

STATISTICAL PRECURSORS TO SPACE STORM ONSET

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Abstract. Fractal fluctuation analysis is applied to ground-based data during quiet times and during magnetic storm times between 1981-2002. For the purposes of this study, quiet times were required to low activity at high latitudes, as measured by K_p , for at least two days. Active times typically corresponded to intense space storms. The data analyzed was from the H_{sym} time series for the selected periods. The new technique computes nonlinear statistics from these ground-based data, and monitors the variation of the statistics with time. Variations in nonlinear statistics indicates a difference in statistical variability for quiet times and storm times, and suggests an interesting new technique to predict space storm onset.

1. Introduction

In recent years it has become evident that many space physics problems can be profitably studied with the tools of statistical physics. For instance, the behavior of the solar wind driver is commonly described in terms of geometric Brownian motion, and demonstrates a scaling behavior [Burlaga and Klein, 1986]. It is probable that to some degree, the solar wind scaling behavior propagates into the magnetosphere, although somewhat different scaling laws are observed in ground-based data, for example geomagnetic indices [Chapman *et al.*, 2004 this volume] and magnetometer data [Wanliss and Reynolds, 2003], and magnetospheric space-based data [Ohtani, 1995].

Space storms, commonly referred to as magnetic storms, characterize the most dynamic magnetospheric behavior. They frequently begin with a sudden worldwide increase in the ground-based horizontal magnetic field by tens of nanoTesla, that lasts several minutes to several hours, known as the initial phase. Following the initial phase comes the main phase, which typically lasts about a day, and features large perturbations in the horizontal component on the order of hundreds of nanoTesla. Subsequent to the main phase, the worldwide horizontal magnetic field slowly returns to pre-storm values during a recovery phase that lasts several days. Space storms include a rich variety of complex plasma electromagnetic processes extending from the surface of the earth into the magnetosphere, with the primary locus of activity being in the near-earth geospace environment [Baker *et al.*, 1997; Li *et al.*, 1997; Reeves, 1998]. These include energetic particle injection and precipitation [Reeves and Henderson, 2001; Horne, 2003], acceleration of relativistic electrons [Li *et al.*, 2001; Summers *et al.*, 2002; Meredith *et al.*, 2003], ring current enhancement, decay, and composition changes [Daglis *et al.*, 1999; Liemohn *et al.*, 2001; Kozyra *et al.*, 2002]. Recent studies on the causes of magnetic storms have found that coronal mass ejections and extreme values of the southward interplanetary magnetic fields appear to be the key factors in storm development [Tsurutani *et al.*, 1992; Gonzalez *et al.*, 1994; Kamide *et al.*, 1998; Richardson *et al.*, 2001]. Coupling and feedback between the ionosphere and magnetosphere also plays an important role in the initiation and development of space storms, and interaction between these two spheres is highly nonlinear [Lui, 2002; Daglis *et al.*, 2003 and the references therein].

Space storms thus form a complex system of nonlinear phenomena that include components of solar and terrestrial origin [Benkevitch *et al.*, 2002; Daglis *et al.*, 2003]. Intense storms have been identified as the cause of extensive damage to many ground and space-based systems [Joselyn, 1995; Odenwald, 2002] and, as such, understanding their dynamics is crucial to space weather studies.

The most widely used statistical descriptor of magnetic storm activity is the D_{st} index. This index is considered to reflect variations in the intensity of the symmetric part of the ring current that circles Earth at altitudes ranging from about 3-8 earth radii (R_E), and is proportional to the total energy in the drifting particles that form the ring current. It is calculated as an hourly index from the horizontal magnetic field component at four observatories, namely, Hermanus (33.3° south, 80.3° in magnetic dipole latitude and longitude), Kakioka (26.0° north, 206.0°), Honolulu (21.0° north, 266.4°), and San Juan (29.9° north, 3.2°). These four observatories were chosen because they are close to the magnetic equator and thus are not strongly influenced by auroral current systems. Convolution of their magnetic variations forms the D_{st} index, measured in nanoTesla, which is considered to provide a reasonable global estimate of the variation of the horizontal field near the equator. It is calculated once every hour.

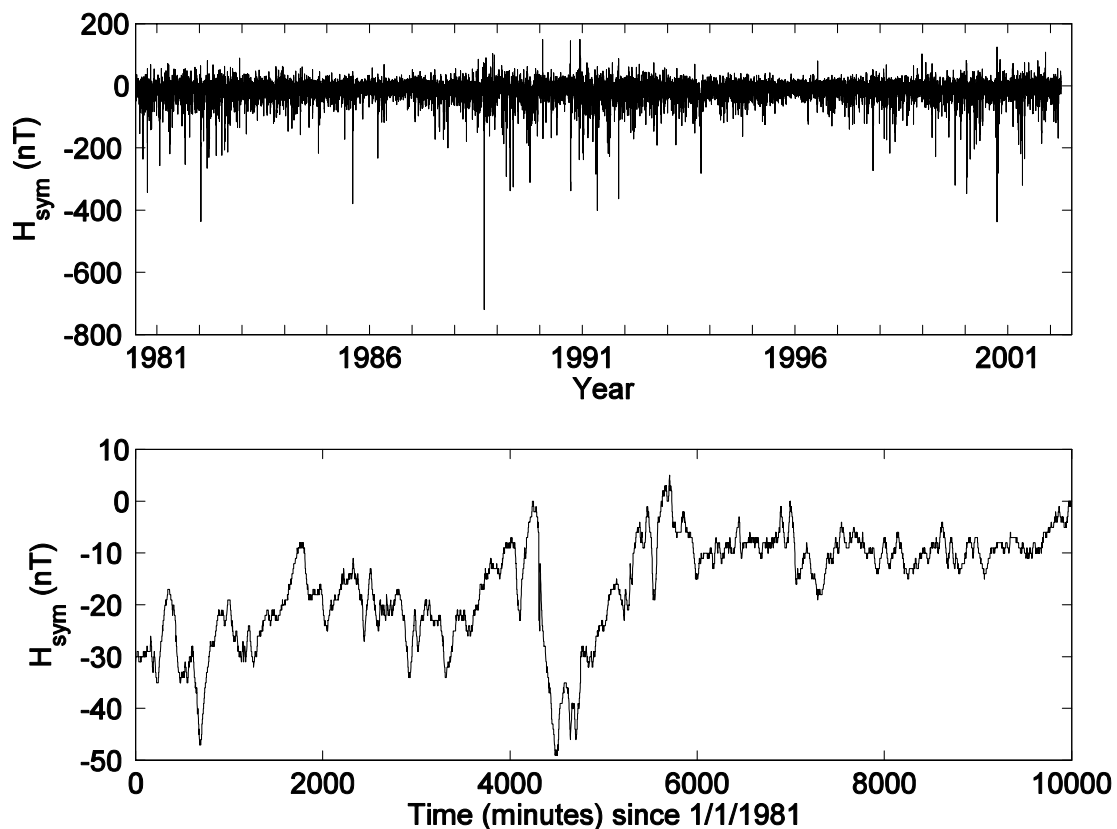


Figure 1. (Top) The entire H_{sym} time series from 1981 through 2002 appears to fluctuate around a zero mean with large intermittent negative perturbations. (Bottom) The first 10,000 minutes of H_{sym} data for 1981 appear to demonstrate long-range dependence.

In this work I examine the statistical nature of the nonlinear scaling properties in the ground-based SYM-H magnetic index [Iyemori *et al.*, 1999], hereafter referred to as H_{sym} . This index

was developed as part of an effort to describe geomagnetic disturbance fields in mid-latitudes with high-time resolution. It is essentially the same as the D_{st} index, although it uses one-minute values from a different set of stations and a slightly different coordinate system. As such, this index also provides an excellent measure of the large-scale behavior of the ring current and magnetic storm dynamics.

The statistics of the space storm fluctuations are related to relaxation, and energization processes, and to transport phenomena in space plasmas. It is clear from Figure 1 that the H_{sym} time series displays evidence of both long-range dependence and intermittency. The large negative spikes in H_{sym} correspond to intervals of intense space storms. In this paper, I will examine H_{sym} to determine the characteristic nonlinear statistical differences, if any, between quiet (Q) and active (A) magnetospheric dynamics. The idea being pursued is that statistically stable, but dissimilar, nonlinear processes are involved in Q and A periods.

The H_{sym} time-series can be tested for nonlinear correlations in numerous ways. A general methodology is to estimate how a fluctuation measure, denoted here by F , scales with the size n of the time window considered. Specific methods, such as Hurst's rescaled range analysis [Hurst, 1951], power spectral analysis, structure function analysis [Abramenko *et al.*, 2002], or detrended fluctuation analysis [Peng *et al.*, 1995], all essentially calculate such a fluctuation measure, although the measure is different for each technique. Typically, $F \propto n^\alpha$, where α is the scaling exponent. For a time series that follows fractional Brownian motion (fBm) the relationships between the scaling exponents of the various methods are simple.

I employ a detrended fluctuation analysis (DFA) to the H_{sym} data. For this analysis technique, an uncorrelated time series gives $\alpha = 1/2$, as for standard Brownian motion. If $\alpha > 1/2$ ($\alpha < 1/2$) the data demonstrate correlation (anticorrelation). The analysis is employed on the H_{sym} time-series covering 22 years of data, from 1981 through 2002. The detrended fluctuation analysis was applied to Q and A periods selected for each year. The scaling exponent for Q periods was generally close to $1/2$, but for A periods was usually greater than $1/2$.

The rest of this paper is organized in the following fashion. In Section 2 I describe the data selection methodology. Section 3 gives background information about fBm and a description of the DFA technique. The results of the DFA of H_{sym} are shown in Section 4, and Section 5 discusses the results and their relevance to space storm prediction.

2. Data selection

To ensure the data were selected that were representative of a magnetospheric quiet or active state, I relied not only on H_{sym} , but also on the Kp index. Generally, when H_{sym} indicates significant activity, there is usually significant Kp activity also. Since H_{sym} is calculated exclusively from low- to mid-latitude magnetometer stations, and Kp includes higher-latitude stations, quiet interval data selection based on Kp ensures that data are selected for which the entire magnetosphere is as close as possible to a ground state.

On the other hand, during active times such as space storms, Kp is large and H_{sym} reaches large negative values. However, sometimes H_{sym} shows only small activity even when Kp is large, demonstrating dynamic activity (for example, magnetospheric substorms) at higher-latitude regions of the magnetosphere. Thus use of Kp to select events ensures that data are selected for which the magnetosphere is truly Q or A over a wide range of latitudes.

For each year, 10,000 consecutive minutes (i.e. 10,000 data points) that have the largest/smallest mean Kp were selected as representative of A/Q states. For each of the 22 years, the active times corresponded to magnetic storms. The average mean values of Kp for each year are shown in Figure 2. The upper curve (stars) shows Kp for the most active intervals, and the lower curve (circles) shows the corresponding average values for quiet intervals.

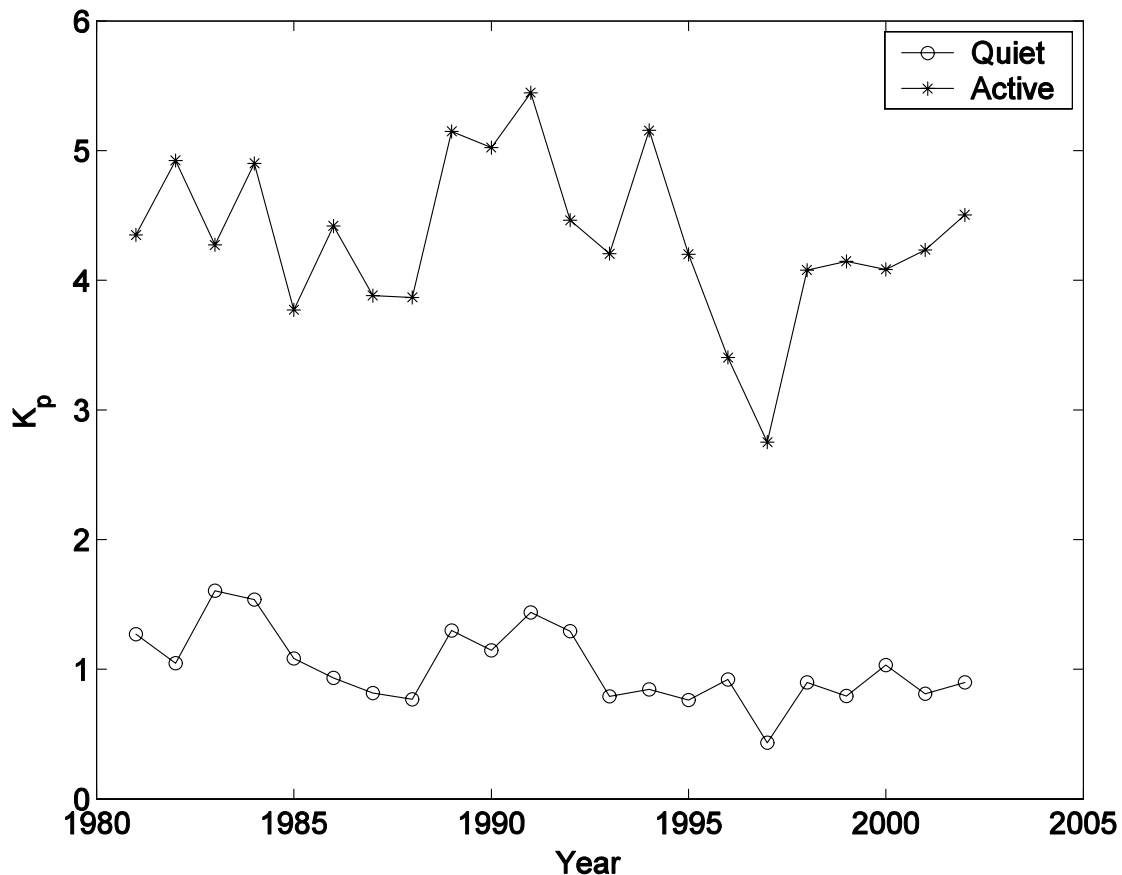


Figure 2. Smallest (circles) and largest (stars) mean values of Kp for 10,000 consecutive minutes in each year from 1981 through 2002.

The solar cycle influence on the data selection criterion is weakly evident as both Q/A events have smallest values near solar minimum (solar minimum around 1986 and 1996). Figure 3 shows the minimum H_{sym} values from each of the yearly 10,000 samples. Intervals of low activity, representing Q periods, generally have $H_{\text{sym}} > -40$ nT (100% of events) and A periods have $H_{\text{sym}} < -80$ nT (82% of events). For the A events, most of the data correspond to intense space storm events [Gonzalez *et al.*, 1994]. The mean and standard deviations are indicated as the dashed lines, with appropriate quiet and active symbols, to the right of the figure.

In Figure 4 the averages of H_{sym} for all 22 years for both Q and A events are shown. This figure indicates that the A periods generally encompass extreme space storms, and that they typically begin with the main phase of a space storm (featuring large negative H_{sym} values), and

include a large proportion of the dynamic recovery phase. Q periods tend to trend upwards with mean values between -10 and $+10$ nT.

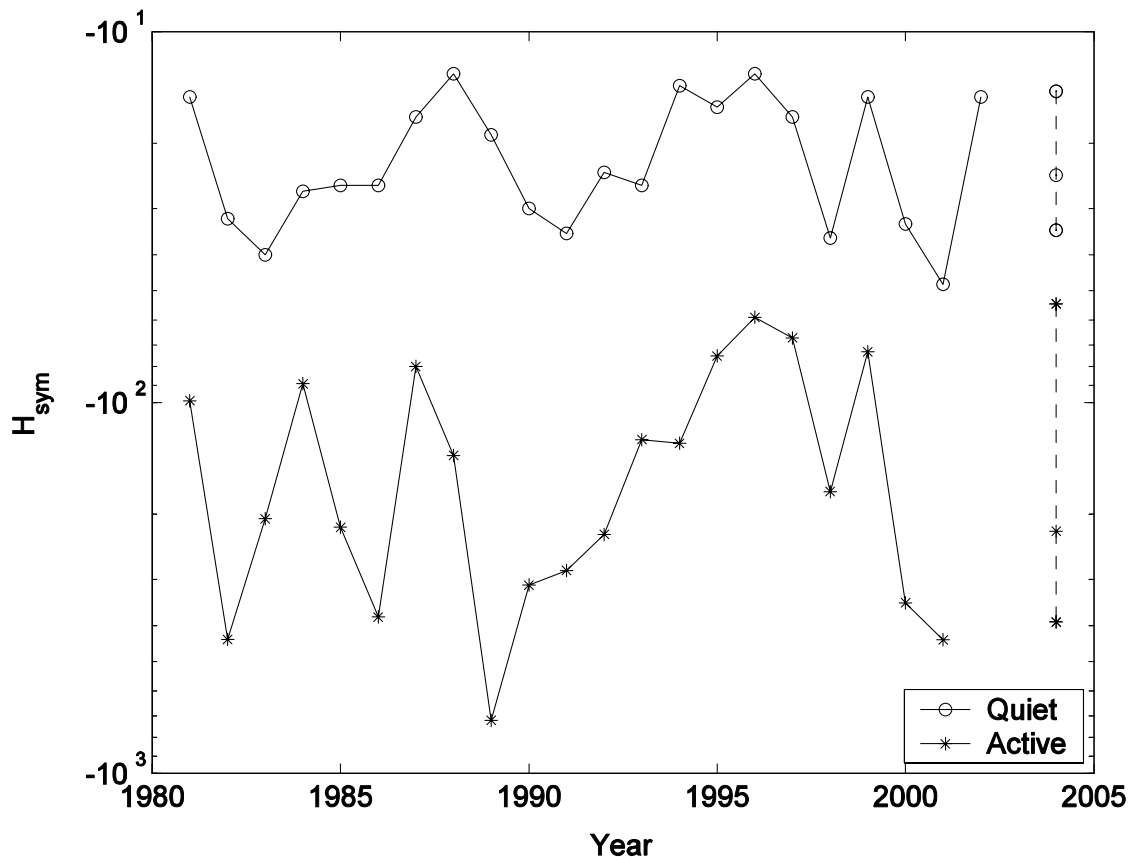


Figure 3. Smallest value of H_{sym} for each year's dataset for Q (circles) and A (stars) intervals.

3. Analysis technique

Many naturally occurring physical phenomena can be effectively modeled using fractal processes. Among the simplest models that display long-range dependence, one can consider the fractional Brownian motion. Fractional Brownian motion (fBm) is the process defined as the fractional integration of a Gaussian pure white noise. Typically, fBm is nonstationary, and thus detection of the presence of memory is a delicate task. It has been observed in the variety of the and scientific fields, including hydrology [Neuman and Federico, 2003], geophysics [Frisch, 1997], biology [Collins and De Luca, 1994], telecommunication networks [Taqqu et al., 1997], and other fields.

Fractional Brownian motion has been observed in numerous space physics data, although they may also be described in other ways. The scaling properties of space physics data during dynamic magnetospheric activity were investigated by Ohtani et al. [1995]. They found that magnetic fluctuations in the magnetotail were well described as self-affine data with a power law spectrum. Studies of geomagnetic indices have served as particularly fruitful examples of fractional Brownian motion in space physics [Sharma, 1995; Takalo et al., 1999; Price and

Newman, 2001; Wanliss and Reynolds, 2003]. It will therefore not come as a complete surprise to discover that the H_{sym} series also presents a space physics example data that may be fBm.

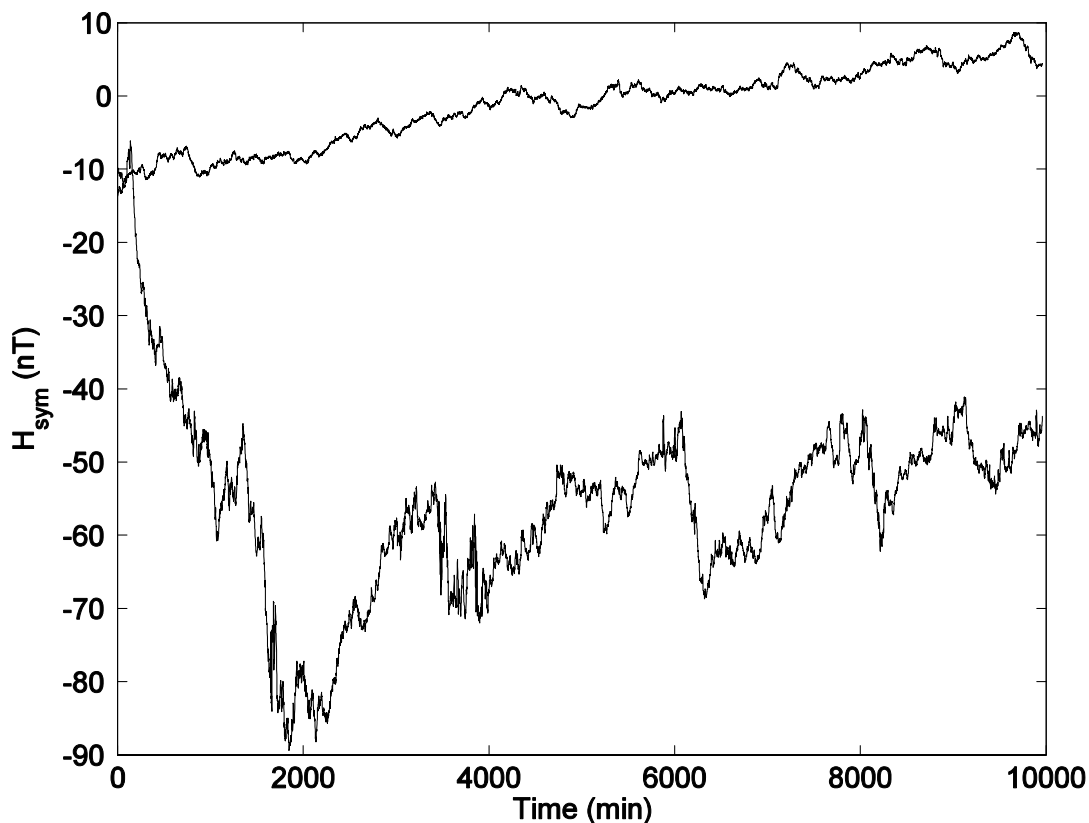


Figure 4. Average value of H_{sym} for the 22 years' data. The upper curve is for Q intervals, and the lower curve is for A events.

In this paper, I present a relatively new method of nonlinear analysis that has only recently seen use in space science research [*Ivanova et al., 2003*]. Novel ideas from statistical physics led to the development of the detrended fluctuation analysis (DFA) [*Peng et al., 1995*]. The method is a modified root mean squared analysis of a random walk designed specifically to be able to deal with nonstationarities in nonlinear data, and is among the most robust of statistical techniques designed to detect long-range correlations in time series [*Taqqu et al., 1996; Cannon et al., 1997; Blok, 2000*]. DFA has been shown to be robust to the presence of trends [*Hu et al., 2001*] and nonstationary time series [*Kantelhardt et al., 2002; Chen et al., 2002*].

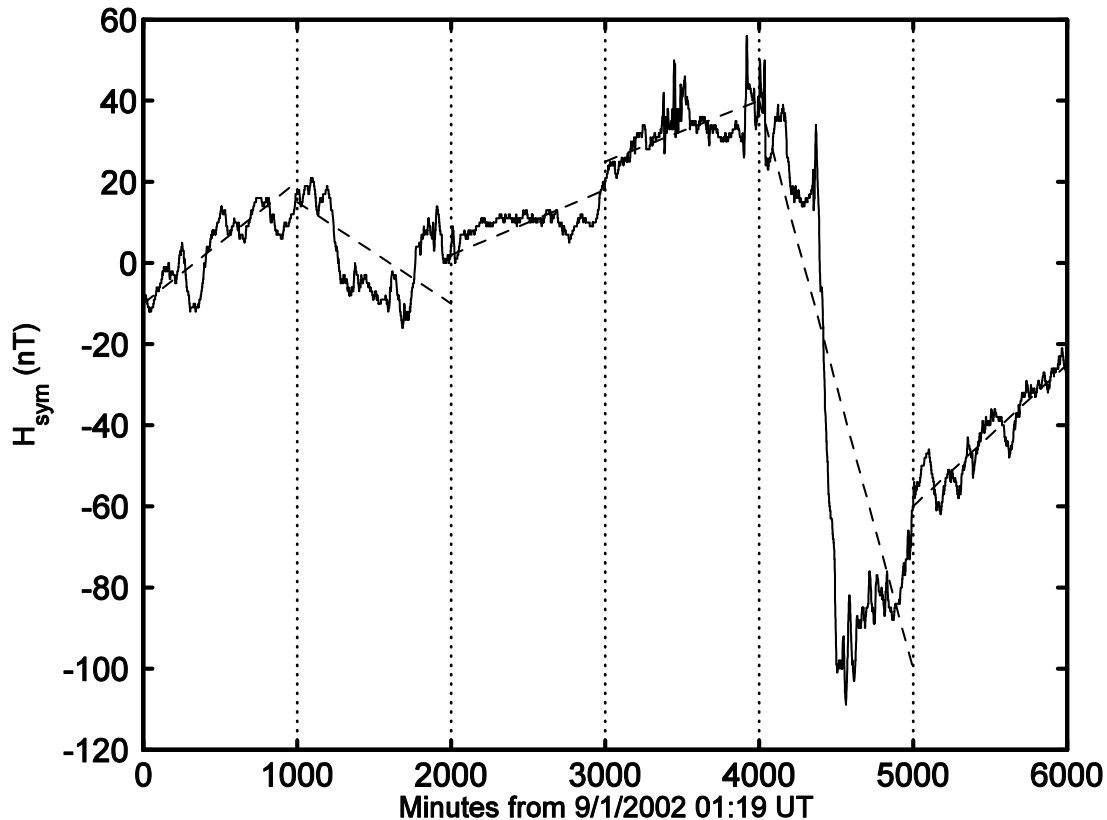


Figure 5. 6000 minutes of H_{sym} data are shown in this figure. The vertical dotted lines indicate box of size $n=1000$, and the dashed straight line segments represent the trend estimated in each box by a least-squares fit.

The technique begins by the division of the time series into boxes of varying length n (Figure 5). In this example, $n=1000$. After this, a least-squares linear fit to the data signal is performed for each box; this linear fit represents the local trend in each box. Next, for each box the root mean squared deviations $F(n)$ of the signal from the local trend is determined. This procedure is repeated for different box sizes. Finally, the log-log plot of the deviation, $F(n)$, versus box size is used to calculate the slope which gives the scaling exponent, α .

4. Results

Figure 6 shows the Q/A H_{sym} data selected for epoch 1985. As was evident in the yearly means, the Q period trends up and the A period includes an extreme space storm near the beginning of the data interval. The Q period is from June 13, 1985 at 3 UT, and the A period is from April 19, 1985 at 12 UT.

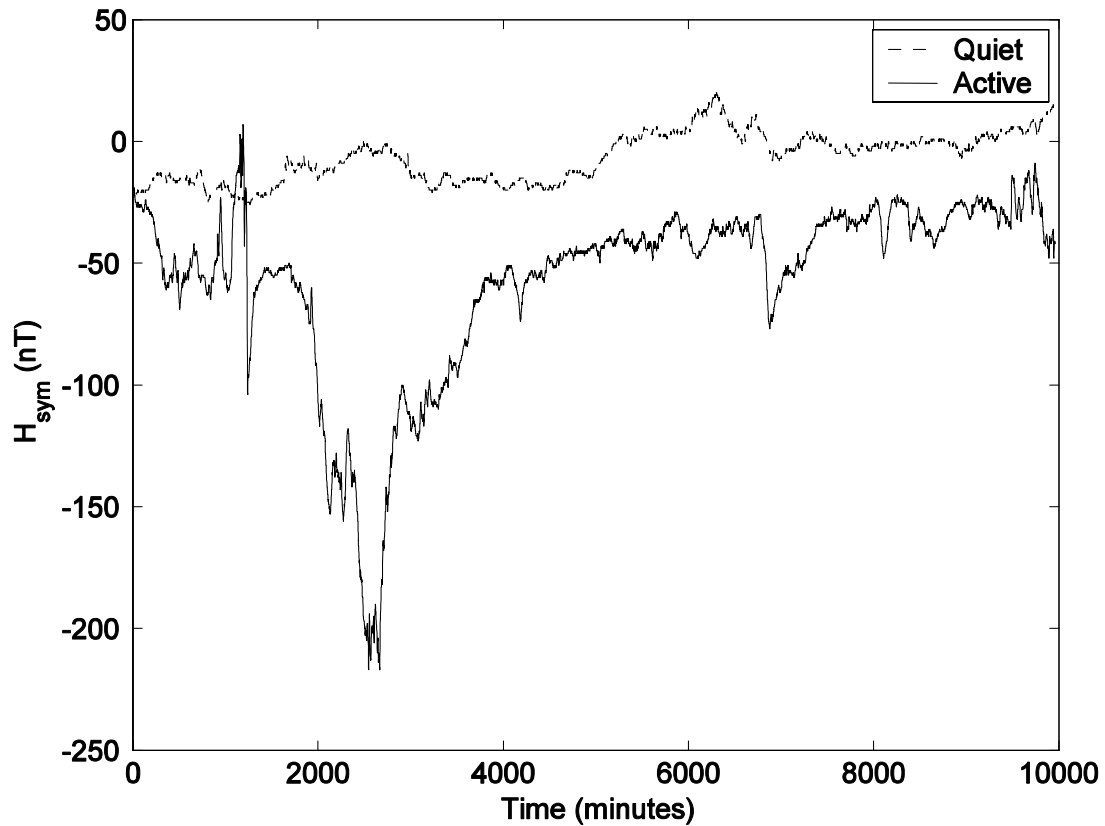


Figure 6. Q and A periods selected for 1985.

The log-log plot of fluctuation versus box size for epoch 1985, calculated from DFA, is given in Figure 7. The upper curve (stars) shows the fluctuations for the A interval, and the lower curve (circles) shows the fluctuations for the Q interval. Both curves are well fit by a straight-line, the upper yielding a scaling exponent $\alpha = 0.60$, quite different from the dashed reference curve, which has $\alpha = 0.50$, corresponding to a random walk. This means that the A data are correlated, or persistent. The nonlinear statistical behavior of the Q data is quite different. They fit $\alpha = 0.50$, consistent with a random walk.

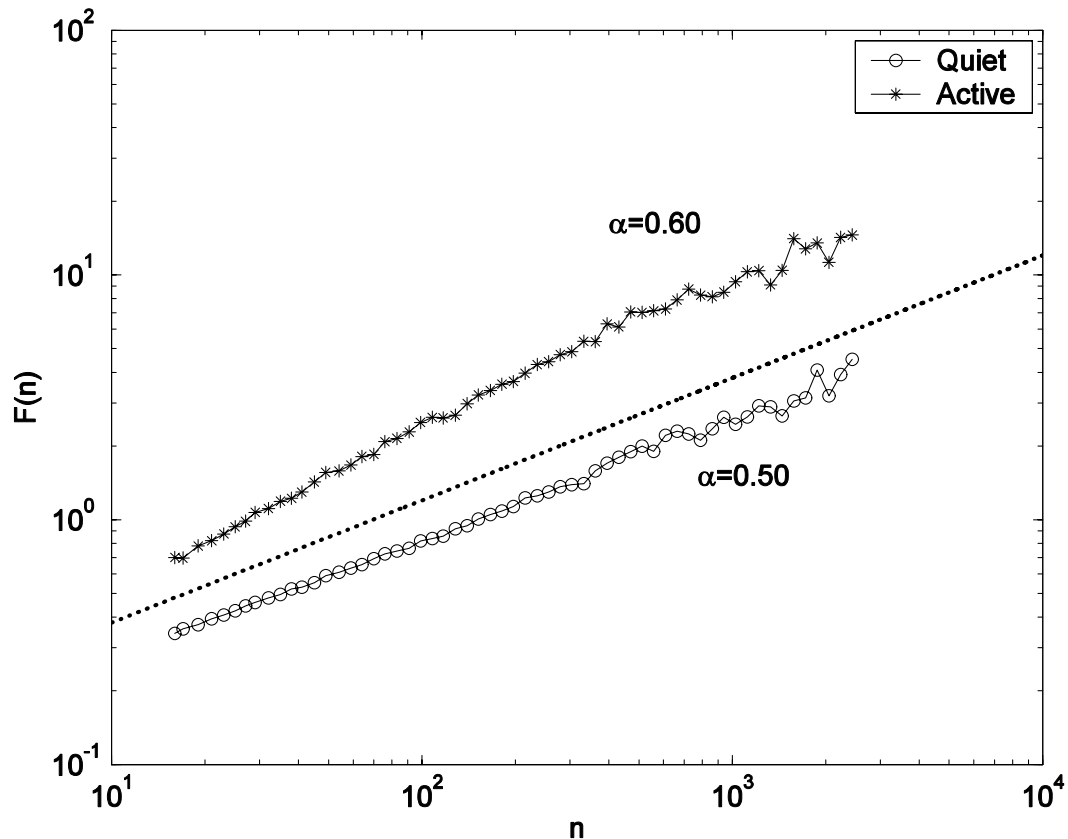


Figure 7. Fluctuation versus box size for Q and A periods for 1985.

In Figure 8 I show the calculated scaling exponents for each of the 22 years in the dataset. The mean and standard deviations are indicated as the dashed lines, with appropriate quiet and active symbols, to the right of the figure. Around solar minimum (near 1996) the scaling exponents for Q/A intervals are quite similar. This is probably an indication that during solar minimum the Kp selection criterion fails to properly separate dynamical behaviors. During the solar minimum the selection criterion gave Kp only slightly larger than 3 for the A interval (Figure 1). All other A intervals typically had Kp~4, usually larger. Even so, for all but two years $\alpha_A > \alpha_Q$.

The variability appears most sensitive for the Q intervals -- the scaling parameters for Q/A intervals, are similar when Kp values are close. For all events, the averages are $\alpha_Q = 0.498 \pm 0.039$ and $\alpha_A = 0.548 \pm 0.044$. To determine whether these averages are significantly different from the null hypothesis - that the difference is due purely to randomness - I apply the students-t test, and find $t = 3.880$, $p = 3.726 \times 10^{-4}$. These results imply that the difference between the statistics computed for Q and A intervals are significant; the likelihood that the means are different due to random processes is only a small fraction of 1%.

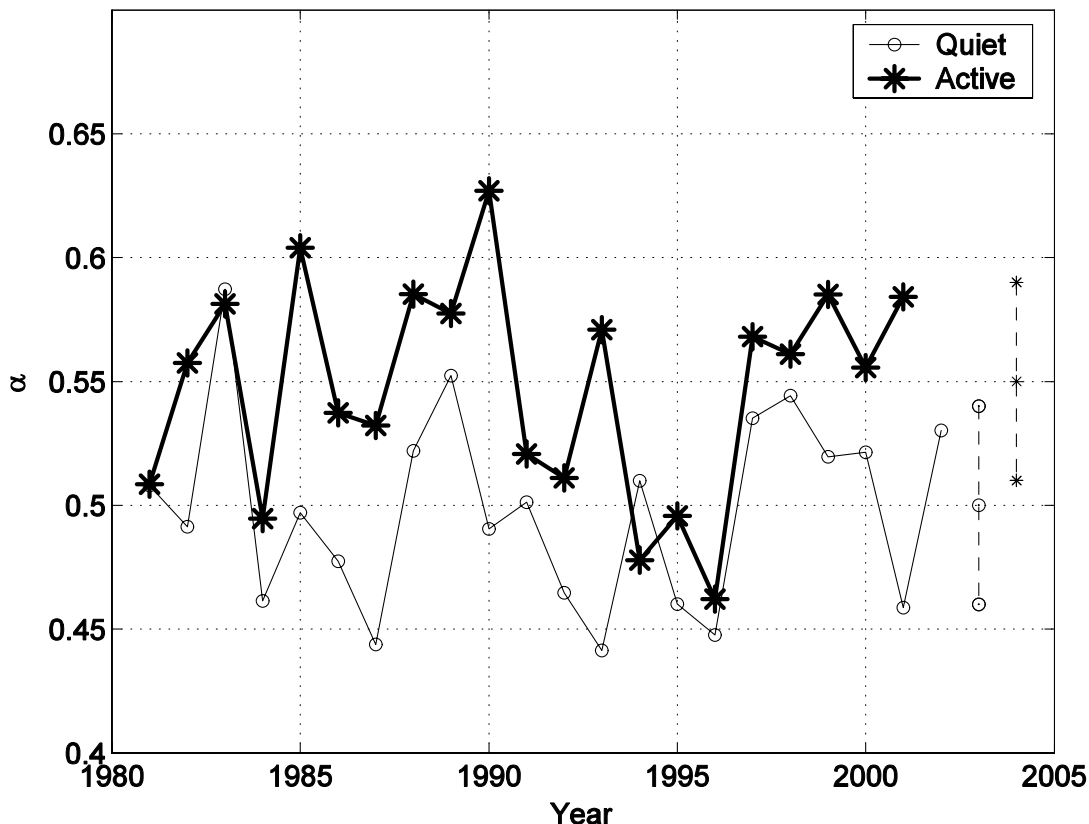


Figure 8. Scaling exponents for both Q and A periods for 1981-2002.

5. Discussion

The goal of this research has been to characterize the differences in the scaling behavior between magnetospheric quiet and active dynamics over two solar cycles. To this end, I have applied the DFA method to quantify long-range correlations embedded in the nonstationary H_{sym} time series. The DFA method was selected because it copes very well with nonlinearity and nonstationarity. The method is particularly well-suited to analysis of the nonstationary H_{sym} data because it avoids spurious detection of correlations that are artifacts of nonstationarity. In particular, I have analyzed the most quiet and active periods for each of the 22 years between 1981 and 2002. For statistical robustness, each Q and A data subset selected for analysis comprised 10,000 consecutive H_{sym} values, at one-minute sampling interval. Through selection of only one representative Q and A interval for each year, it is possible to characterize the variation of the scaling exponents over two solar cycles.

The nonlinear statistical properties between Q and A events were noticeably different. In general, however, for each year, Q and A subsets generally clustered around their own unique values. A statistically consistent difference was found between the nonlinear scaling exponents for Q and A the events; $\alpha_Q = 0.498 \pm 0.039$ and $\alpha_A = 0.548 \pm 0.044$.

When the calculated scaling exponents are compared to the minimum H_{sym} for each selected interval, an interesting trend is apparent, as shown in Figure 9; less negative H_{sym} corresponds to smaller scaling exponents. Similarly, more negative H_{sym} , most common for the active intervals

(stars in Figure 9) tends to result in larger scaling exponents. This trend will be investigated in future research with a larger subset of the H_{sym} series.

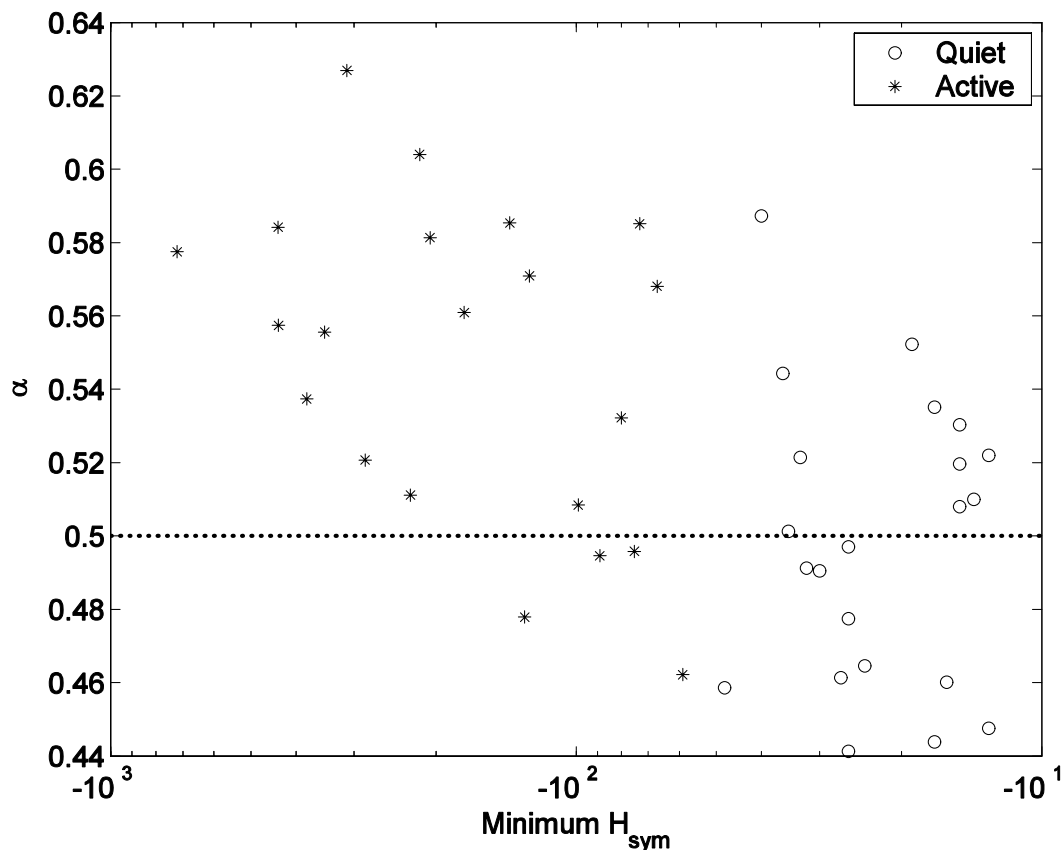


Figure 9. Comparison of the computed scaling exponent versus the minimum H_{sym} for the chosen interval.

In conclusion, these results demonstrate that the nonlinear statistical behavior of the magnetosphere, as derived from H_{sym} , is markedly different during Q and A intervals. The transition from Q to A phases during a space storm represent a period of potentially increased statistical variability, because it represents a transition from a random walk ($\alpha \sim 0.5$) to weakly correlated ($\alpha \sim 0.6$) regulation of the magnetospheric dynamics. The active intervals selected in this study included space storms in 100% of the cases. Since space storms frequently are preceded by quiet intervals, and are themselves characterized by global dynamic activity, the results presented here raise interesting questions that will be investigated further. For example, does the transition to storm times feature a repeatable change in nonlinear statistical behavior? Preliminary results indicate that the onset of storm times (Q to A intervals) are presaged by alterations in the scale-invariant properties of H_{sym} . By monitoring the variations of these scale-invariant properties one may be able to develop a method to predict the coming storm onset (to be presented in another paper).

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