constant (for the Vassouras Observatory it is 0.26) and A_{pp} is the peak-to-peak amplitude in a daily register.

The procedure was tested for many observatories around the world. The difference between the manual and the computed K-indexes was used as a test for the method. For an agreement (maximum allowed difference between both indexes) equal to ±1 the number of cases was 100%. The main difference for the present study is that the total time for analysis must be as long as possible in order to have several decades for the statistical description of stormy and calm periods.

After the filtering and returning to time domain processes the signals present the shape depicted in Figure 3. All the irregular behavior (that is actually our interest) has been erased off.

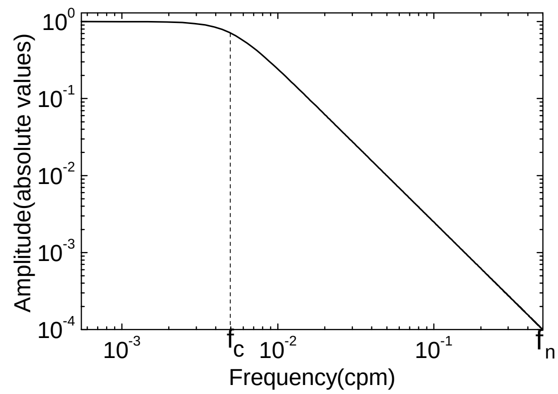

Figure 2 – Butterworth's low-pass filter. The cut-off frequency (f_c) and the Niquisty frequency (f_n) are also represented.

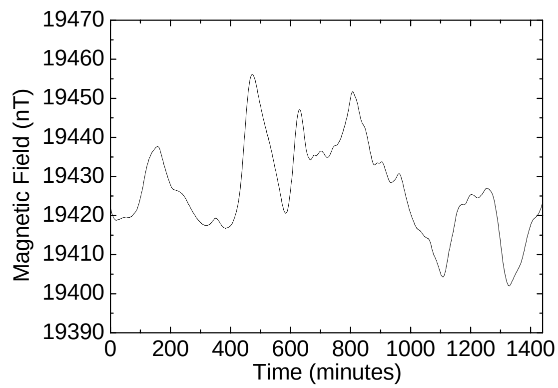

Figure 3 – Time dependence of the signal in Figure 1 after the appropriate filtering procedure, as described by Equation 1 and Figure 2.

The next step was to calculate the difference between the filtered and unfiltered signals. The result is shown in Figure 4. Through this procedure we isolated the spike-like characteristic. To study the frequency distribution of amplitudes, of stormy periods and of first return times it was previously obtained the absolute value of the difference between data of the type presented in Figure 1 and Figure 3. The objective was to avoid artificial bisections of single stormy periods. It is know that during those periods the magnetic field components change the sign continuously.

Our first study was the frequency distribution of peak highs. The results are shown in Figure 5. There are two apparent power law regimes. For values up to 20 nT the slope is –1.86, for higher values it was obtained a value of –3.70 for the slope. We are bent to think that the double power-law originates from two very different networks of concomitant phenomena at the Sun surface. Future modeling works will help to explain this result.

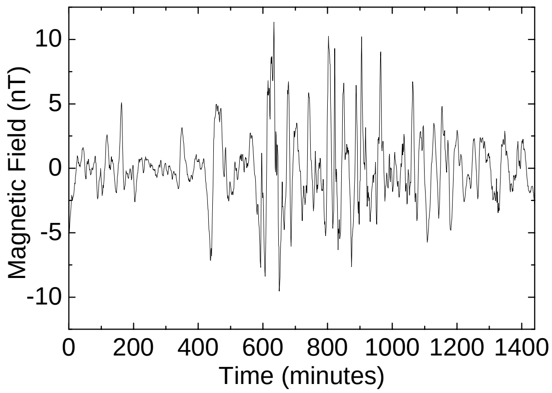

Figure 4 – Difference between the signals in figures 1 and 3. Note the spike-like shape. On this type of data set were performed the final data analysis.

Double power-laws have been found in other scientific areas, for example, on the structure of large social networks (Csányi et al., 2004). They have also been found in the luminosity of some galactic nuclei (Zhao, 1997) and more recently in solar flares (Zharkova et al., 2005).

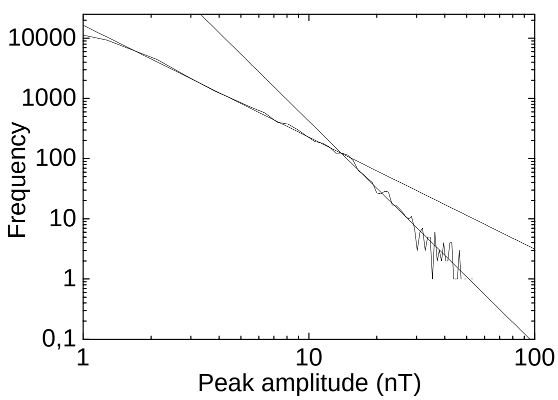

Figure 5 – Frequency distribution for peak highs. The straight lines are guides for the eye. A double regime seems to be present.

Figure 6 shows the frequency distribution of stormy periods. It was calculated over a period of one month with magnetic field measures every 1 minute. For Figure 6 it was assumed a cut-off of 0.9 nT (i.e., it was considered as “a storm” every continuous activity above 0.9 nT). We have also represented in Figure 6 a straight line of slope equal to –2.61 that helps to call the attention to the power-law-like distribution for stormy periods.

Finally, it is presented in Figure 7 the frequency distribution for first return times measured on the same one month period with magnetic field measurement every one minute. For Figure 7 it was also assumed a cut-off of 0.9 nT of the maximum obtained value (i.e., it was considered as “a calm period” every continuous activity below 0.9 nT). It is also depicted in Figure 7 a straight line of slope equal to –2.17 that helps to call the attention to the power-law-like distribution of first return times.

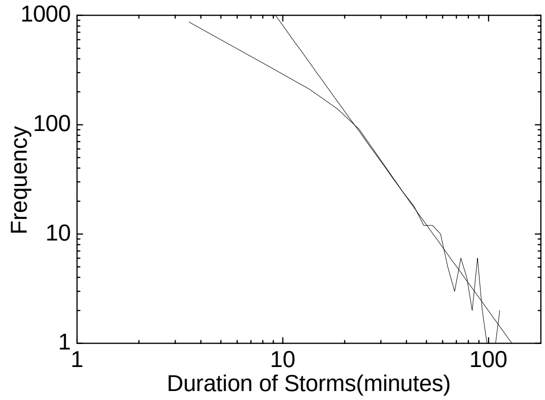

Figure 6 – Frequency distribution for storms duration times. The straight line is a guide for the eye. It has a slope of –2.61.

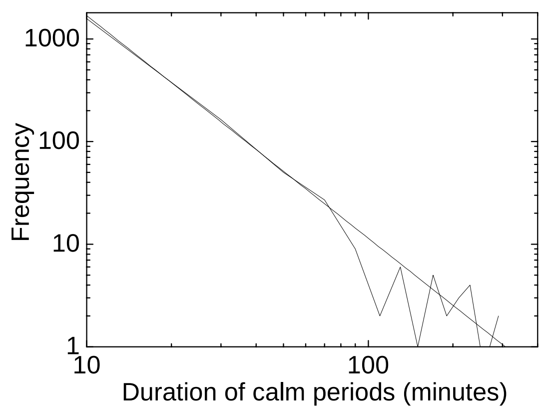

Figure 7 – Frequency distribution of first return times (calm periods). The straight line is a guide for the eye. It has slope –2.17.

The results shown in figures 5, 6 and 7 are a strong evidence of power laws for the frequency distribution of peak highs and of stormy and calm periods in magnetic measurements on the Earth surface. This might give support to more detailed treatments of available data in future works and to the search and construction of models to appropriately represent this fact. The first published evidence in this direction that we have found was published more than forty years ago (Alldredge et al., 1963) and presented as the harmonic analysis of the around-the-world magnetic profile. But at that time it was not clear all the consequences that 1/f noise could carry with it.

Resuming, we have found for the frequency distributions of stormy periods duration, of calm periods duration and of peak highs, laws of the type:

$$f(q) = cq^{d} \qquad (2)$$

where *f(q)* is the frequency distribution on the variable *q*, *c* is some proportionality constant and *d* the exponent of the power law. When *q* represents the duration of stormy periods *d* = –2.61 and when it represents first return times (duration of calm periods) *d* = –2.17. For the distribution of peak highs we have found two laws of the type shown in Equation 2. Up to, approximately, 20 nT, *d* = –1.86. For higher values *d* = –3.70.

Conclusions

Both frequency distributions, of stormy periods and of first return times, point to a threshold system as the source of magnetic storms measured on the Earth. Models for the Sun (which is the ground for this system) should describe this particularity. They should also describe the double power-law present in the amplitude distribution. Simulations of models based on interacting bubbles are currently running trying to represent and explain those facts (but they are out of the scope of the Congress). The results will be published elsewhere. Independently of the success of those models in explaining the results here advanced, the present work shows that together with earthquakes and many others systems known to be threshold driven system there should be considered the magnetic storms.

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