3.10 Analysis of IMF fluctuations during solar energetic particle and magnetic storm events

Tak David Cheung, Donald E. Cotten *, Paul J Marchese, and George Tremberger, Jr.
City University of New York Queensborough Community College

1. Abstract

Signatures of high flux solar energetic particle (SEP) events related to strong magnetic storms in the interplanetary magnetic field (IMF) fluctuation were investigated. Events were identified with SEP proton flux from 15000 to 30,000 pfu (> 10 MeV proton) and Dst value less than -150 nT. The SEP proton flux data is from NOAA and the IMF data is from ACE. Several storm dates have been selected which meet the criteria. A high correlation coefficient (r~.95) between the SEP flux and the IMF 4-min sigma B distribution tail feature (the number of peaks in the pre-storm 6-hr period) was obtained. The dB-rms data was also considered. Together with our previous result that a similar high correlation existed between the peak Dst value during the storm and the IMF 4-min sigma B distribution tail feature in the pre-storm 6-hr period (AMS-Space Weather symposium 2004, Seattle, paper 3.9), this paper concludes that the IMF distribution tail feature is a significant characteristic of the fluctuation. The tail feature could serve as a marker for SEP diffusion through the IMF. Fractal dimension of the sigma-B time series was also studied and was found to be lower during large IMF fluctuation. Diffusion of SEP was investigated and the result provided support for the correlation of SEP peak flux with Dst values. Application to medium SEP proton flux events such as the Jan 20, 2005 events was discussed.

2. Introduction

Geomagnetic storm prediction has been an active research area. It was reported recently that all models so far used quiet day baseline subtraction and that would dilute the result (Tsyganenko 2003). Therefore this project focused on strong storm events with no input from quiet days. The objective was to find correlation between the data series.

Correlation study is a powerful method in weather research. Recent examples include such diverse topics as fluctuation analysis of cloud radar data (Ivanova 2003), and solar wind parameters (Hnat 2003). It was thus shown that the fluctuation in the interplanetary magnetic field energy density $B^2/2\mu$ is a mono-scaling single parameter probability density function of the Levy type (long-tailed distribution as compared to the Gaussian distribution) and is indicative of an underlying Langevin equation (or Fokker-Planck equation) dynamics associated with non-Brownian diffusion. On the other hand, the interplanetary magnetic field magnitude fluctuation $\delta B(t,\tau) = B(t+\tau) - B(t)$ for lag $\tau = 2^k \times 46$ sec, given k = 1, 2, …14 (that is, from about 2 min to 26 hours) was found to create a probability density function $P(\delta B, \tau)$ that had no apparent rescaling property and was described as multi-fractal, consistent with earlier results (Forman 2003).

Solar energetic particles SEP derive their energy from a solar magnetic source. LASCO revealed that coronal mass ejection CME events are rather common and average about 3 events per day. Recent study showed that coronal mass ejection CME collisions are an important aspect of SEP production (Gopalswamy 2002). The fast primary CME overtakes the preceding CME within a distance of about 20 solar radii. Thus SEP are accelerated from the preceding CME's matter. A recent review summarized the development of SEP event studies (Kallenrode 2003).

Solar eruptions often produce coronal mass ejections (CME) that generate high flux solar energetic particles (SEP). These SEP and fluctuations in the interplanetary magnetic field (IMF) result in geomagnetic storms that affect Earth atmosphere. Cheung (2004) showed that the peak values in the high flux SEP events correlate with the CME speed parameter (r > 0.9). Cotten (2004) showed that the fluctuation of the IMF as measured by sigma-B distribution tail area also had a high correlation (r > 0.9) with the observed Dst peak value. In this paper we study the correlation of IMF fluctuation with high SEP flux during strong magnetic storms.

3. Data

The data for strong geomagnetic storms were selected. The criterion was –150 nT or lower in the Dst index. The Dst data source was obtained from the site swdcdb.kugi.kyoto-u.ac.jp/Dstdir/index/html.

The interplanetary magnetic field fluctuation was represented by the σ_B value. The variance of |B| over the time interval, in nT, $\sigma_B = \sqrt{\left(|B| - |\overline{B}|\right)^2}$. The σ_B is calculated by ACE data center for the 4-minute average. It is calculated using the 16-second averages as input. Data source is from California Institute of Technology website (www.srl.caltech.edu/ACE/ASC/level2/index.htm).

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

The CME data is available from the LASCO website. The proton flux and dates were from NOAA website http://www.sec.noaa.gov/Data/. SEP events with proton (>10 Mev) peak flux larger than 15,000 pfu and Dst value minimum less than -150 nT are selected.

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The selected storms are:
2000 July 15, 24000 pfu (-301 nT)
2000 Nov 09, 14800 pfu (-152 nT)
2001 Nov 06, 31700 pfu (-300 nT)
2001 Nov 24, 18900 pfu (-225 nT)
2003 Oct 29, 29500 pfu (-375 nT average of two extremes)

4. Analysis and Discussion

This project assumed that the σ_B distribution tail area is proportional to the fluctuation severity. That is, the tail area is proportional to the number of σ_B values larger than a certain value. A typical distribution is displayed in figure 1.

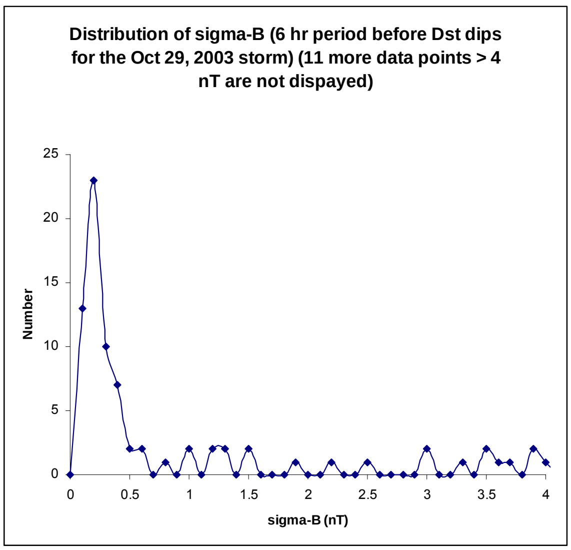


Figure 1: Frequency plot of sigma-B distribution, 6 hr period before Dst dips for the Oct 29 storm. There are 11 more data points larger than 4 nT not displayed. The start time is 2003.824886 (floating year format)

The distribution in the 6-hr period before the figure 1 data is also displayed for comparison.

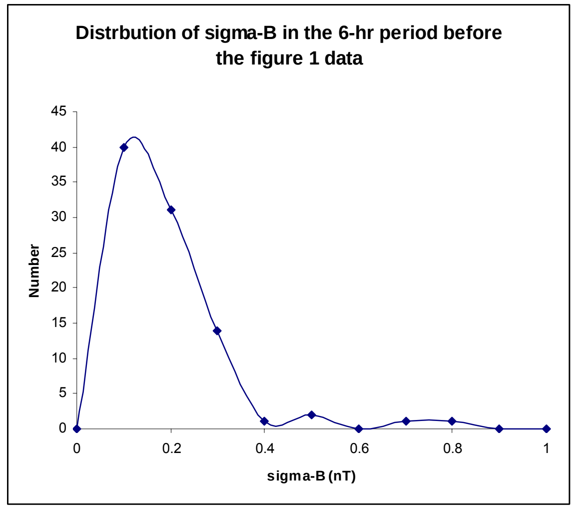


Figure 2: Frequency plot of sigma-B distribution, 6 hr period before the figure 1 data, using the same bin as in figure 1.

The distribution in figure 1 has a long tail as compared to that of figure 2. The figure 1 graph is not a gaussian-like distribution. An investigation of the corresponding fractal dimensions was performed.

The fractal analysis was performed using the Higuchi method (Higuchi 1988). The observational intensity (int) random series with equal intervals could be used to generate a delta series for different lags in the time variable in analogy to the auto-correlation algorithm. The non-normalized apparent length of the time series curve is simply L(k) = Sum of absolute (Int(j)-Int(i)) for all j-i pairs that equal to k. The normalization constant depends on k and is given in the literature. If the Int(i) is a fractal function, then the graph ln (L(k)) versus ln (1/k) should be a straight line with the slope equal to the fractal dimension. This project's Higuchi fractal algorithm was calibrated with the Weierstrass function.

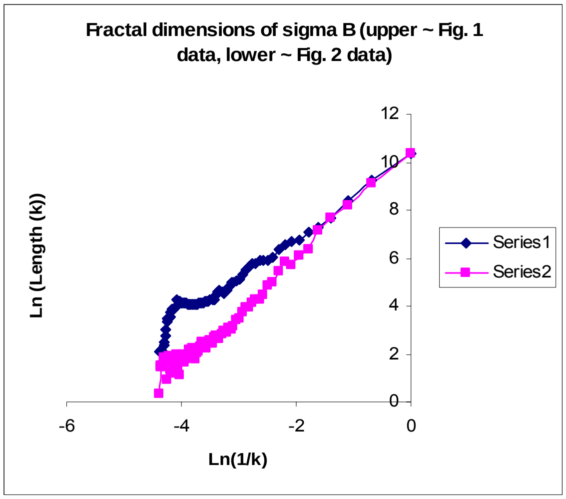


Figure 3: Fractal dimensions of sigma B. The series 1 data corresponds to Figure 1 sigma-B data and the slope is ~ 1.7. The series 2 data corresponds to figure 2 sigma-B data and the slope is ~ 2.3. Series 2 was displayed vertically by about 5.7 so that it matches series 1 at the origin for easy comparison.

The fractal dimension for the figure 1 sigma-B data is about 1.7. This low fractal dimension is consistent with a long tail feature usually found in Levy distribution. This value is consistent with an earlier study of IMF data from the IMP spacecraft (Kabin 1998). The fractal dimension for figure 2 sigma-B data is 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.

From figures 1 and 2, a value of 0.5 nT was selected as the cut off so that the characterization of IMF fluctuation is consistent with Cotten (2004). The number of σ_B values larger than 0.5 nT in the 6-hour pre-storm interval for each storm was listed together with the SEP peak flux value

SEP (10^3 pfu)	Number sigma-B > 0.5 nT
18.9	19
31.7	48
14.8	14
24	35
29.5	35

Table 1: SEP and Number of sigma-B > 0.5 nT data

The graph is shown below.

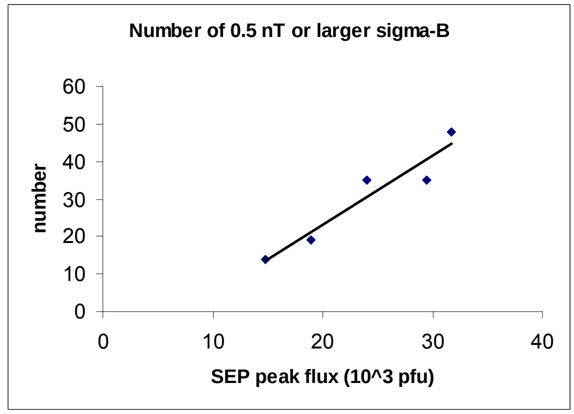


Figure4: Number of 0.5 nT or larger sigma-B versus SEP peak flux for the selected storms.

In figure 4, the correlation coefficient is 0.95. The coefficient of determination is 0.91 suggesting that 91% of the variation is accounted for in the regression. The log-log plot gives a correlation coefficient of 0.97. Similar procedure using the dB-rms instead of the sigma-B gives same conclusion.

The study of the SEP transport suggests that the pitch angle undergoes a random walk (Kato 2000, Saul 2004). The SEP pitch angle random walk may not have affected the spatial dimension (of the magnetic cloud) but the pitch angle random walk certainly could affect the sigma-B fluctuation. Earth is a spatial ionization chamber detector and the Dst value is a marker of the SEP effect. The high correlation suggests that when the GOES spacecraft measures the SEP spatial peak by chance, there is a strong correlation of SEP peak flux to the IMF fluctuation during strong geomagnetic storm (as measured by the Dst values). The basic mechanism is that strong storms are coming from the SEP, regardless whether the spacecraft detects the peak or tail part of the spatial distribution. This viewpoint may explain the March 31 2001 storm which produced a Dst of -300 nT but the SEP peak flux posted by NOAA was about a few hundred pfu. There was a CME halo on March 29. It appears that the transport was highly focused and the spacecraft was not sampling the SEP. The Nov 21 2003 storm was similar with a rather low SEP peak flux of a few hundred pfu and a Dst value of -450 nT.

The reverse phenomenon can also occur. When the spacecraft samples a small region of the SEP cloud, a high peak value of SEP flux may be registered due to the fluctuation within the cloud while the Dst effect may be less than expected. A plot of the Dst values versus the SEP peak flux is displayed in figure 5.

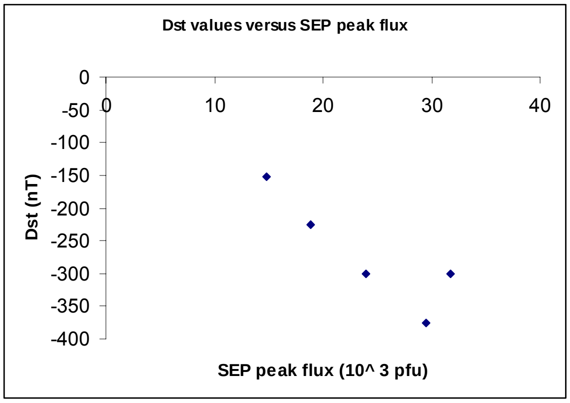
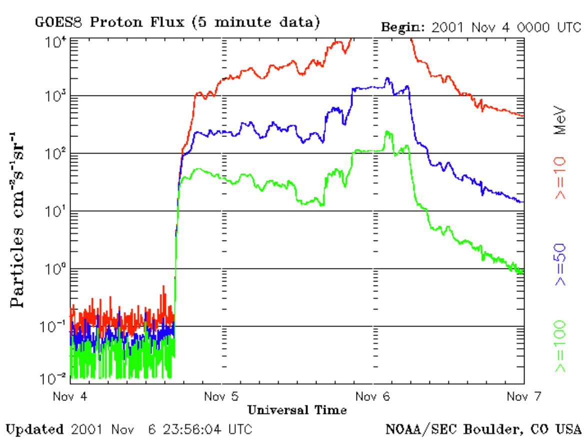


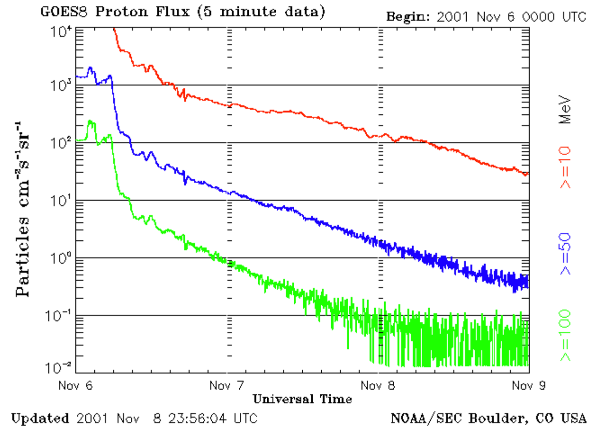
Figure 5: Dst values versus SEP peak flux for the 5 selected storms.

The 31,700 pfu event produced the same Dst effect as the 24,000 pfu event. The regression fit excluding the 31,700 event has a correlation coefficient of -0.9982 which gives a determination coefficient of 99.6%. The regression fit including the 31,700 pfu event has a correlation coefficient of -0.88 which gives a determination coefficient of only 77%.

The GOES proton data for this 31,700 pfu event is displayed below.

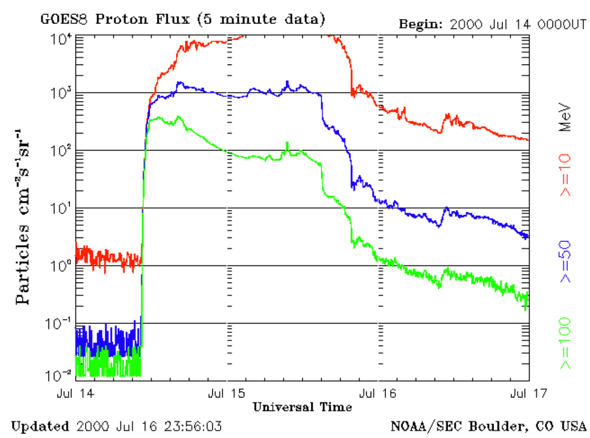


The decay phase:

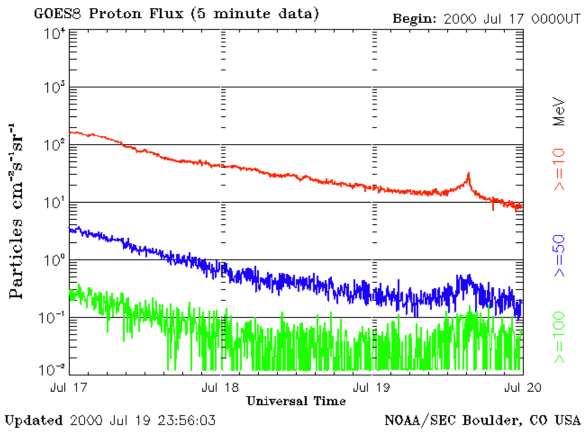


The extra hump on Nov 6 appears to be a superposition on a secondary event. The 100 MeV data shows that the decay started on Nov 5. The hump duration is about 0.5 day superposition on the 3.5-day event for the 100 MeV data. If the extra hump is taken as a secondary event and be subtracted, the effective peak flux would scale down by about 25% to about 24,000 pfu.

The 24,000 pfu event is displayed below for comparison.



The decay phase:



The 24,000 pfu event also has a small hump between July 15 and July 16. This local disturbance may be indicative of another small secondary event.

The Fokker Planck equation description of the convection and diffusion of solar cosmic rays could be used to analyze the two events. The Fokker-Planck approach is presented here for easy reference.

$$\frac{\partial U}{\partial t}+\frac{1}{r^2}\frac{\partial}{\partial r}(r^2VU)-\frac{1}{3r^2}\frac{\partial}{\partial r}(r^2V)\cdot\frac{\partial}{\partial T}(\alpha TU)=\frac{1}{r^2}\frac{\partial}{\partial r}(r^2\kappa\frac{\partial U}{\partial r})$$

$U(r,T,t)$	Number density
T	Kinetic Energy
$V(r)$	Solar wind speed
$\kappa(r,T)$	Diffusion Coefficient

$$\alpha=(T+2mc^2)/(T+mc^2)$$

The analytical solution showed that the number density as a function of time t scales as (t^{-n}) for large t for the following three cases (Fisk 1968). Let V be the solar wind speed, D = kr where k is the constant diffusion coefficient and r the radial distance, and the energy injection follows a power law E^{-u} with u as the index.

Case 1:
n = 3 for simplified diffusion equation only

Case 2:
n = (3 + V/k) for the simpflied convection and diffusion equation

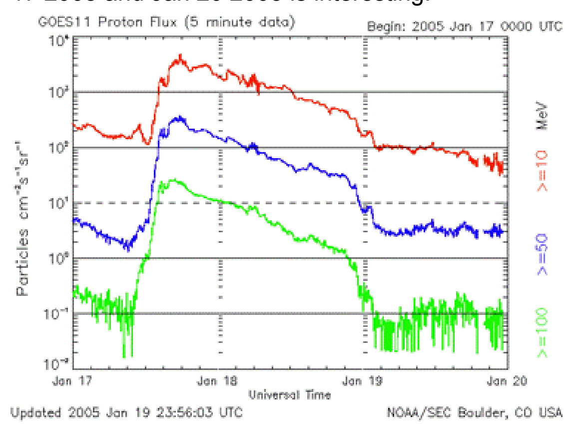
Case 3:
n = (1 + η) for the full Fokker Planck equation, that is, with energy loss in scattering, convection and diffusion

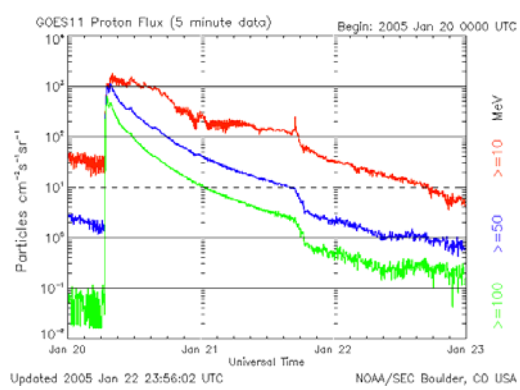
$\eta = (2+V/k)^2 + 16V(u-1)/3k$

Using the numerical values in Fisk 1968 where V = 400 km/s, u= 4, D = kr = 2×10^{21} cm ^{2} sec $^{-1}$ at r = 1 AU, the value n ~ 5 for the 24,000 pfu event and n ~ 6 for the 31,700 pfu event were obtained. The 24000 pfu event 100 Mev proton flux rate decayed as t^{-6} and the 31700 pfu event 100 Mev proton flux rate decayed as t^{-7}. These fast decay rates might suggest a focused transport mechanism (Kocharov 1996, 1998). The sharp rise in the proton flux in these two events is also consistent with a focused transport mechanism.

The Fokker-Planck approach classifies the two events to be similar and provides support on the correlation interpretation of Figure 5. If these two data points are taken away, the figure 5 with 3 data points gives correlation coefficient of 0.9986. The regression t-value is 18.78 and t(0.05,1) = 12.71. In comparison, the regression fit with 4 data points (that is, including the 24,000 pfu event but excluding the 31,700 pfu event) gives a correlation coefficient of 0.9982 with a t-value of 23.28 and t(0.05,2)=4.303.

The application of figure 5 to the SEP events on Jan 17 2005 and Jan 20 2005 is interesting.





The SEP peak flux is about a few thousand pfu and the graph suggests a Dst value of about a few tens of -nT for these two events, and that was actually observed. The sharp rise in proton flux such as in the Jan 20 2005 event was due to a favorable alignment of the IMF, which controls the transport across the distance of 1 AU.

5. Conclusions

When the GOES spacecraft measures the SEP spatial peak, there is a strong correlation of SEP peak flux with the IMF fluctuation during strong geomagnetic storm (as measured by the Dst values). The basic mechanism is that strong storms are coming from the SEP, regardless whether the spacecraft detects the peak or tail part of the spatial distribution. The model is also useful to account for events with low SEP flux but severe Dst values. The SEP peak flux high correlation with the Dst values is also useful in accounting for medium SEP peak events with minimal Dst disturbance. Together with Cotten (2004), this paper concluded that the IMF distribution tail feature is a significant characteristic of the fluctuation. The tail feature could serve as a marker for SEP diffusion through the IMF. Whether fractal dimension characterization could be served as another alternative marker for SEP diffusion will be an interesting question for future studies.

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