



Solar Energetic Particle Events and Geomagnetic Storms

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Outline of the talk

- **Solar energetic particle (SEP) events**
- **Characteristics of intense magnetic storms**
- **Data Base**
- **SEP events and Low-latitude Geomagnetic Signatures**
- **Summary**



Solar energetic particle (SEP) events

The solar energetic particle (SEP) events are the energetic outbursts as a result of acceleration and heating of solar plasma during solar flares and coronal mass ejections (CMEs).

The first observation of SEPs recorded by Forbush (1946) in the form of abrupt enhancement in the intensity in ground-level ion chambers during large solar flares that occurred in February and March 1942.

SEP events associated with solar flares are called **Impulsive where as those associated with CMEs are **Gradual** (Cliver et al., 1983, Cane et al., 1988 and Kahler, 1986, 1992).**



Solar energetic particle (SEP) events.....

- Cane et al. (1986) observed difference in the ratio of proton to electron populations for the two classes of SEPs.
- The SEP events are characterized by abrupt enhancements in the proton flux in the energy range of keVs to MeVs as measured by spacecraft at 1 AU.
- On impacting the earth's magnetosphere, the SEP events can lead to a sudden disturbance of the earth's magnetic field, known as **Geomagnetic storms** (Sugiura and Chapman, 1960; Gonzalez and Tsurutani, 1987).



Solar energetic particle (SEP) events.....

Investigations by Smith et al. (2004) and Gleisner and Watermann (2006) emphasized the discriminating contribution of SEP flux characteristics to assess the geoeffectiveness of CMEs to produce strong magnetic storms.

In particular, during SEP events, protons in energy range of 47 - 187 keV fed to the magnetosphere have been found to contribute substantially to enhancement of ring current leading to intense magnetic storms.

Gleisner and Watermann (Space Weather, 4, 2006) have suggested the SEP flux as an indicator of the geoeffectiveness of halo CMEs rather than CME speed⁵.



Solar energetic particle (SEP) events.....

The observation of SEP events at satellites located at L1 is a potential tool for predicting the arrival of interplanetary shocks, well associated with geomagnetic storms, hours before they arrive at L1 (Smith et al., JGR, 109, 2004).

Thus study of SEP events is relevant for Space weather prediction.

Here we will study the 4 major SEP events (gradual type) of the current solar cycle 23 for their geoeffectiveness in producing intense magnetic storms.



Magnetic Storms

Geomagnetic storm: characterized by a *Main Phase* during which the horizontal component of the Earth's low-latitude magnetic fields are significantly depressed over a time span of one to a few hours followed by its *recovery* which may extend over several days (Rostoker, 1997)

Interplanetary causes: mainly the solar ejecta (due to CMEs, solar flares etc), like SEP events, having unusually intense magnetic fields and high solar wind speeds near the Earth.

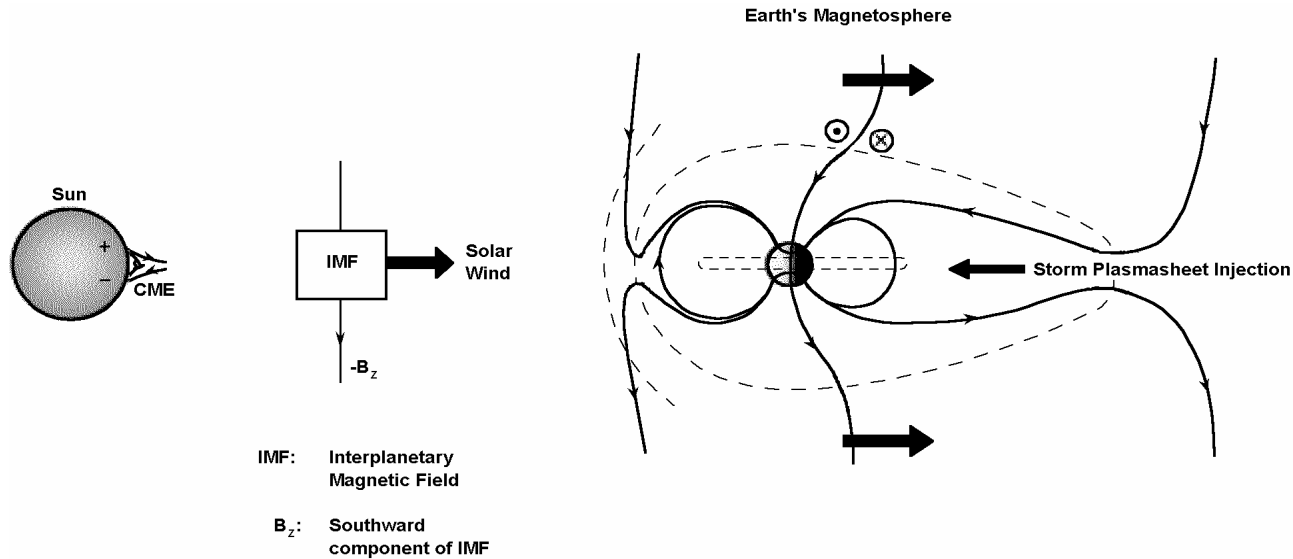


Magnetic Storm continued

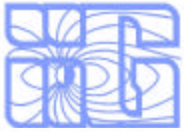
- A large fraction of the energy associated with the solar ejecta is transferred into the earth's magnetosphere mainly by the process of magnetic reconnection (Dungey, 1961; Akasofu, 1981; Gonzalez et al., 1994, 1999).
- The magnetotail plasma gets injected into the nightside magnetosphere, the energetic protons drift to the west and electrons to the east, forming a ring of current around the Earth. This current, called the “ring current”, causes a diamagnetic decrease in the Earth's magnetic field measured at near-equatorial stations.



Solar wind energy transfer due to Magnetic reconnection Process



Magnetic Reconnection is very effective when the interplanetary magnetic field is directed southwards leading to strong plasma injection from the tail towards the inner magnetosphere causing intense auroras at high-latitude nightside regions.



Auroras during substorms



Pictures of aurora taken at Indian station Maitri at Antarctica on 19 June, 2003 by Dr. Arun Hanchinal, IIG, Mumbai.



Magnetic Storm continued

The auroral activity becomes intense and auroras are not confined to the Auroral Oval only, rather the Auroras could be seen at the sub-auroral to midlatitude stations.

Subsequently, this energy is distributed in various regions of the magnetosphere in different quantities.



DATA BASE

The current solar cycle 23 witnessed many intense SEP events as reported by SOHO/CELIAS. The effects of 4 strong SEP events of the current solar cycle 23 on various magnetic storm processes are investigated.

We use **Solar flare** and **CME** data from geosynchronous satellite **GOES-8**, and **LASCO** instrument onboard **SOHO** Near L1 point (GSE $\sim 240 R_E$), respectively.

Interplanetary plasma and magnetic field data from NASA's Advanced Composition Explorer (ACE) located at L1 point (GSE $\sim 240 R_E$) and Wind satellite (GSE $\sim 0.1 R_E$ to $\sim 85 R_E$).



DATA BASE

- **Actual CME onset time is taken as the time when CME is at the height of $1.1R_s$.**
- **Proton flux data is taken from EPAM instrument of ACE**
- **The ground magnetic field data from Alibag (geographic lat. 18.63° N, long. 72.87° E; geomagnetic lat. 10.02° N, long. 145.97°) and Tirunelveli (geographic lat. 8.7° N, long. 77.8° E; geomagnetic lat. 0.32° S, long. 149.76°) magnetic observatories.**
- **The main focus will be to highlight the low latitude geomagnetic signatures produced by these SEP events.**¹³



DATA BASE

- Diurnal departures are computed by subtracting the mean midnight level for the day and have been depicted by ΔH_{ABG} and ΔH_{TIR} for respective magnetic observatories.
- Hourly average values of storm time disturbance index *Dst*, 1-minute resolution values for auroral electrojet (*AE*) index have been acquired from World Data Center, Kyoto.
- Magnetic disturbances at polar cap are measured by polar cap index (*PC*) and the data is taken from Thule for northern polar cap.



SEP events and Low-latitude Geomagnetic Signatures

14 July 2000 (Bastille day) SEP event:

Solar flare onset = 1003 UT; SF peak: 1024 UT.

Proton Event onset= 1100 UT; Shock time = 1435 UT on 15 July;
persistence of high proton flux ($\sim 3 \times 10^6$ particles/cm²/s/sr/MeV)
for nearly a period of ~ 4 hrs after the shock.

SSC amplitude: 105 nT at 1440 UT on 15 July

Dst (min): - 301 nT

4 November 2001 SEP Event:

Solar flare onset = 1603 UT; SF peak: 1620 UT

Proton event onset=1705 UT; Shock time = 0120 UT on 6
November;

persisting high proton fluxes ($\sim 2 \times 10^6$ particles/cm²/s/sr/MeV) for
a period of ~ 9 hrs after the shock.

SSC amplitude: 76 nT at 0153 UT on 06 November

Dst (min): - 292 nT



SEP events continued ...

8 November 2000 SEP Event: 3 consecutive flares

M7.4 Solar flare onset = 2242 UT; SF peak: 2328 UT

Proton event onset= 2305 UT; Shock time = 0600 UT on 10

November; shock time = 0600 UT on 10 November, **proton fluxes decrease after attaining peak at the shock passage.**

SSC amplitude: 50 nT at 0629 UT on 10 November

Dst (min): -96 nT

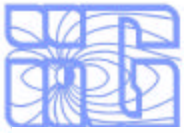
24 September 2001 SEP Event

Solar flare onset = 0932 UT ; SF peak: 1038 UT

Proton Event onset =1115 UT; Shock time =1925 UT on 25 September, **proton fluxes decrease after attaining peak at the shock passage**

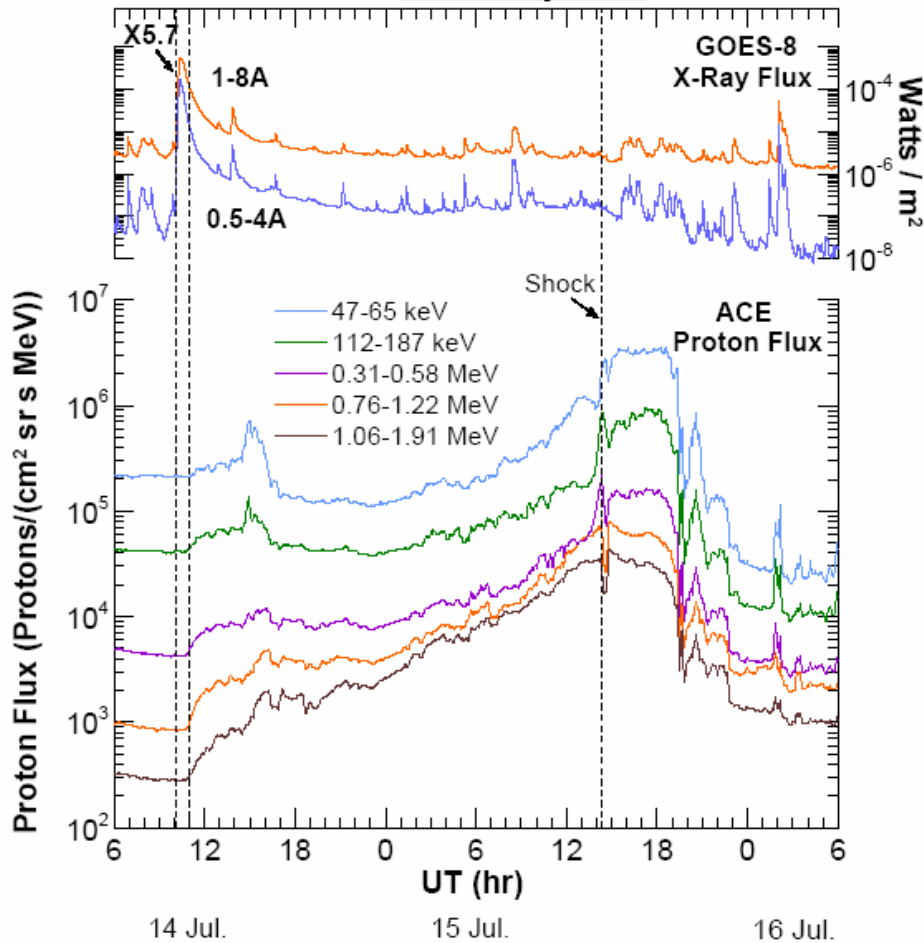
SSC amplitude: 55 nT at 2027 UT on 25 September

Dst (min): -102 nT

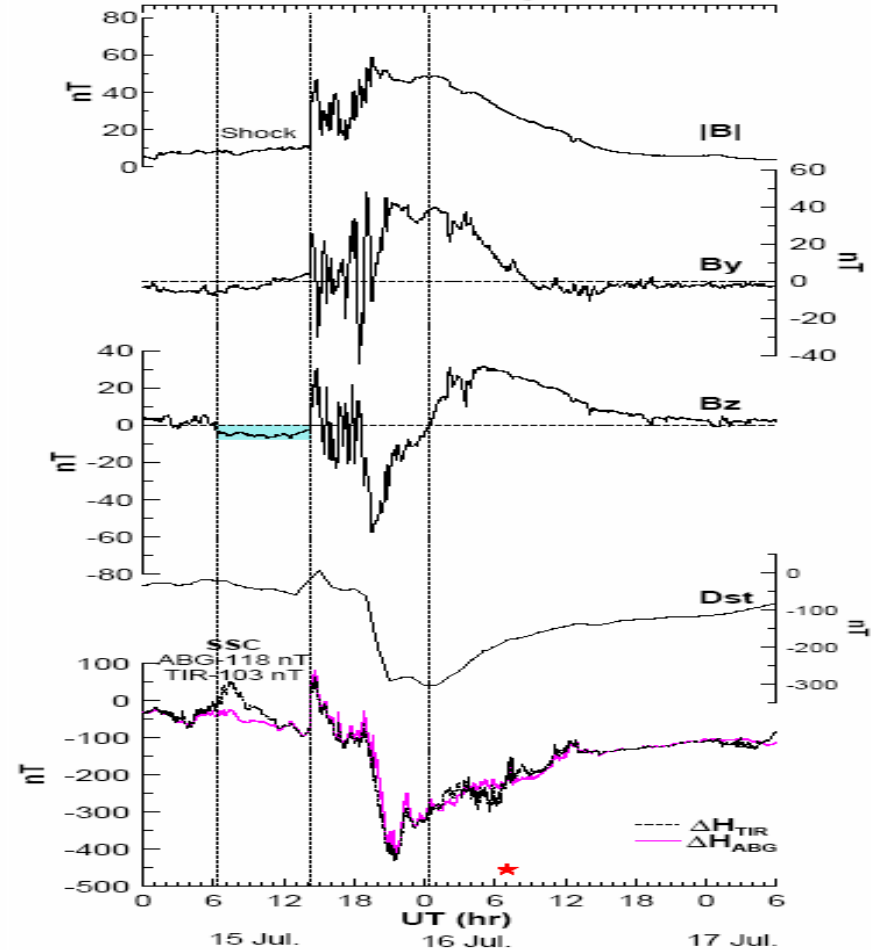


14 July 2000 (Bastille day) SEP event

14-16 July 2000



15-17 July 2000

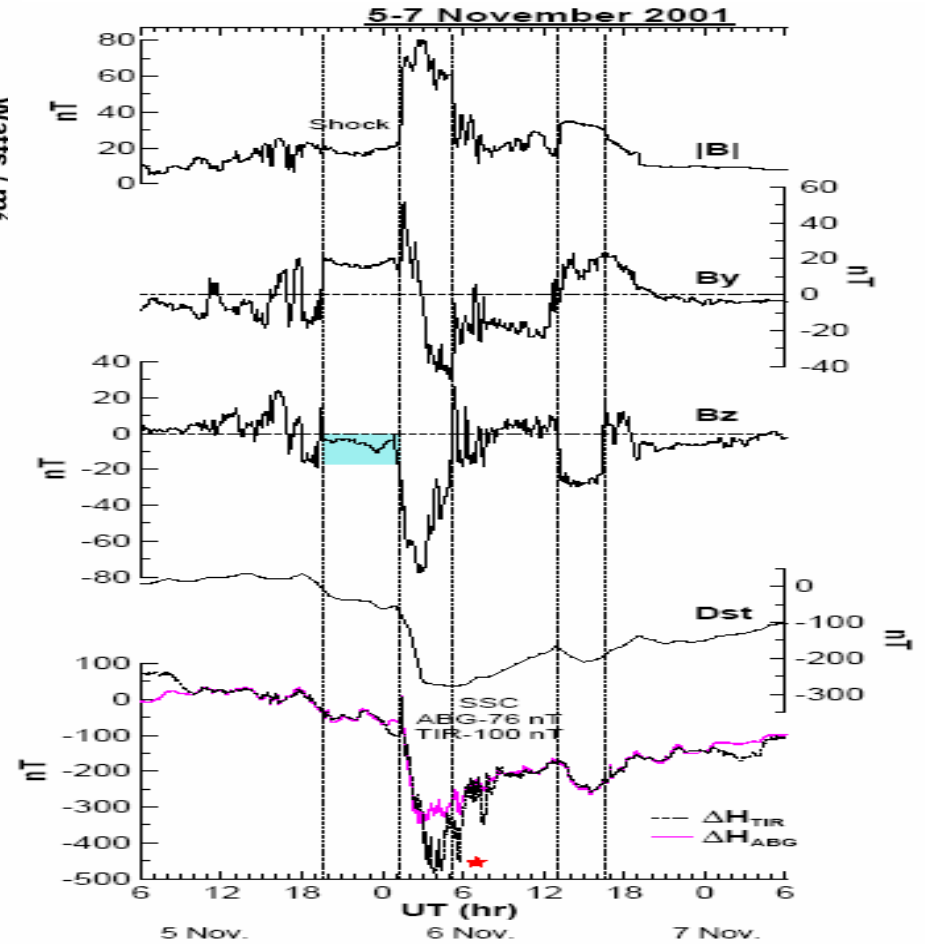
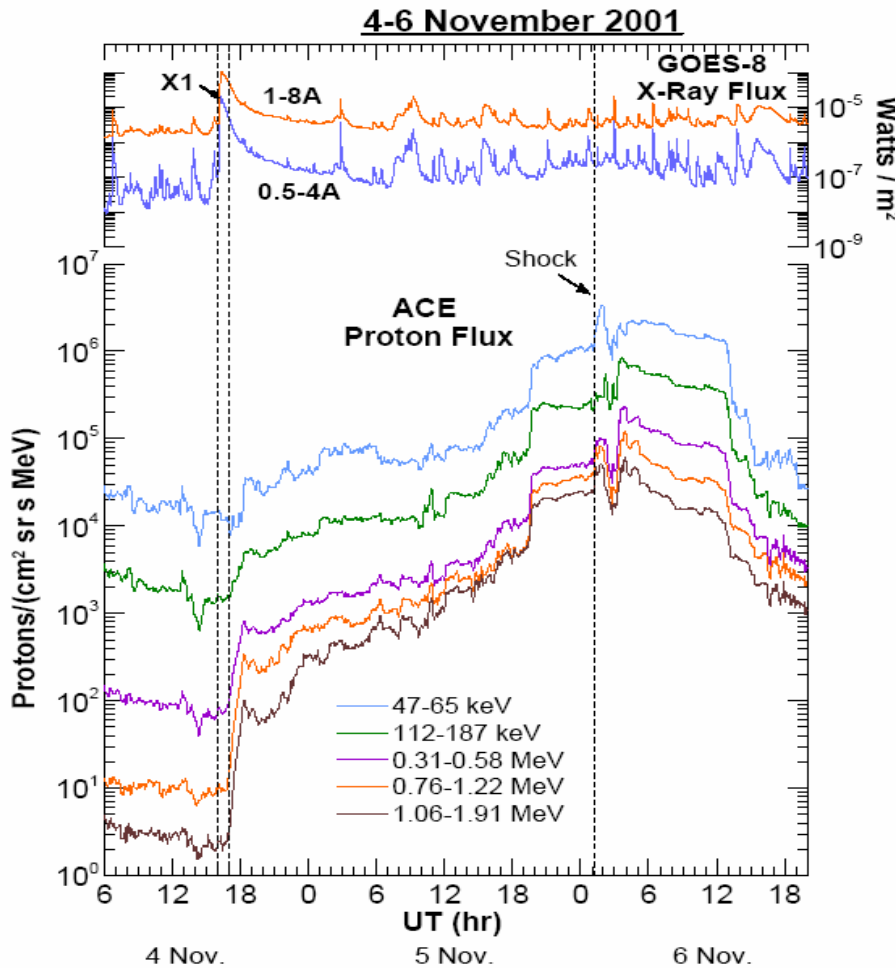


Upper panel shows X-ray flux at two wavelengths 0.5-4 Å and 1-8 Å GEOS-8. Lower Panel shows Proton flux in various energy levels from ACE.

From top to bottom: IMF $|B|$, B_y , B_z , hourly averaged Dst index, 1-minute digital magnetic data H_{ABG} and H_{TIR} for 15-17 July 2000.

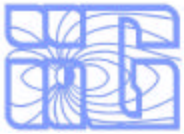


4 November 2001 SEP Event

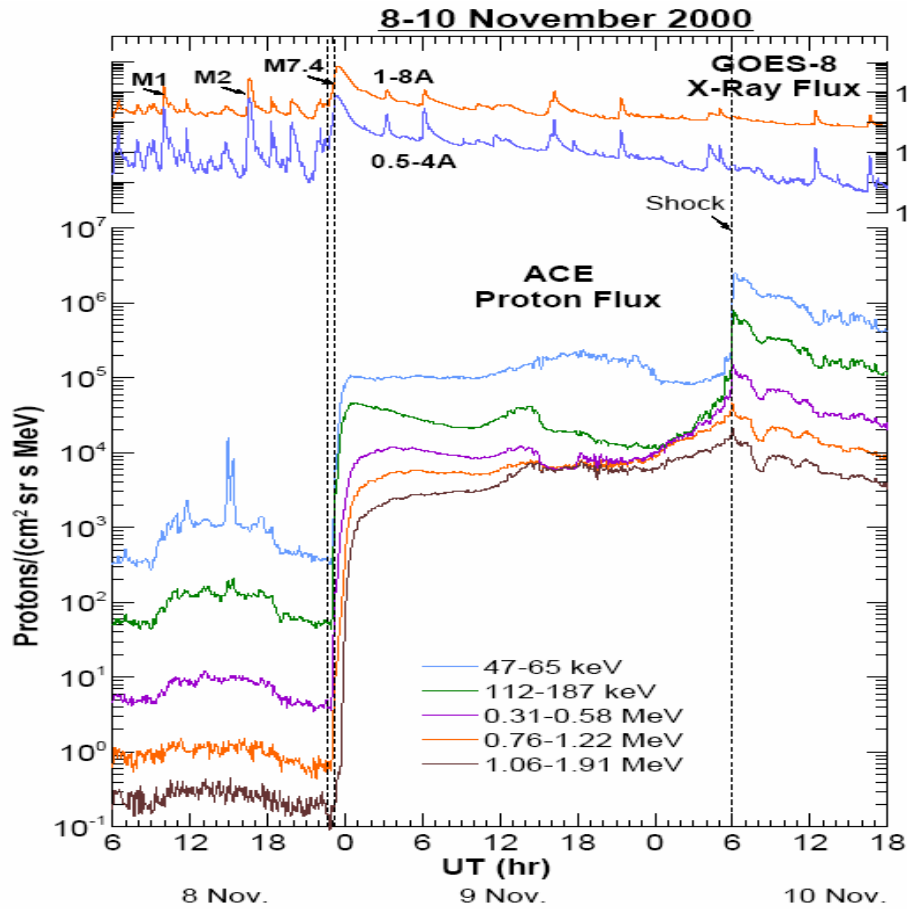


Upper panel shows X-ray flux at two wavelengths 0.5-4 Å and 1-8 Å GEOS-8. Lower Panel shows Proton flux in various energy levels from ACE.

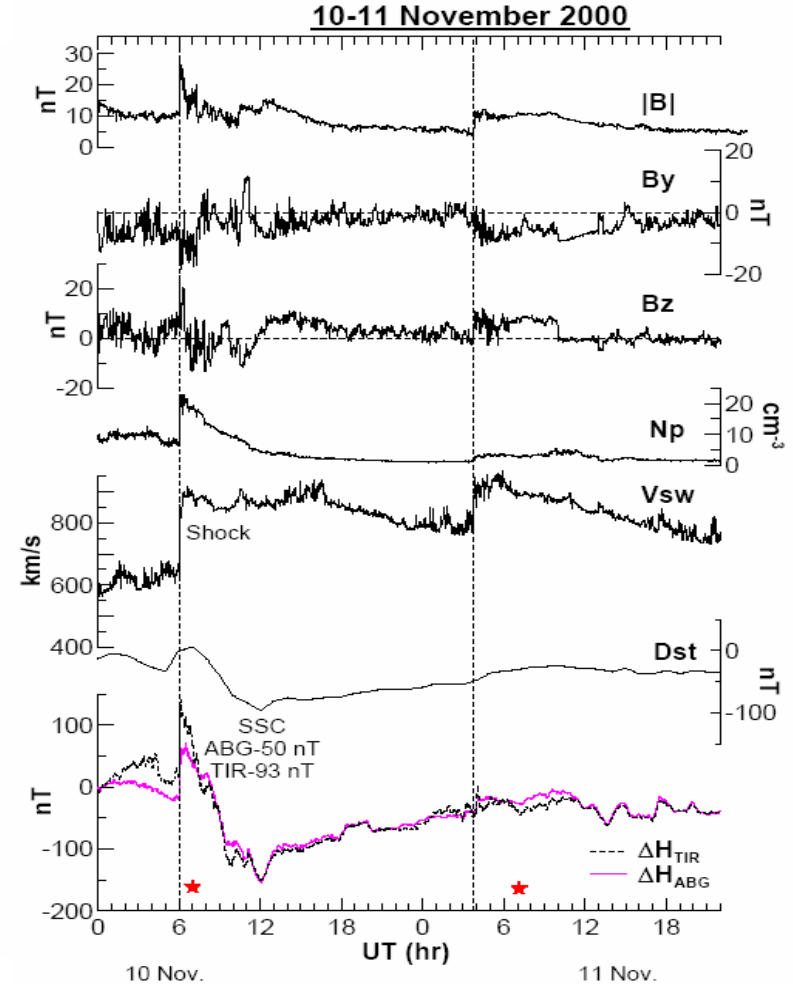
From top to bottom: IMF |B|, By, Bz, hourly averaged Dst index, 1-minute digital magnetic data ? HABG and ? HTIR for 4-5 November 2001 18



8 November 2000 SEP Event



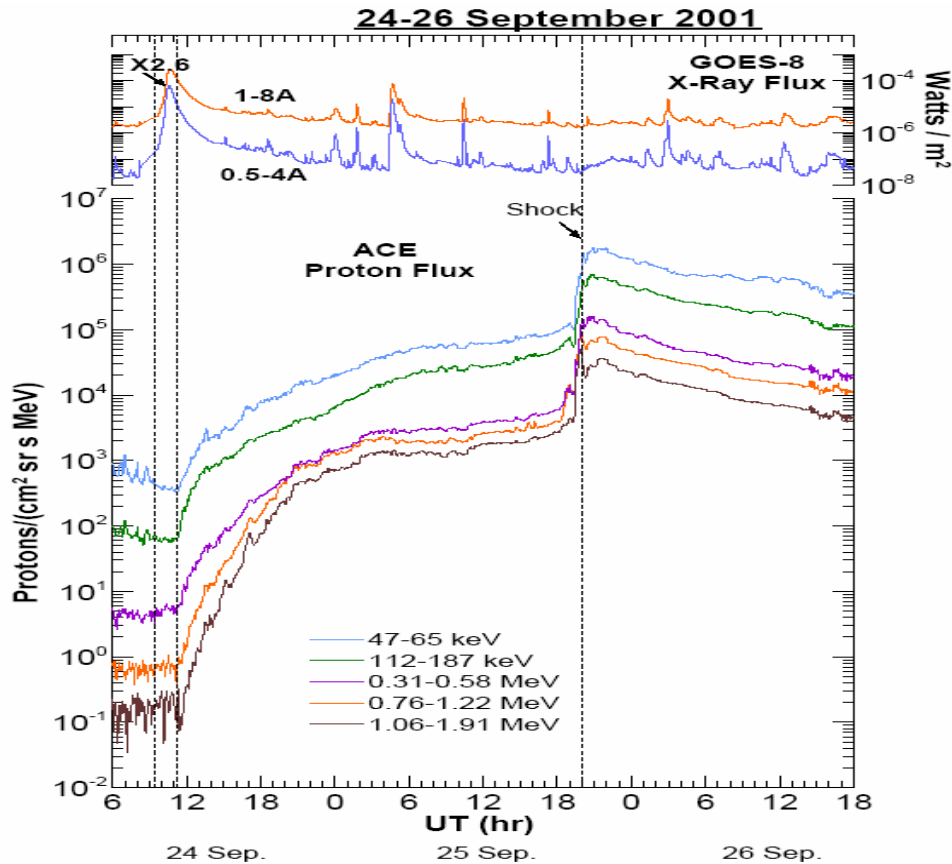
Upper panel shows X-ray flux at two wavelengths 0.5-4 Å and 1-8 Å GEOS-8. Lower Panel shows Proton flux in various energy levels from ACE.



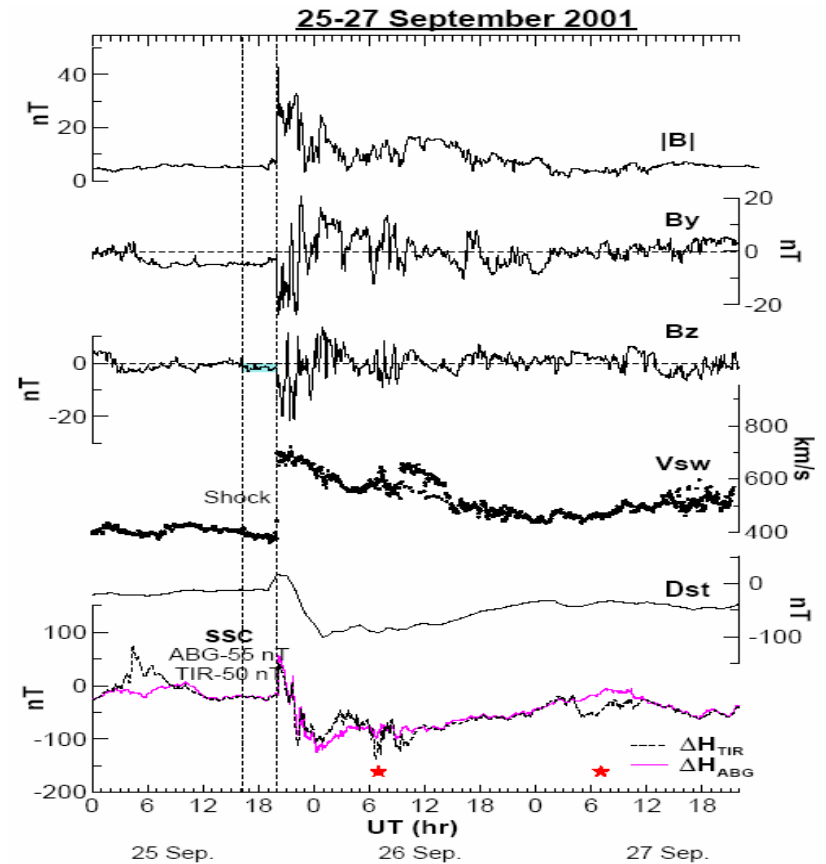
From top to bottom: IMF |B|, By, Bz, hourly averaged Dst index, 1-minute digital magnetic data ΔH_{ABG} and ΔH_{TIR} for 10-11 November 2000¹⁹



24 September 2001 SEP Event



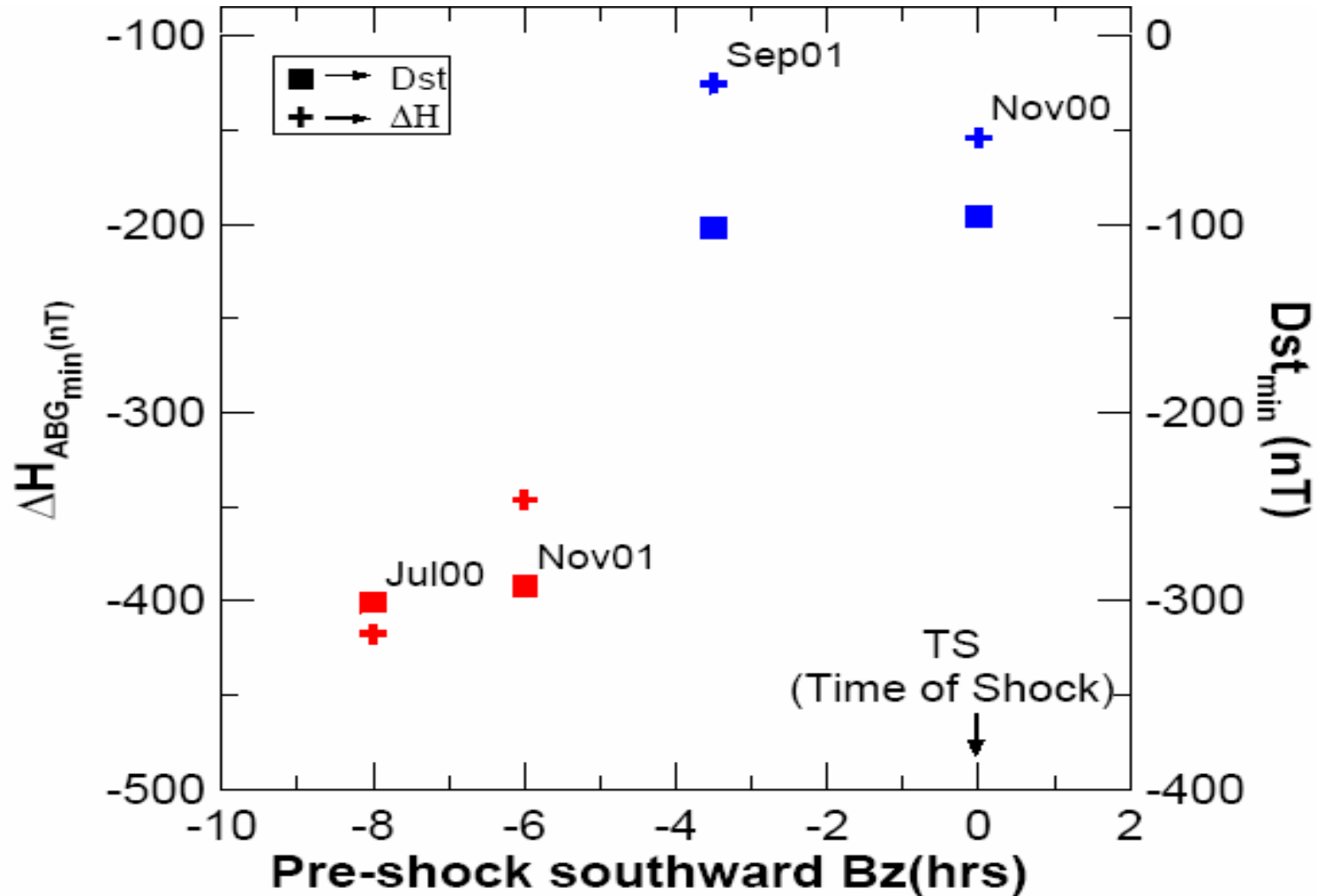
Upper panel shows X-ray flux at two wavelengths 0.5-4 Å and 1-8 Å GEOS-8. Lower Panel shows Proton flux in various energy levels from ACE.



From top to bottom: IMF $|B|$, B_y , B_z , hourly averaged Dst index, 1-minute digital magnetic data ΔH_{ABG} and ΔH_{TIR} for 25-27 September 2001₂₀

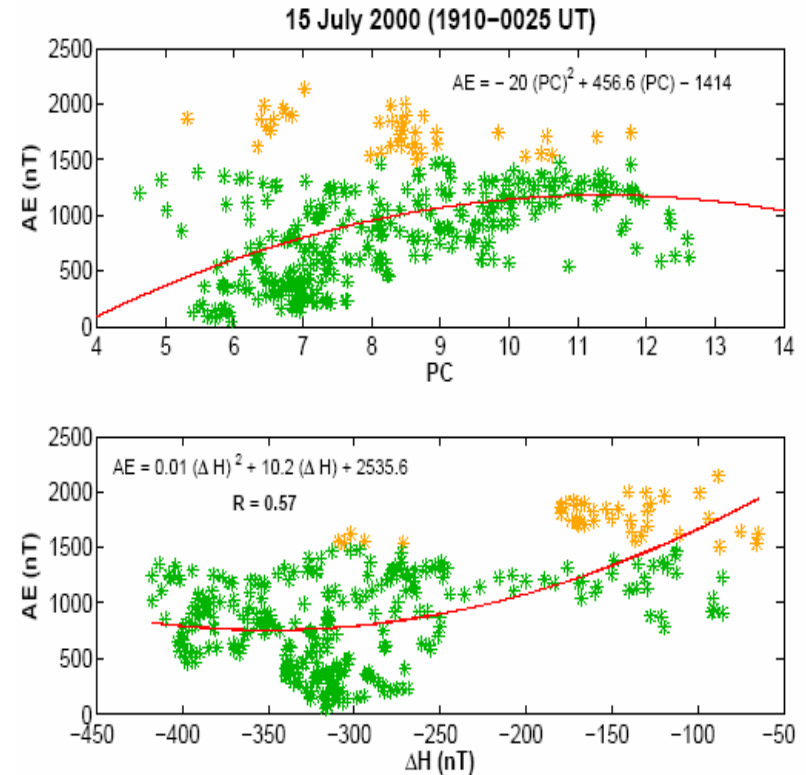
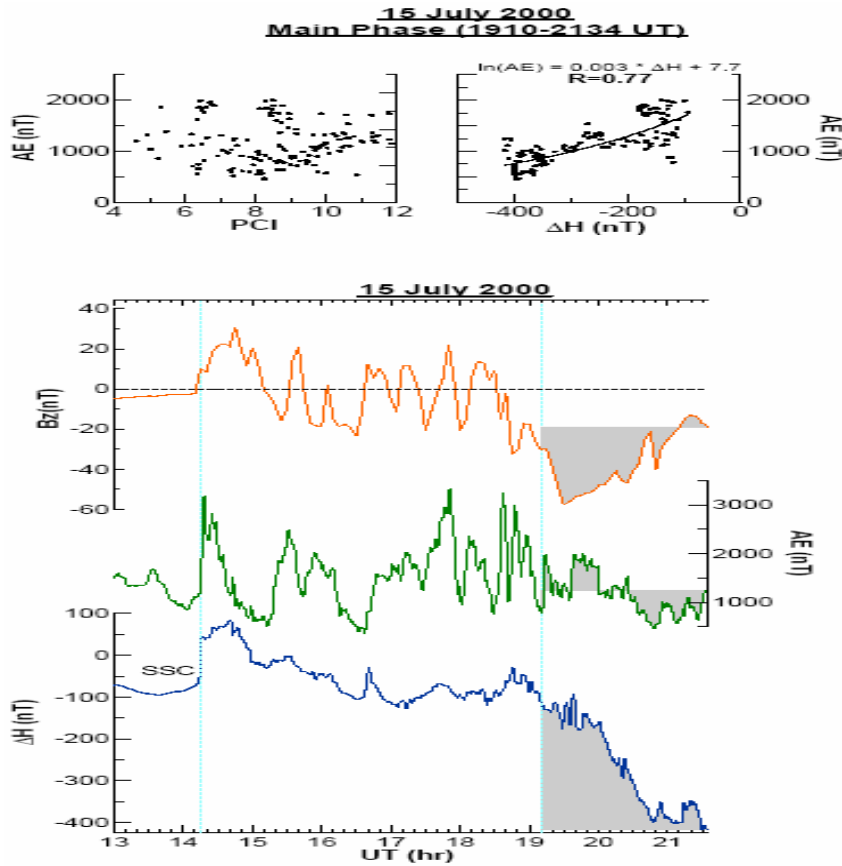


Control of Geomagnetic activity by southward Bz duration before shock





IMF conditions, main phase and High latitude-low latitude coupling



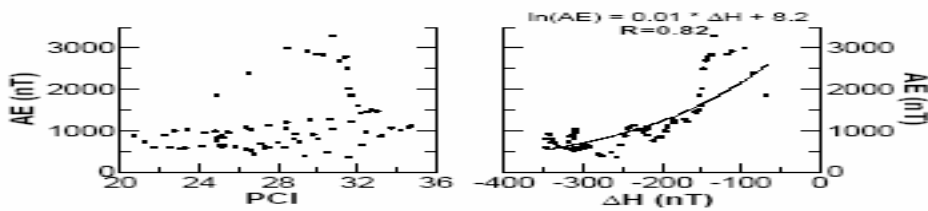
Correlations of PC index and AE index (top panel) and ΔH and AE index (bottom panel) for 'T2' duration (1910-0025 UT) for the 15 July 2000 storm. Green (orange) colour symbols for AE values less (more) than 1500 nT.

**Upper panel: correlations of PC index and low latitude geomagnetic field ΔH_{ABG} with AE index
Bottom panel: variations of AE index and ΔH_{ABG} with IMF north-south component B_z , for 15 July 2000 for 'T1' (1910-2134 UT) period.**

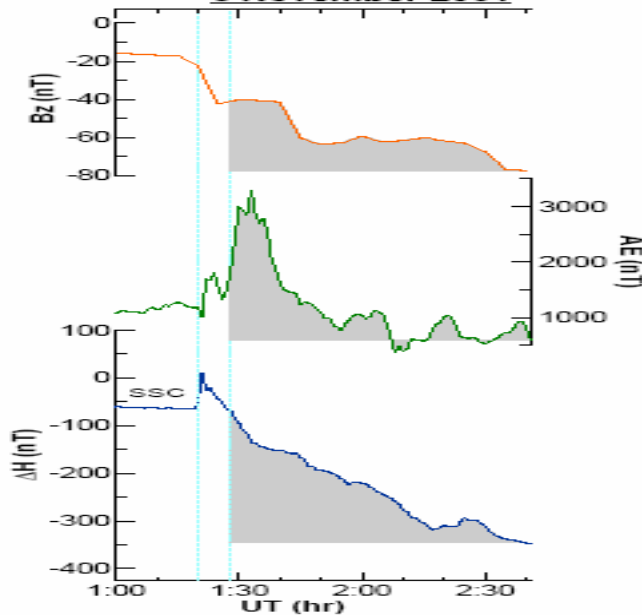


IMF conditions, main phase and High latitude-low latitude coupling...

6 November 2001
Main Phase (0128-0241 UT)

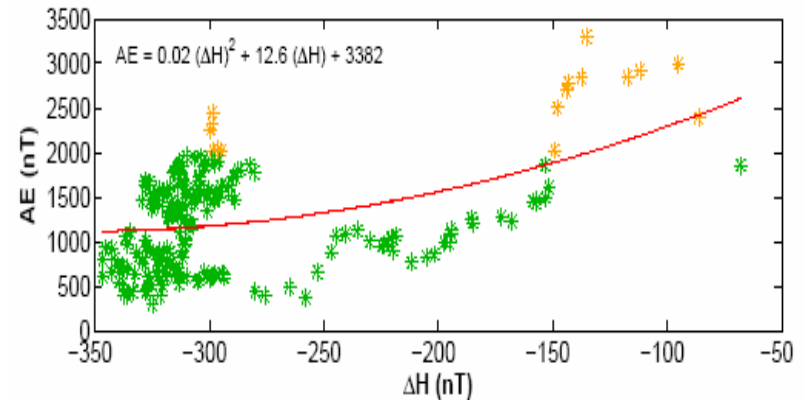
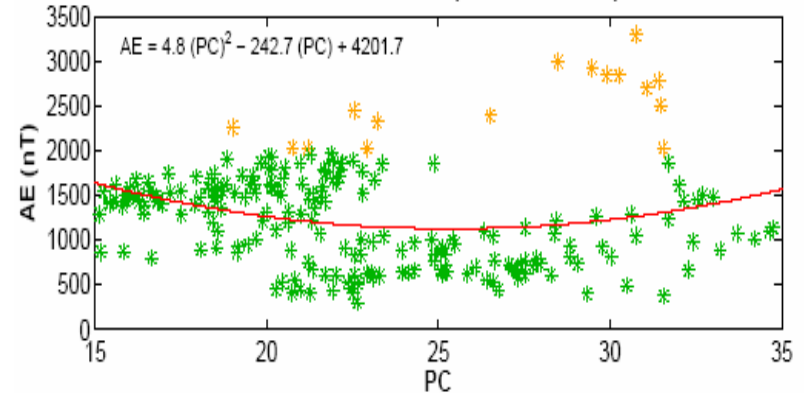


6 November 2001



Upper panel: correlations of *PC* index and low latitude geomagnetic field ? HABG with *AE* index Bottom panel: variations of *AE* index and ? HABG with IMF north-south component *Bz*, for 6 November 2001 for 'T1' (0128-0241 UT) period.

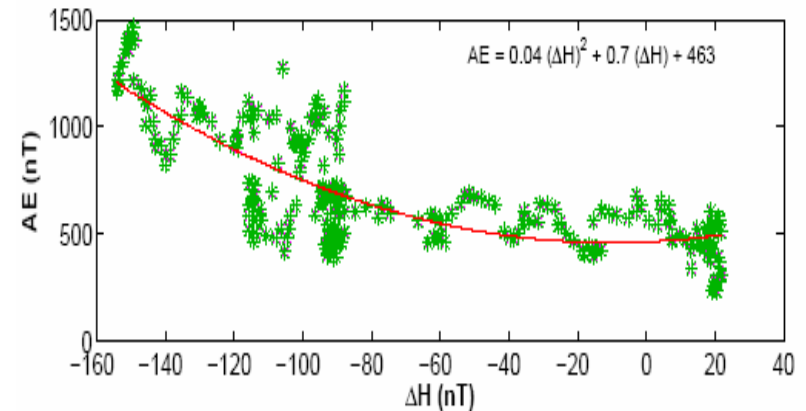
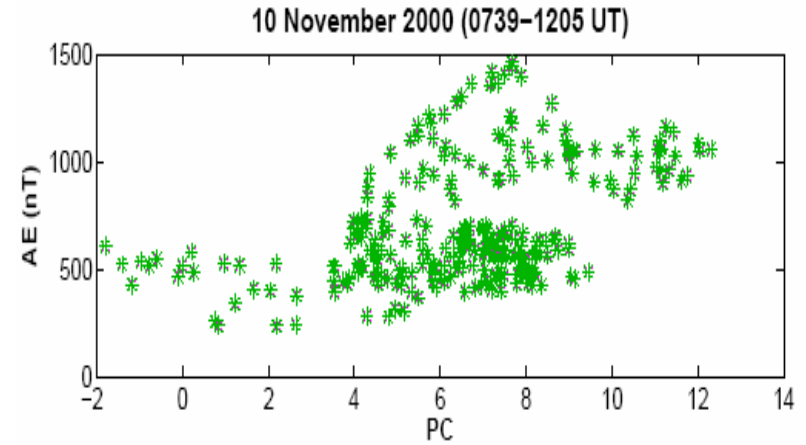
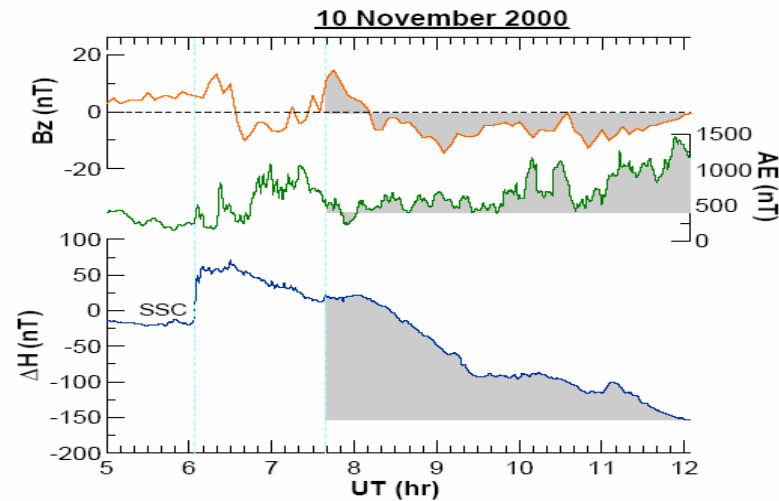
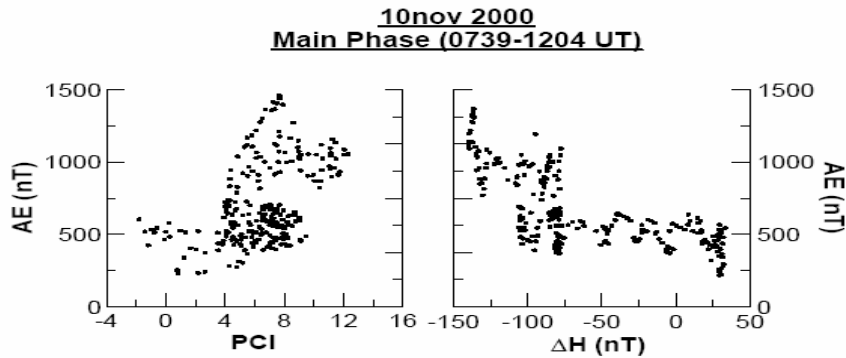
6 November 2001 (0128-0500 UT)



Correlations of *PC* index and *AE* index (top panel) and ? HABG and *AE* index (bottom panel) for 'T2' duration (0128-0500 UT) for the 6 November 2001 storm. Green (orange) colour symbols for *AE* values less (more) than 2000 nT.



IMF conditions, main phase and High latitude-low latitude coupling...

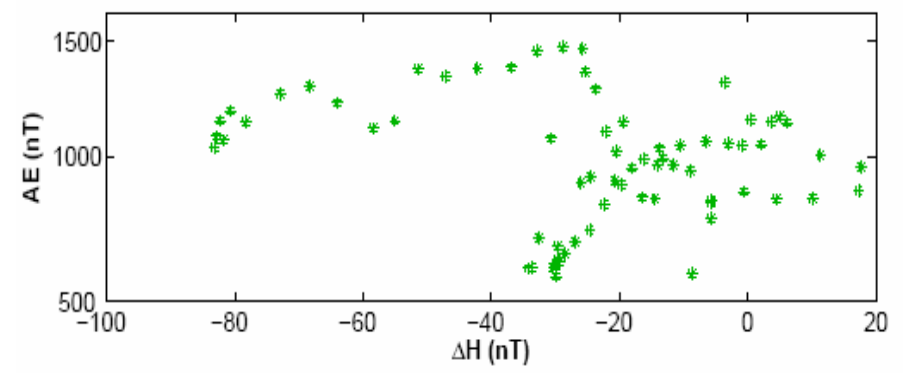
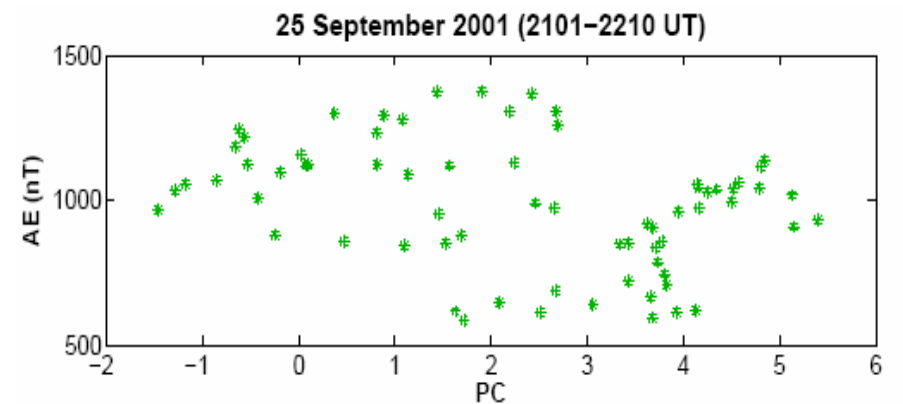
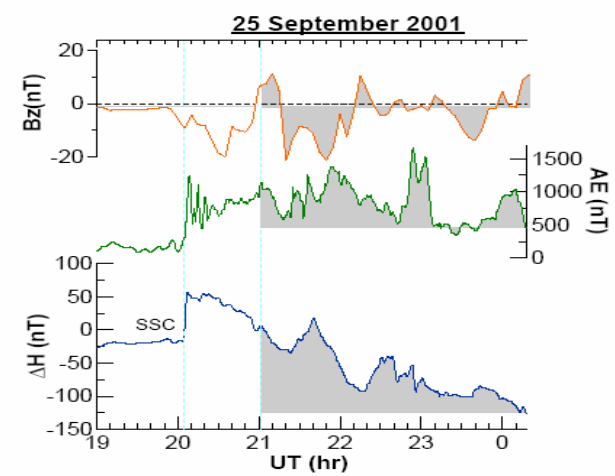
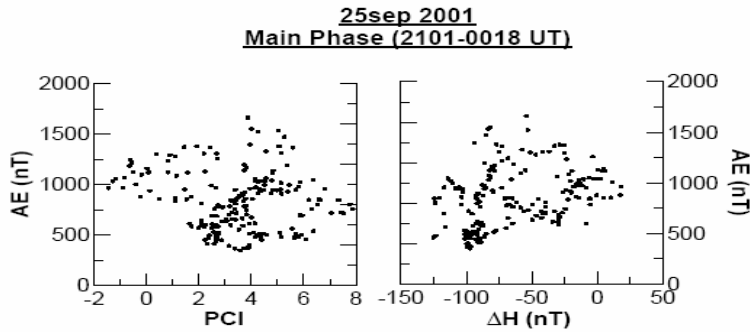


Upper panel: correlations of *PC* index and low latitude geomagnetic field ? HABG with *AE* index
 Bottom panel: variations of *AE* index and ? HABG with IMF north- south component *Bz*, for 10 November 2000 for 'T1' (0739-1204 UT) period.

Correlations of *PC* index and *AE* index (top panel) and ? HABG and *AE* index (bottom panel) for 'T2' duration (0739-1205 UT) for the 10 November 2000 storm.



IMF conditions, main phase and High latitude-low latitude coupling...



Upper panel: correlations of PC index and low latitude geomagnetic field ? H_{ABG} with AE index Bottom panel: variations of AE index and ? H_{ABG} with IMF north-south component B_z , for 25 September 2001 for ‘T1’ (2101-0018 UT) period.

Correlations of PC index and AE index (top panel) and ? H_{ABG} and AE index (bottom panel) for ‘T2’ duration (2101-2210 UT) for the 25 September 2001



IMF conditions, main phase and High latitude-low latitude coupling...

For two intense events of 15 July 2000 and 6 November 2001: during the main phase, large scatter between AE and PC indices whereas AE and $?H_{ABG}$ follow good exponential fits describing an exponential decay of auroral activity with the buildup of ring current.

On the other hand, for two weak storm events of 10 November 2000 and 25 September 2001 events: a clear scattering between AE and PC indices and $?H_{ABG}$ is observed during the main phase.

This clearly shows influence of interplanetary conditions and persisting high proton flux on low latitude magnetic field variations.



Summary

- 1. The SEP events with high flux levels or a ‘plateau’ after the shock passage (i.e., 15 July 2000 and 6 November 2001) produce much more intense storms than the events where the SEP flux levels decrease after the shock passage, e.g., 10 November 2000 and 25 September 2001, even when the maximum SEP flux achieved is similar.**

The association of SEP flux enhancement with coronal mass ejections and their geoeffectiveness has been dealt with in the recent work of Gleisner et al. (2006) and Smith et al. (2004).



Summary continued...

Smith et al. (2004) suggested the existence of overlapping energetic ion enhancements (EIE) during post shock period when smaller EIE follows a larger one and a maximum flux attained prevails for longer duration, thus leading to the development of intense storms.

A Probable explanation: during plateau SEP events, the magnetotail gets pre-populated with large fluxes of energetic particles due to the dayside magnetic reconnection. Subsequent injecting of these energetic particles to the inner magnetosphere produces an intense ring current leading to high $|Dst|$ values.



Summary continued...

2. For both 15 July 2000 and 6 November 2001 SEP events with high flux levels, during the main phase of the ensuing geomagnetic storms, the AE index decreased as the main phase developed. The converse was true for the SEP events where flux level decreased after shock (10 November 2000 and 25 September 2001).

3 For all the four SEP events, a good correlation between AE index and PC index was found when the AE index was below some threshold value, similar to Lu et al (1998) results. Above this threshold value, there is a large scatter and the correlation is poor.



Summary continued...

Earlier studies Vassiliadis et al. (1996) and Troshichev et al. (2002) had shown the existence of good correlation between *PC* index and the auroral electrojet (*AE*) indices for all levels of *AE*.

In fact, it was concluded that the relationship can be used for the specification of auroral geomagnetic activity and also for now casting the intensity of auroral substorms (Vassiliadis et al 1996; Troshichev et al. 2002).

Our study suggests “threshold level of *AE* index” as an important extra factor for now-casting substorms.



Summary continued...

4. The duration of the southward IMF B_z just before the shock impingement plays an important role on the development of magnetic storms. SEP events of 15 July 2000 and 6 November 2001 had long durations (~ 8 hrs and ~ 6 hrs respectively) of pre-shock southward B_z , they produced much intense magnetic storm than SEP events having negligibly low pre-shock conditions of southward B_z .

This result could well be used to explain the precursory signature for the intense storm phenomena and space weather predictions



Thank You

