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STUDY ON THE COMPLEXITY MEASUREMENTS ON MAGNETOSPHERE DURING SOLAR MAXIMUM AND MINIMUM OF 23rd SOLAR CYCLE

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ABSTRACT

The Earth's magnetosphere is a cavity filled with hot, but dilute plasma embedded in the fast-flowing denser, but colder solar wind plasma and is a vast laboratory for plasma physics. The interaction between the terrestrial magnetic field and magnetoplasma structures that originate at the Sun results in Geomagnetic storms. The dissimilarity of complexity between pre-storm period and major magnetic storms (Dst <-100) during solar maximum and solar minimum of 23rd solar cycle are studied. The space plasma is a nonlinear system that evolves dynamically and generates complex fluctuations in its output signals reflecting the complex dynamics .The system dynamics is studied using different statistical tools namely Tsallis Entropy, Rényi Entropy and Hurst Exponent. For the study of complexity variations during solar maximum and solar minimum of 23rd solar cycle we used the time series derived from the Horizontal component of Earth's Magnetic field (H), namely ΔH time series. Our study shows that Tsallis and Renyi entropies detect the alterations of pattern in ΔH time series prior to the intense storm events. These parameters are capable of discriminating different states of the magnetosphere. The patterns followed by the entropies exhibit variations in solar maximum and minimum. The Hurst exponent values representing the persistent and antipersistent behaviour agree with Tsallis and Renyi entropy values.

KEYWORDS: Magnetosphere, Magnetopause, Dst, Tsallis Entropy, Rényi Entropy, Hurst Exponent.

A geomagnetic storm is a temporary disturbance of Earth's magnetosphere caused by a solar wind shock wave and/or cloud of magnetic field that interacts with Earth's Magnetic field. The interaction between the terrestrial magnetic field and embedded hot plasma and particular magnetoplasma structures that originate at the Sun and propagate to the near-Earth space environment results in Geomagnetic storms. A geomagnetic storm has three phases: initial, main and recovery. The level of geomagnetic activity is measured using different activity indices, such as Dst, Kp and AE, most of which are derived from ground-based magnetic field measurements.

In the present study we analysed whether certain signatures of ΔH time series indicate the transition from pre-storm activity to magnetic storms. The Dst data used in this study include 17 intense magnetic storms occurred during the solar maximum and 4 during the minimum of 23rd solar cycle. The complex system of the Earth's magnetosphere corresponds to an open spatially extended non-equilibrium (input - output) system; therefore we employ the time-dependent Tsallis entropy (Sq), Rényi Entropy and Hurst Exponent as measures of dynamics complexity.

DATA AND THEORY

ΔH Time Series

ΔH time series indicates the variation of horizontal component of Earth's magnetic field from its midnight value. ΔH is calculated as

$$\Delta H_i = H_i - H_{\text{Midnight}}$$

H_{Midnight} is calculated as the average of midnight H values.

The periods of study includes Solar Maximum (2000-01) and Solar Minimum (2005-06) of the 23 rd Solar Cycle.

Selection Of Stations

For data collection stations are selected from different latitudes. In the present study stations are selected from three latitude regions: Low (0^0-20^0 N), Mid (21^0-45^0N), High (46^0-80^0N), all lie in same longitude region (< 20^0), so that the effect of longitudinal variation can be neglected (Table 1).

Tsallis Entropy

If p_i are the probabilities associated with a microscopic configurations whose total number is W, an expression for nonextensive Boltzmann-Gibbs entropy was proposed by Tsallis [1988, 1998] as

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$$Sq = k \frac{1}{q-1}\left(1 - \sum_{i=1}^{w} P_i^q\right)$$

where q denotes the measure of the nonextensivity.

The entropic index q characterizes the degree of nonadditivity reflected in the following pseudoadditivity rule:

$$Sq(A+B) = Sq(A) + Sq(B) + (1-q)Sq(A)Sq(B)$$

Using the concept of symbolic dynamics, the Sq for the word length L is

$$S_q(L) = k\frac{1}{q-1}\left(1 - \sum_{(A1,A2,\ldots AL)} \left[P(L)_{A1,A2,\ldots AL}\right]^q\right)$$

If the Tsallis entropy is smaller for a particular period of the signal, it implies the reduction of complexity of the signal for that period. Thus, the Tsallis entropy and its temporal variation highlight the dynamic variability of the complexity of a system. The technical details of estimation of Tsallis entropy were given in Balasis et al. [2006, 2008 and 2009].

Renyi Entropy

The Rényi entropy of order α, where $\alpha \geq 0$ and $\alpha \neq 1$, is defined as

$$H_{\propto}(X) = \frac{1}{1-\propto} log\left(\sum_{i=1}^{n} P_i^{\propto}\right)$$

Here, X is a discrete random variable with possible outcomes 1, 2, 3, … n and corresponding probabilities pi = Pr (X = i) for i=1, 2, 3, … n, and the logarithm in 4 is base 2.The Rényi entropy is a measure of information of order associated with probability distribution $P = (p_1 \ldots p_n)$. The Rényi measure of information H may also be viewed as a measure of uncertainty.

Hurst Exponent

To quantify the tendency of a time series either to regress to the mean value or to cluster in a direction, Hurst in 1951 introduced the so-called Hurst exponent [Masci and Thomas, 2013]. For a given discrete time series P of length N, divide it into subseries p_n of length n = N, N/2, N/4, … Let p_{nmean} and S_n be the mean and standard deviations of each series p_n of length n. Now, for j=1, 2, 3,…, n, create the series of differences from the mean

$$t_j = P_j - Pn_{mean}$$

The cumulative deviate series from the mean

$$T_j = \sum_{i=1}^{j} t_j$$

The range R_n is estimated as

$$Rn = (T_j)_{max} - (T_j)_{min}$$

It is observed that R_n/S_n scales, with respect to the length n of the subseries p_n, by the power law

$$\frac{R_n}{S_n} \propto n^H$$

Hurst exponent (H) is estimated by the slope of the best fit line in log (R_n/S_n) versus log (n) representation of the R_n/S_n power law [Masci and Thomas, 2013].

The value of H lying in the range, $0<H<0.5$ indicates that fluctuations of a system will try to attain stability by inducing a negative feedback mechanism - antipersistent behaviour. If $0.5<H<1$, the time series exhibits persistent behavior. That is, if the fluctuations increase in a particular interval, there is a chance to increase it further in the next interval by a positive feedback mechanism.

RESULTS AND CONCLUSION

The present study shows that Tsallis and Renyi entropies detect the alterations of pattern in ΔH time series prior to the intense storm events and are able to discriminate between the different states of the magnetosphere. These tools clearly distinguish between two distinct patterns, one corresponds to intense magnetic storms (Disturbed periods), which is characterised by a higher degree of organisation and the other corresponding to the normal periods (quiet periods), which is characterised by a lower degree of organisation (Fig.1 & Fig.2).

The results suggest that a significant complexity decrease coupled with appearance of persistency can be confirmed in the ΔH value at the transition from pre-storm activity to intense magnetic storms. Hence this may be used as a tool for analysing forthcoming extreme events in space plasmas (Fig.3 & Fig.4).

The Hurst exponent values representing the persistent and antipersistent behaviour agree with Tsallis and Renyi entropy values. Also the values show variation during solar maxima and minima. In short, Tsallis and Renyi entropies, along with Hurst exponent can be used as powerful tools in space weather applications.

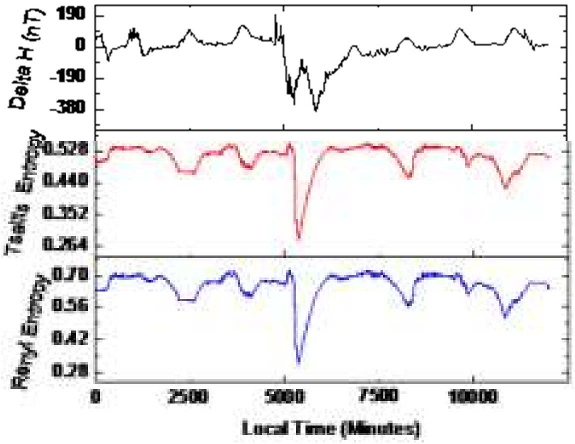

Figure 1: Plots representing the temporal variation of Delta H, Tsallis Entropy & Renyi Entropy during the MS event → Bangui -- 31st March 2001

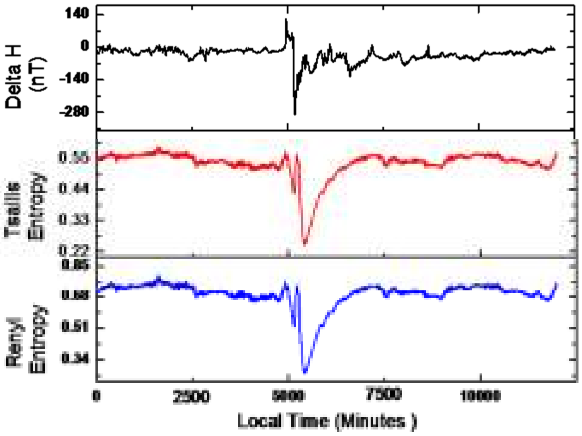

Figure 2: Plots representing the temporal variation of Delta H ,Tsallis Entropy & Renyi Entropy during the MS event → Dourbes 15th May 2005

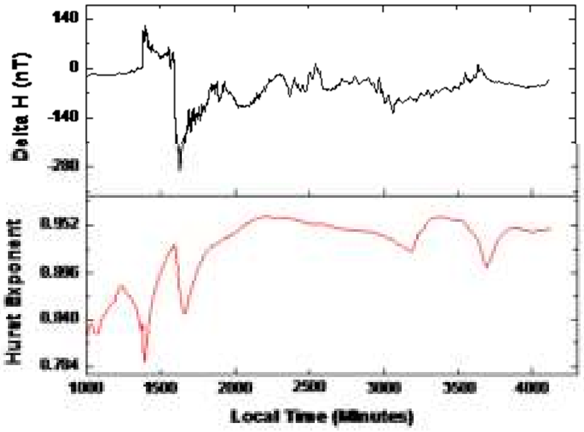

Figure 3: Plots representing the temporal variation of Delta H & Hurst Exponent during the MS event → Dourbes 15th May 2005

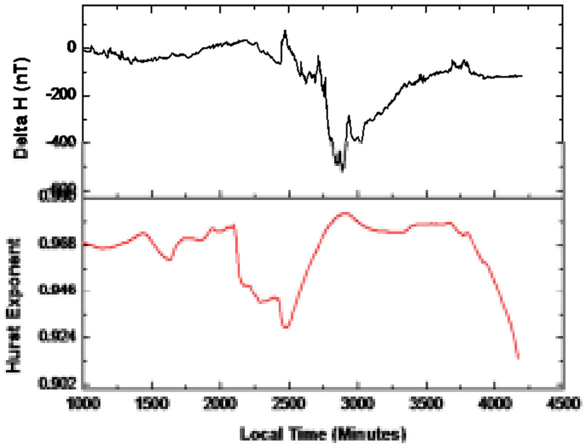

Figure 4: Plots representing the temporal variation of Delta H & Hurst Exponent during the MS event →Bangui 15th July 2000

Table 1: Selected stations from Low, Mid and High latitudes.

Low Latitude

Name of Station	Abbreviation	Geodectic Lat	Geodectic Long
Bangui	BNG	4.33N	18.57E
Mid Latitude			
Tamanrasset	TAM	22.79N	5.53E
L'Aquila	AQU	42.38N	13.32E
High Latitude			
Dourbes	DOU	50.10N	4.60E
Nurmijarvi	NUR	60.51N	24.66E
Homsund	HRN	77.00N	15.55E

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