7.2 FRACTAL STATISTICS OF SUN AND IMF, A PRACTICAL PREDICTION TOOL

Donald E. Cotten*, T. D. Cheung, P. J. Marchese, G. Tremberger, L. P. Johnson, S. A. Austin, G. Brathwaite, M. Chow, L. Corrales, J. Espinoza, and K. Leon
City University of New York

1. Abstract

Past results presented by the City University of NY (CUNY), (2006 AMS Space Weather Symposium paper 3.10), related the Higuchi fractal dimension of the interplanetary magnetic field (IMF) fluctuation sigma-B data, taken from the ACE (Advanced Composition Explorer) spacecraft, and found it to be lower when the fluctuation (sigma-B) was large. Sigma-B was found to correlate well with the peak flux of solar energetic particles (SEP). These results have been extended, along with assimilation of data from the SOHO (Solar Heliographic Observatory), GOES (Geostationary Orbiting Environmental Satellite), and POES (Polar Orbiting Environmental Satellite) spacecrafts, and consideration of the directions and strengths of the IMF and CME (coronal mass ejections) of the various selected storms. These efforts have related the fractal analysis of the IMF fluctuations preceding several magnetic storms to fractal analyses of the solar photospheric pixel brightness across the solar disc (taken from the SOHO spacecraft), near and including the identified eruption regions. It was thus found that a sub-eruption preceding the final eruption was itself preceded by a peak in the time sequence of fractal dimension and of the auto-correlation of the Solar pixel brightness data. POES data interpretations suggest that CME energy may be partly deposited in the Earth's lower atmosphere, and we find a possibly related timing coincidence. CUNY expects to continue and to expand these statistical studies, and to attempt to develop the use of fractal dimension and other statistics as a magnetic storm forecasting tool.

2. Introduction

SOHO observes the Sun; ACE measurements include the IMF, both from near the Lagrangian point L1. GOES and POES are spacecraft near earth. SEP derive their energy from a solar magnetic source. LASCO (Large Angle Spectrometric Coronagraph, on SOHO) revealed that CME events average about 3 per day. CME collisions are an important source of SEP production, along with magnetic reconnection in and below the corona.

Solar eruptions can produce CME that generate high flux SEP. Both high and low flux SEP, and IMF fluctuations, result in geomagnetic storms that affect Earth's atmosphere. Cheung (2004) showed that peak values in the high flux SEP events correlate with CME speed (r = 0.94). Cotten (2004) showed that the fluctuation of the IMF as measured by a sigma-B distribution tail area parameter (the number of occurrences of 0.5 nT or larger sigma-B during the 6 hours preceding the onset of Dst) also had a high correlation (r = 0.92) with the observed Dst (Disturbance storm time) peak value. Cotten (2006) showed correlation (r = 0.95) of IMF fluctuation with high SEP flux in strong magnetic storms. There are also many low flux events. Of the few thousand known magnetic storm events, this preliminary report covers about 100 selected storms.

This study used the transverse Solar spatial data of the SOHO EIT (Extreme Ultraviolet Imaging Telescope) data and the IMF time series data of ACE, along with data from GOES, and data and conclusions from a POES study. An analysis of several storm events is reported herein. The October 28-29, 2003 storm carried SEP peak flux of 29500 pfu (> 10 MeV) and a Dst of about -400 nT.

IMF time series data are a somewhat random series. The spatial data across the SOHO image is shown herein to be a random data series, via auto-correlation analysis. Thus, fractal dimension can be appropriately used, and was used to characterize the spatial series random data as well as the corresponding IMF time series data.

The fractal analysis was performed using the Higuchi method (Higuchi 1988). The observational intensity (Intensity count) random series with equal intervals was used to generate a delta series for different lags $\tau = 2k$ in the time variable, in analogy to the auto-correlation algorithm. The non-normalized apparent length of the Intensity I time series curve is simply L(k) = Sum of absolute (I(j)-I(i)) for all j-i pairs equal to k. The normalization constant depends on k and is given in the literature (Higuchi 1988). If the Int(i) is a fractal function, then the graph ln (L(k)) versus ln (1/k) should be a straight line with slope equal to the fractal dimension. The Higuchi fractal algorithm was calibrated with the Weierstrass function: $W(x) = \Sigma a^{-nh} \cos(2 \pi a^n x)$ for all the n values 1,2,3… The fractal dimension of the Weierstrass function was given by 2-h where h takes on an arbitrary value between zero and one. The random digits in the pi sequence were also used for calibration of the algorithm, which gave the fractal dimension to be about 2.3 for the first 5,000 digits.

* Affiliations: (DEC) City University of New York NYC Space Science Research Alliance, (PJM, & TDC) City University of New York (CUNY) Queensborough Community College, email: decotten@aol.com, tcheung@qcc.cuny.edu, pmarchese@qcc.cuny.edu

3. Data

The SOHO EIT 19.5 nm 1024x1024 images captured the October 28, 2003 eruption at UT 1112 and location S16E8, on the Solar surface (photosphere). The EIT instrument measured the 17.1 nm and 19.5 nm emissions, giving a temperature of about 1.5 million Kelvin. Many 19.5 nm frames before the eruption are also available for analysis. The data was a spatial series across the eruption region. The data was taken between (391, 400) to (490, 400) in pixel coordinates in each SOHO 19.5 nm FITS data file. The CME data is from ACE and GOES. The He++/H+ ratio is taken from the SWEPAM data from ACE. The IMF fluctuation was represented by the sigma-B value, as calculated by the ACE data center for the 4-minute averages.

4. Analysis and Discussion

An auto-correlation of the spatial series data was performed, along with Higuchi fractal dimension analysis. The fractal dimension is taken to be the slope between ln(1/k) of -1.5 and -3, which is consistent with a previous fractal study of IMF data (Cheung, 2006). SOHO EIT images from UT 924 to UT 1110 on Oct 28, 2003, were analyzed. The plot of auto-correlation width and fractal measure versus time plot for the SOHO Solar surface data is displayed in Fig. 1.

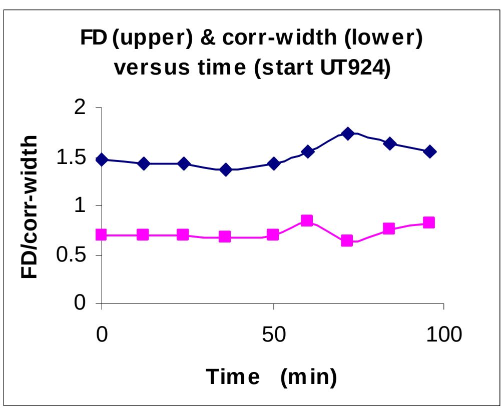

Fig. 1: Fractal dimension and auto-correlation width (arb unit) versus time, Oct 28, 2003

The auto-correlation width peaks on the UT 1024 frame (the 6-th data point) while the fractal dimension peaks on UT 1036 frame (the 7-th data point). The SOHO EIT recorded the solar eruption at UT 1112, 108 min on the plot's tick mark. The sub-eruption preceding the final eruption was preceded by the auto-correlation width peak as well as by the fractal dimension peak.

ACE also recorded the disturbance the next day, Oct 29, and the fractal analysis of sigma B is displayed in Fig. 2. Typical fractal length curves of the solar disc spatial series data were similar to those of sigma B.

The fractal dim of sigma B decreased as the disturbance arrived. The fractal dimension for the sigma-B data in the 6-hr period (called period A) preceding the dip of Dst was about 1.7. This low fractal dimension is consistent with a long tail feature usually found in Levy distributions. This value is consistent with an earlier study of IMF data from the IMP spacecraft (Kabin 1998). The fractal dimension

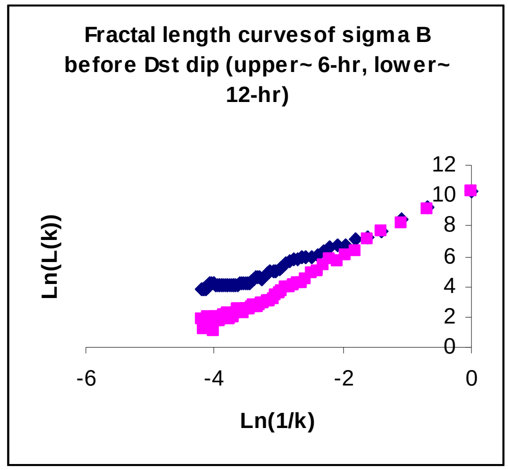

Fig. 2: The fractal length curve of sigma B for two time periods (Oct 29 2003 storm). Upper is the 6-hr period before the Dst dip. Lower is the 6-hr period before that of the upper curve data. The lower curve (slope ~ 2.3) was shifted vertically by about 5.7 so that it matches the upper curve (slope ~ 1.7) at the origin for easy comparison.

for the sigma-B data in the 6-hr period preceding period A was about 2.3, which is consistent with a Gaussian-like distribution. The fractal dimension of sigma-B may serve as another marker for IMF fluctuation.

Other high SEP flux solar eruptions with face-on SOHO 19.5 nm spatial data were also analyzed and the results were similar. The analyzed events were 2000-7-14 (SEP 24,000 pfu), 2001-9-24 (SEP peak 12,900 pfu), and 2001-11-22 (SEP peak 18,900 pfu). In all these events, the fractal dimension changed in the period preceding the eruption.

The IMF fractal dimension changes at ACE were also useful for analyzing low SEP flux events, not observable in the SOHO data. A low SEP flux solar eruption CME event on Sept 7, 2005 generated a SEP peak flux of 1,880 pfu on Sept 11, 2005. The Dst value was about -150 nT. ACE recorded the disturbance on Sept 11, 2005. The fractal dimension for the sigma-B data in the 6-hr period (period A) preceding the dip of Dst was about 1.7. The fractal dimension for the sigma-B data in the 6-hr period preceding period A was about 2.0. The fractal analysis of sigma B is displayed in Fig. 3.

A very low SEP flux solar eruption CME event on Aug 22 2005 (peak 330 pfu) was also analyzed. This very low SEP flux CME caused a Dst dip of -200 nT when the maximum SEP flux was observed just a few hours after the solar eruption, indicative of a very high speed CME. Nonetheless, the IMF fractal dimension decreased as the CME disturbance arrived for the very low flux Aug 22, 2005 event. The fractal dimension for the sigma-B data in the 6-hr period (A) preceding the dip of Dst was about 2.0. The fractal dimension for the sigma-B data in the 6-hr period preceding period A was about 2.2. The fractal analysis of sigma B is displayed in Fig. 4.

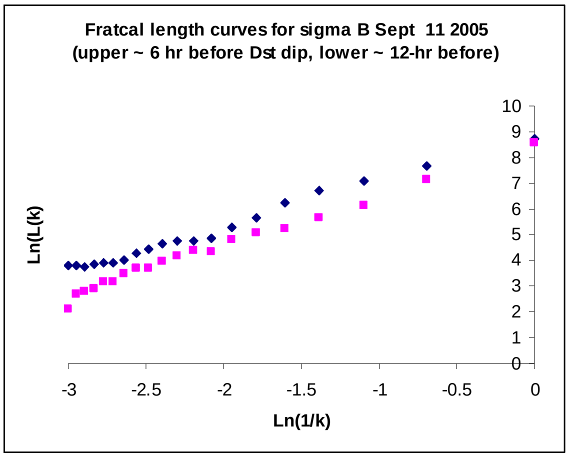

Fig. 3: The fractal length curve of sigma B for two time periods (Sept 11 2005 Dst dip). Upper is the 6-hr period before the Dst dip. Lower is the 6-hr period before that of the upper curve data. The lower curve (slope ~ 2.0) was shifted vertically by about 3 so that it matches the upper curve (slope ~ 1.7) at the origin for easy comparison.

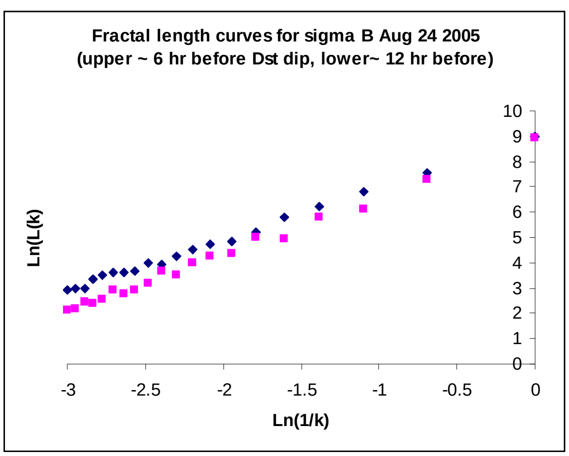

Fig. 4: The fractal length curve of sigma B for two time periods (Aug 24 2005 Dst dip). Upper is the 6-hr period before the Dst dip. Lower is the 6-hr period before that of the upper curve data. The lower curve (slope ~ 2.2) was shifted vertically by about 5 so that it matches the upper curve (slope ~ 2.0) at the origin for easy comparison.

The IMF fluctuation characterization is important for studying the energy dissipation on Earth. The CMEs and IMF fluctuations generated gigawatt power dissipation in the Earth atmosphere as indicated by the NOAA POES satellite data. The 29,500 pfu Oct 28, 2003, event generated 600 gigawatt peak power and was recorded by POES as it orbited the poles (Fig. 5). The POES data is consistent with the CME pushing onto the magnetosphere and producing higher magnetic field on the dayside. The power dissipation phase exhibited an exponential decay with constant of -0.45 per day from Oct 30 to Nov 3 (Fig. 6).

Similarly the low SEP flux event of Sept 11, 2005 generated 350 gigawatt peak power with an exponential decay constant of -0.25 per day from Sept 13 to Sept 21. Both events exhibited the enhancement of He++/H+ ratio to about 0.2. The very low SEP flux Aug 24, 2005 event, however, generated 1,200 gigawatt peak power with a relatively fast decay constant of -0.79 per day from Aug 24 to Aug 28 and the enhancement of He++/H+ ratio was not observed.

The IMF fractal dimension of this very low SEP solar eruption was about 2, suggesting that the absence of He ion enhancement would favor a more Gaussian-like distribution.

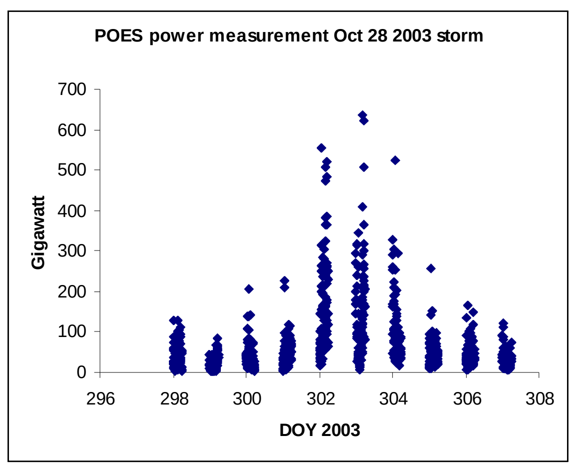

Fig. 5: POES power measurement Oct 28 2003 storm. The power peak was on Oct 30 DOY 303.

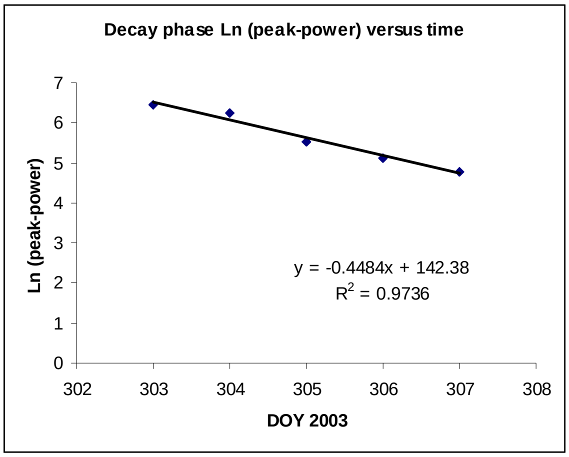

Fig. 6: Decay phase Ln (peak-power) versus time. The decay constant ~ 0.45 per day up from DOY 303 to DOY 307; Oct 30 – Nov 3, 2003

There are atmospheric processes, such as thunderstorms and hurricanes, which require high power levels as well as energy. It is interesting to note the time-coincidence of low-flux SEP event power dissipations, which were completed just before the wind-peaks of hurricanes Katrina and Rita (maximum wind speeds on Aug 28 and Sept 21, 2005, respectively).

The Earth's power budget may be related to the geo-effectiveness of a CME, at least near the equinox, and the power dissipation may be partly in the Earth's atmosphere. Whether CME power dissipation is associated with a mechanism that can energy-enhanced hurricanes deserves further study. It was reported recently that increase of magnetic field on the day side would shield more cosmic rays and thus produce less clouds, leading to surface warming (Svensmark, 2006) at near-equatorial latitudes, where hurricanes form and strengthen.

The IMF data fractal analysis was on sigma B, a second order statistic. Analyzing the SOHO data using a definition similar to sigma B in the SOHO data would be: sigma-count = abs(counts-average).

The fractal dimension of sigma-count series data resembled that of the count series data. The fractal dimension on sigma-count is consistent with the interpretation that the fractal measure represents the capacity dimension of the second order sigma statistics.

The percent increment was also investigated. The log-count-increment (which is the percent increment, d log brightness over adjacent pixel) data behaves the same as the count data in fractal dimension variation, but with a more pronounced peak at UT0948 (Fig. 7), for the Oct 28, 2003 storm.

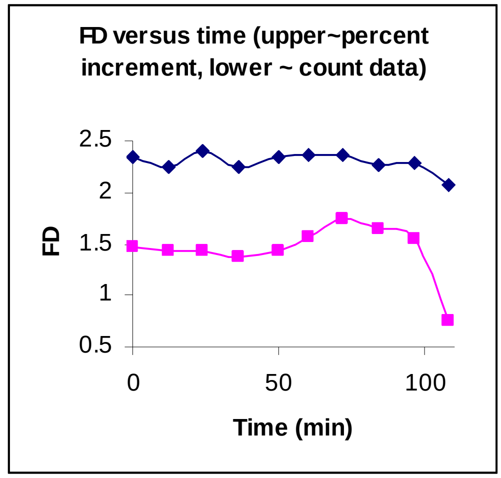

Fig. 7: Fractal dimension versus time for the percent increment data and the count data, start UT924, explosion at 108 min is included); Oct 28, 2003

The distribution width and fractal dimension for Oct 28, 2003, varied in time as in Fig. 8.

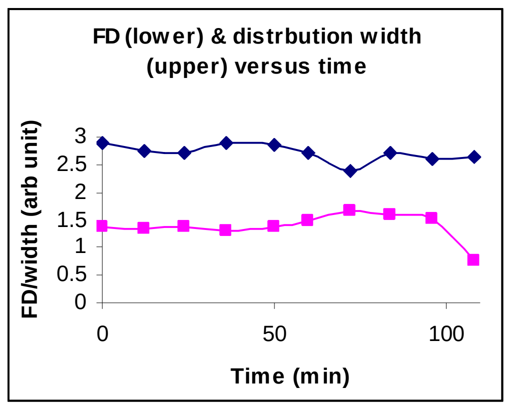

Fig. 8: Percent increment distribution width and fractal dimension versus time for the percent increment data, start UT924, Oct 28. 2003

The width increase and fractal dimension decrease for Oct 28, 2003, are consistent with a long-tailed distribution feature.

5. Conclusions

We analyzed data from SOHO, ACE, GOES and POES to acheive a consistent description of solar eruption. We have shown that fractal analysis is a useful tool to characterize the SOHO face-on solar eruption and ACE IMF fluctuation. Preceding a solar eruption, the SOHO spatial series across the solar disc appeared to exhibit an increase of fractal

dimension, as did the auto-correlation of the Solar pixel brightness data, while the CME induced IMF fluctuation appeared to exhibit a decrease of fractal dimension preceding the Dst dip. The data implies that the CME has a Levy-like distribution in the forward direction and a Gaussian-like distribution in the transverse direction. The POES data on the 1200 gigaWatt dissipation is very important. It indicates that we also need radial IMF fractal information, as well as the transverse SOHO fractal informatrion. The use of the IMF fractal for very low SEP events is important, because these events come from a very small transverse (across the solar disc) eruption but yet have a high peak power (of order 1200 gigaWatts) at Earth as indicated by the POES data near the poles.
Therefore, the IMF fractal information from ACE is an important prediction tool, although the time until arrival at earth is very short. The SOHO fractal prediction tool is valuable because the CME needs time to come, thus providing prediction lead time. But SOHO is useless for very low SEP events. The recently launched STEREO twin spacecrafts, for measuring solar events and CME in 3-dim, will provide data for further testing this fractal analysis forecasting tool. STEREO will allow us to know the forward direction fractal or distribution before the CME comes to ACE. This paper shows that fractal analysis in the radial direction can supplement the SOHO transverse fractal analysis, especially in small flux events that may have consequences on Earth.

The fractal dimension and other statistics appear to be useful magnetic storm forecasting tools, looking at the Solar photosphere just before the eruption or flare occurs.

6. Acknowledgements

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