Study of the Temporal Evolution of Complexity in the Sun-Earth System

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Introduction

Complexity studies in plasma physics have been of great interest as they provide new insights and reveal possible universalities on issues such as geomagnetic activity, turbulence in laboratory plasmas, physics of the solar wind, etc. [1, 2].

The main objective of this work is to characterize the occurrence of events such as geomagnetic storms and solar flares by means of the fractal dimension, as a measure of the complexity of magnetic field time series and spatial patterns. We study three years: 1989, 2000 and 2001. In each case, we calculate the fractal dimension for hourly D_{st} time series (World Data Center for Geomagnetism, Kyoto, `http://wdc.kugi.kyoto-u.ac.jp/index.html`) and daily magnetograms (MDI Daily Magnetic Field Synoptic Data, Solar Oscillations Investigations project `http://soi.stanford.edu/magnetic/index5.html`). In particular, we focus on three big storms occurred during the period studied. We identify geomagnetic storms in the D_{st} series, by locating peaks where $D_{st} < -220$ (nT). Then we define three types of windows to analyze the D_{st} time series as shown in the following sections.

Fractal dimension of D_{st} time series

A fractal dimension for each D_{st} time series is estimated from their scattering diagram. If D_{st}^i is the i-th D_{st} datum in the series, and N is the total number of data, the scattering diagram is a plot of D_{st}^{i+1} versus D_{st}^i, for $1 \leq i \leq N-1$. For example, for the first storm state in 1989, the following scattering diagram is obtained:

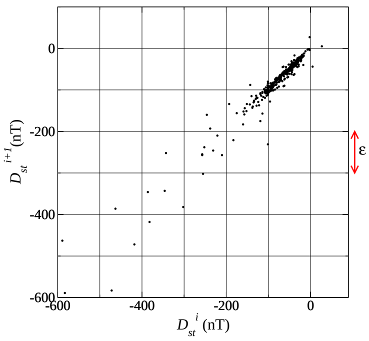

Figure 1

The fractal dimension D is estimated by the box-counting method [3], dividing the diagram in square cells of size ε.

Storm and quiet states

We define a "storm state" as a window starting one week before and ending one week after a peak. The "quiet state" corresponds to the period of time between two "storm states".

Performing the procedure described above, we calculate the box-counting dimension for each storm and quiet state of the three years in study. The following figure shows the result for 1989:

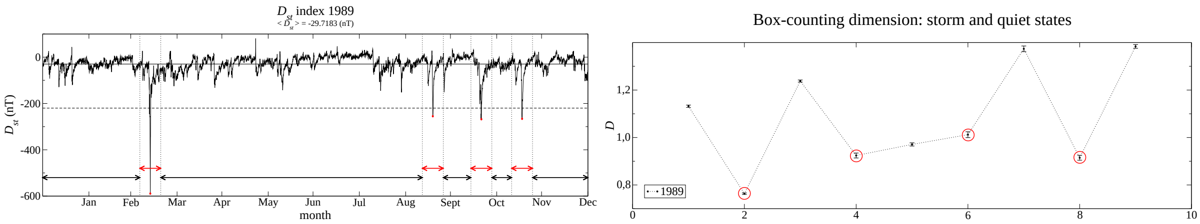

Figure 2

We note that in general, a storm stage has less fractal dimension than the surrounding quiet states. However, we can not determine a global criterion for how small D has to be in a storm state.

Variable width windows around a storm

In this case, we change the window size around a storm. We take windows starting/ending n weeks before/after the peak, with $n = 1, \ldots, 6$. We analyze the behavior of three big storms as we widen the window around it: 13 march 1989, 6 april 2000 and 2 april 2001, with intensities -538 (nT), -387 (nT) and -288 (nT), respectively. As an example, we show the results obtained for 1998:

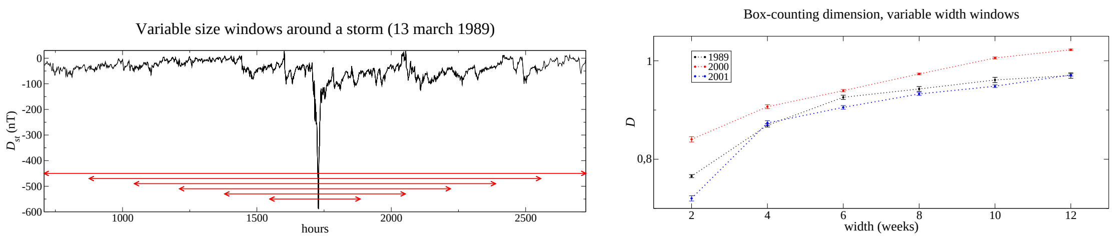

Figure 3

We note that the box-counting dimension increases when we zoom out from the storm.

In the case of the storm in 1989, in particular, the box-counting dimension increases almost linearly with the D_{st} time series average.

Moving windows across a storm

In this case, we take a window of width equal to two weeks, place it initially well before the peak (in the first day of the year), and move it in steps of one week across the peak, until it reaches the third week after the peak.

In addition to calculating the fractal dimension, we compare these results with the corresponding coronal index (National Geophysical Data Center, NOAA, `http://www.ngdc.noaa.gov/ngdc.html`). Figure 4 shows the results for 1989.

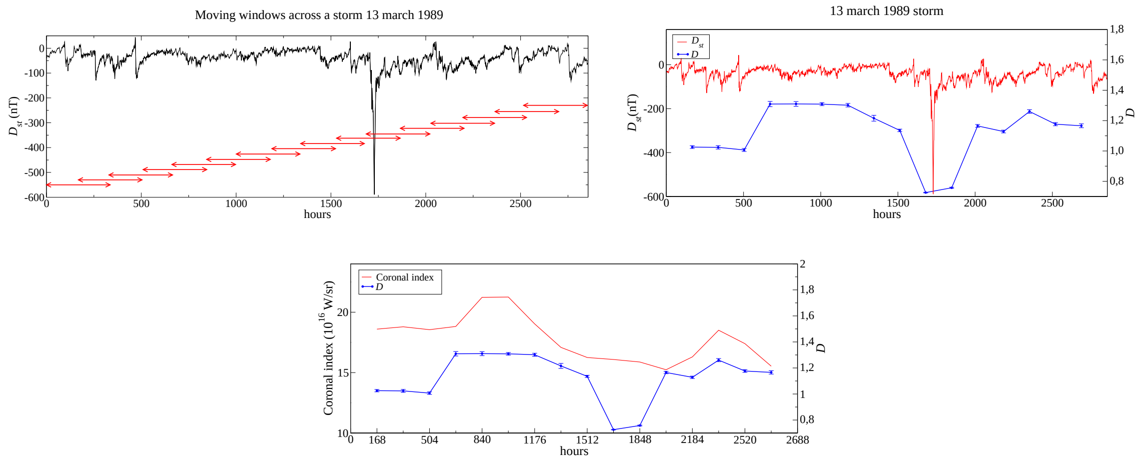

Figure 4

In all cases studied, the box-counting dimension decreases as the storm approaches, reaching a minimum value at the windows containing the D_{st} peak. Also, we observe that approximately one or two weeks before the storm, there is a maximum in the coronal index, showing the connection between solar activity and the fractal features of the Earth's magnetosphere.

Magnetogram analysis

We analyzed daily magnetograms for two years: 2000 and 2001. We start from an image like the one shown below. We first transform the image to gray scales, and then we select a threshold (α), above (below) which a point is considered white (black). Then, a fractal dimension for each magnetogram is estimated following a procedure similar to Fig. 1. We choose $\alpha = 140$ because in this region the box-counting dimension is not so sensitive to the choice of α, while still retaining fractal features of the pattern.

As an example, we show the original and the transformed images for a magnetogram obtained in 2000:

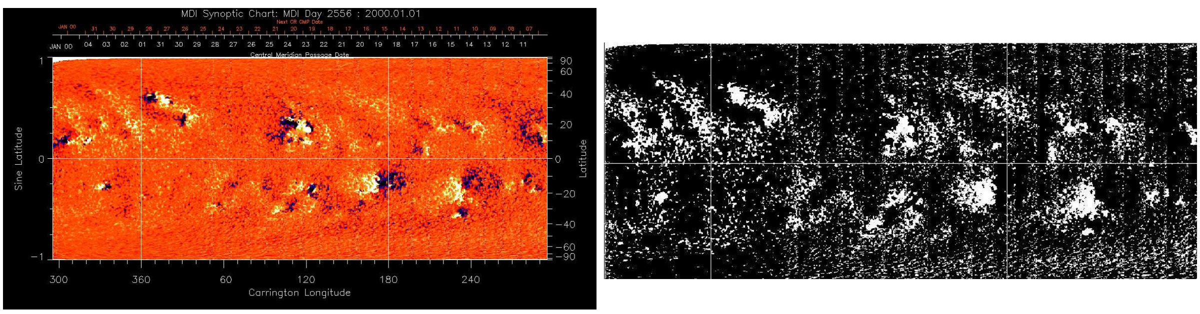

Figure 5

With the purpose of comparing the results obtained with the occurrence of solar flares, we calculate both the fractal dimension and the solar flare index, both for the original daily data, and for moving averages over one week. Below we show the results for 2000:

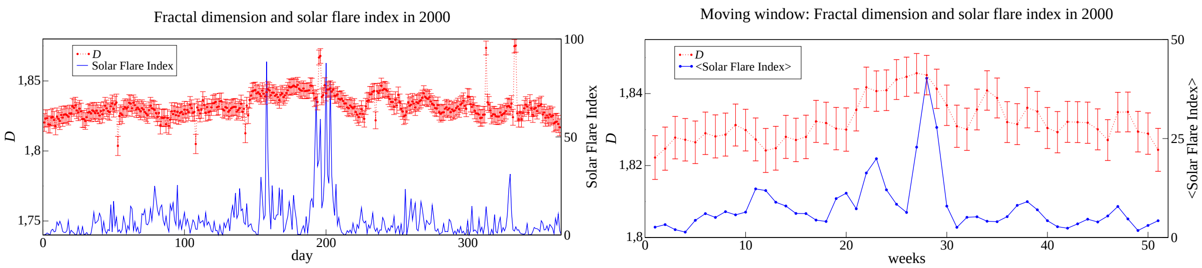

Figure 6

We also compare the fractal dimension with the D_{st} index:

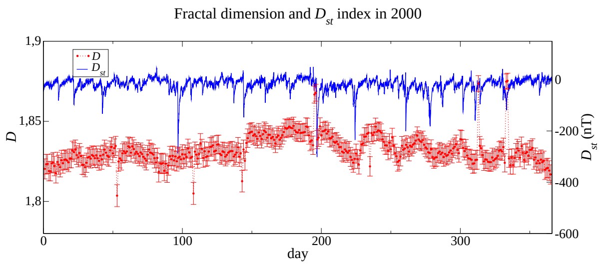

Figure 7

We observe a slight relationship between D and solar flare index. However, this relation is more transparent in the moving windows analysis. On the other hand, we do not observe a global pattern relating D and the D_{st} index.

Future Work

We intend to perform a more systematic analysis of the correlation between the time series studied. Also, we intend to study a complete solar cycle, including solar wind data, as well as other complexity properties such as multifractality and nonextensivity.

Acknowledgments

This project has been financially supported by FONDECYT under contracts No. 1170131 (J.A.V.), No. 1080658 (V.M.) and No. 1121144 (V.M). M.D. also thanks a doctoral fellowship from CONICYT.

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