Study of Space weather events of Solar cycle 23 and 24 and their Geoeffectiveness

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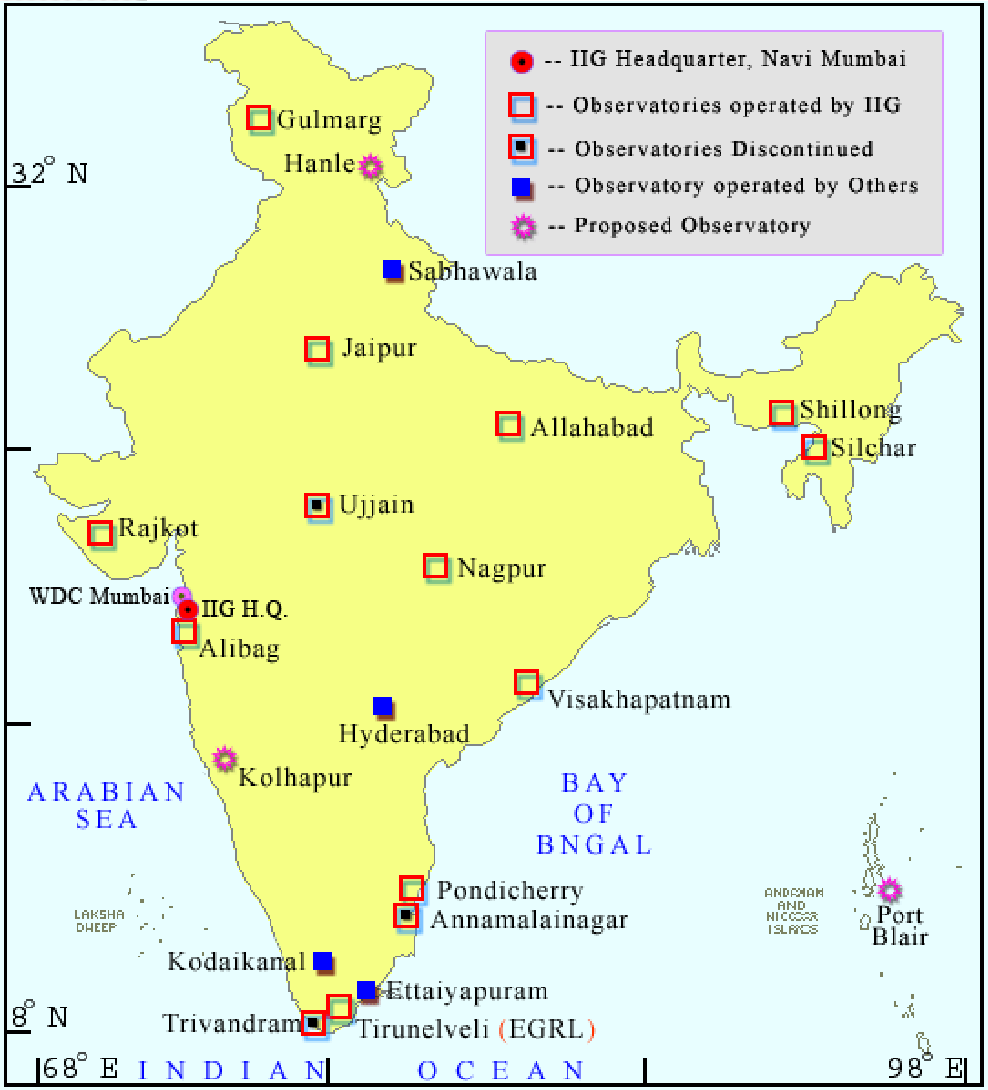
Out line

- Colaba - Bombay old magnetic records
- Solar and Interplanetary drivers, estimation of interplanetary conditions.
- Space weather events – Solar cycle 23 and 24
- Geomagnetic response from low and equatorial latitudes
- On the reduced geoeffectiveness of solar cycle 24: a moderate storm perspective
- summary

Magnetic Observatories In India by IIG

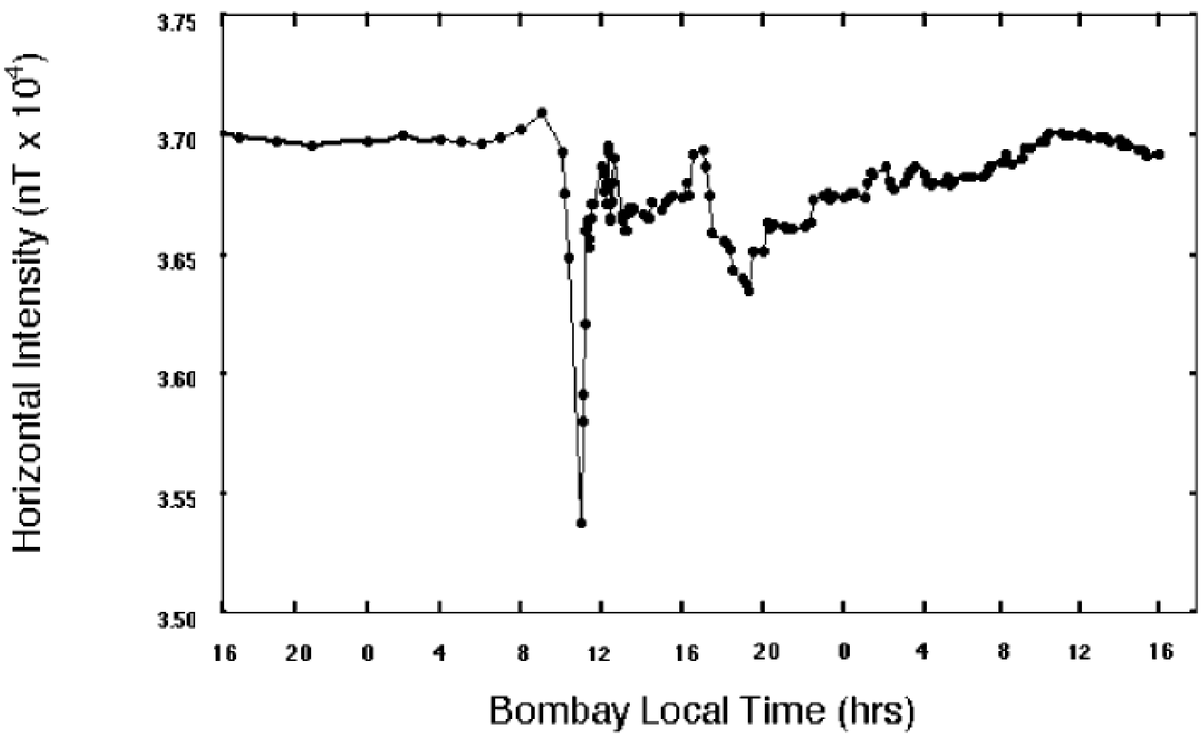


Oldest Indian magnetic observatory at Alibag, established in 1904.

Alibag(ABG) and Jaipur(JAI) are INTERMAGNET Observatories

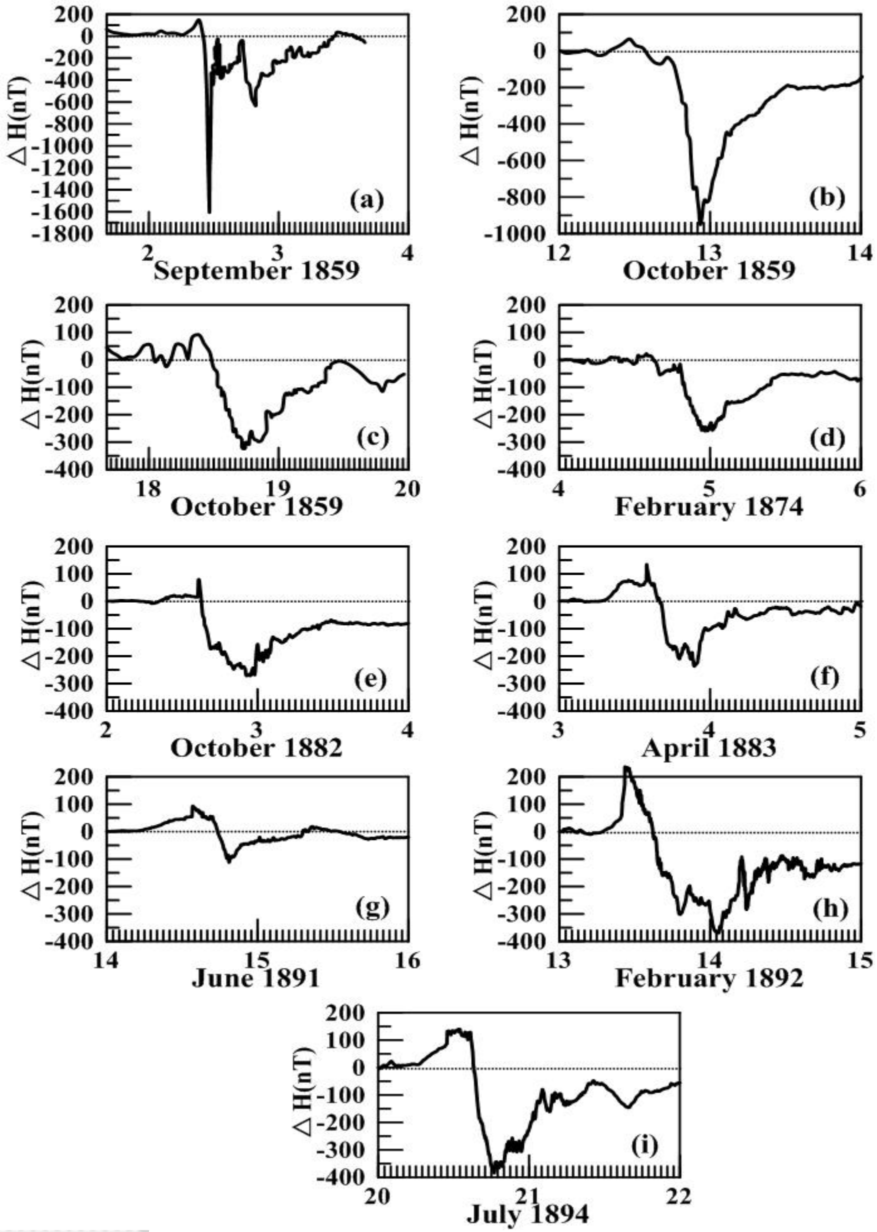
World Data Center (WDC) Mumbai - is member of ISCU World Data center(WDS),.

The Colaba (Bombay) magnetogram for the extreme Geomagnetic storm 1-2 September, 1859.

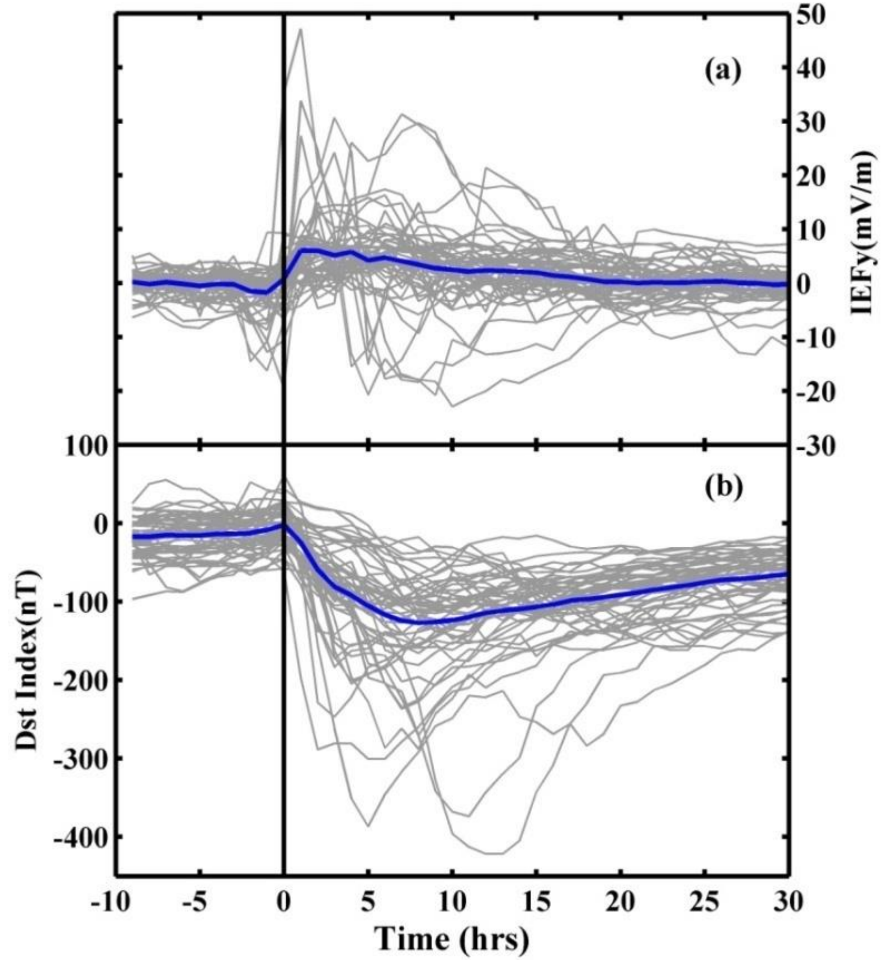


Tsurutani, B. T., W. D. Gonzalez, G. S. Lakhina, and S. Alex, The extreme magnetic storm of 1–2 September 1859, J. Geophys. Res., 108, 2003.

The 1 September 1859 Carrington solar flare most likely had an associated intense magnetic cloud ejection which led to a storm on Earth of DST ~ -1760 nT. This is consistent with the Colaba, India local noon magnetic response of H = 1600 ± 10 nT. It is found that both the 1–2 September 1859 solar flare energy and the associated coronal mass ejection speed were extremely high but not unique.



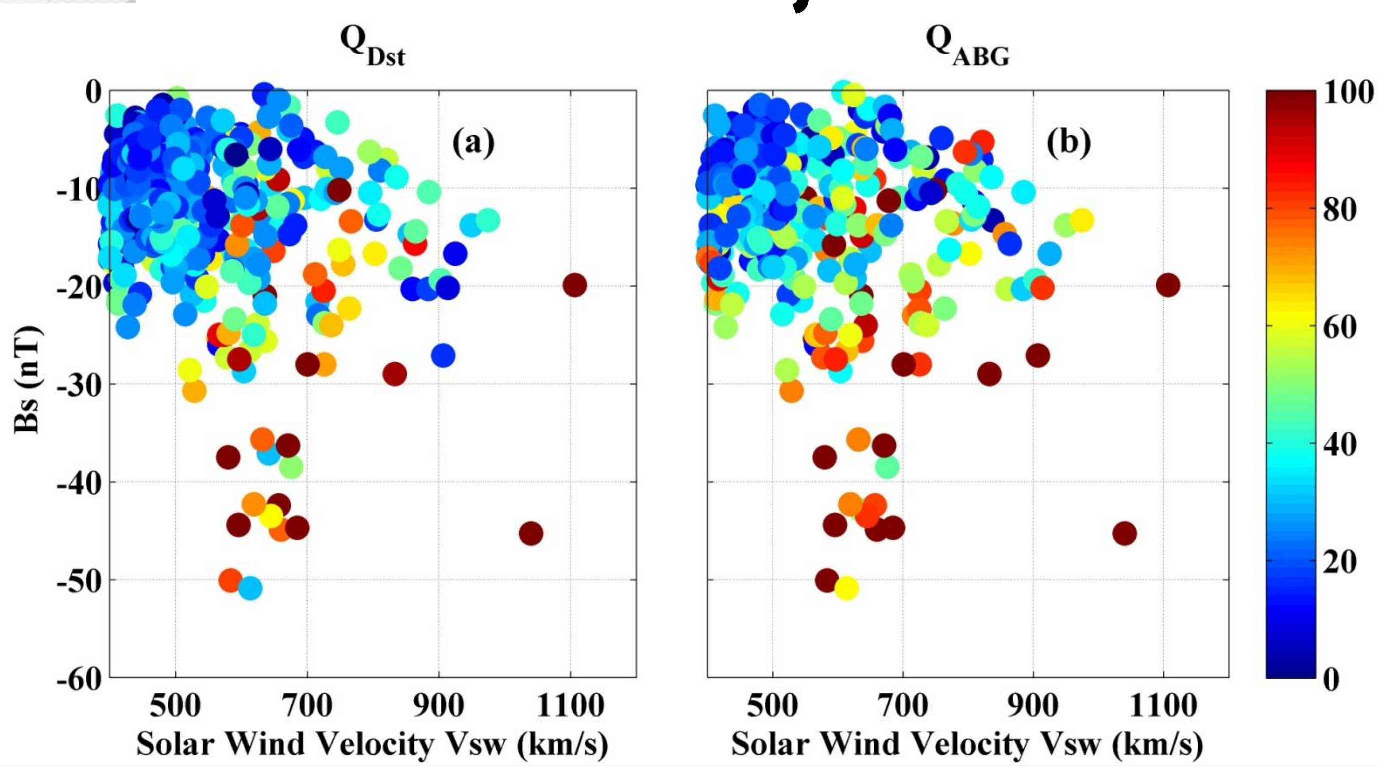
Some of the intense magnetic storms recorded at Colaba magnetic Observatory.



Superposed epoch plot of 69 magnetic storms (-100nT) with clear main phase were selected during the solar cycle 23 period.

(a) the associated interplanetary electric fields
(b) the Dst index. The solid black line shows the main phase onset.

Role of IMF Bz and Vsw on Ring Current injection



Dst is directly related to the total energy of the ring current and hence is a good measure of energetic of a magnetic storm.

The variation of ring current energy (Q) with IMF Bs and solar wind velocity (Vsw). The panel (a) and (b) shows the variations of Q_{Dst} and Q_{ABG} respectively. The color bar shows the strength of Q.

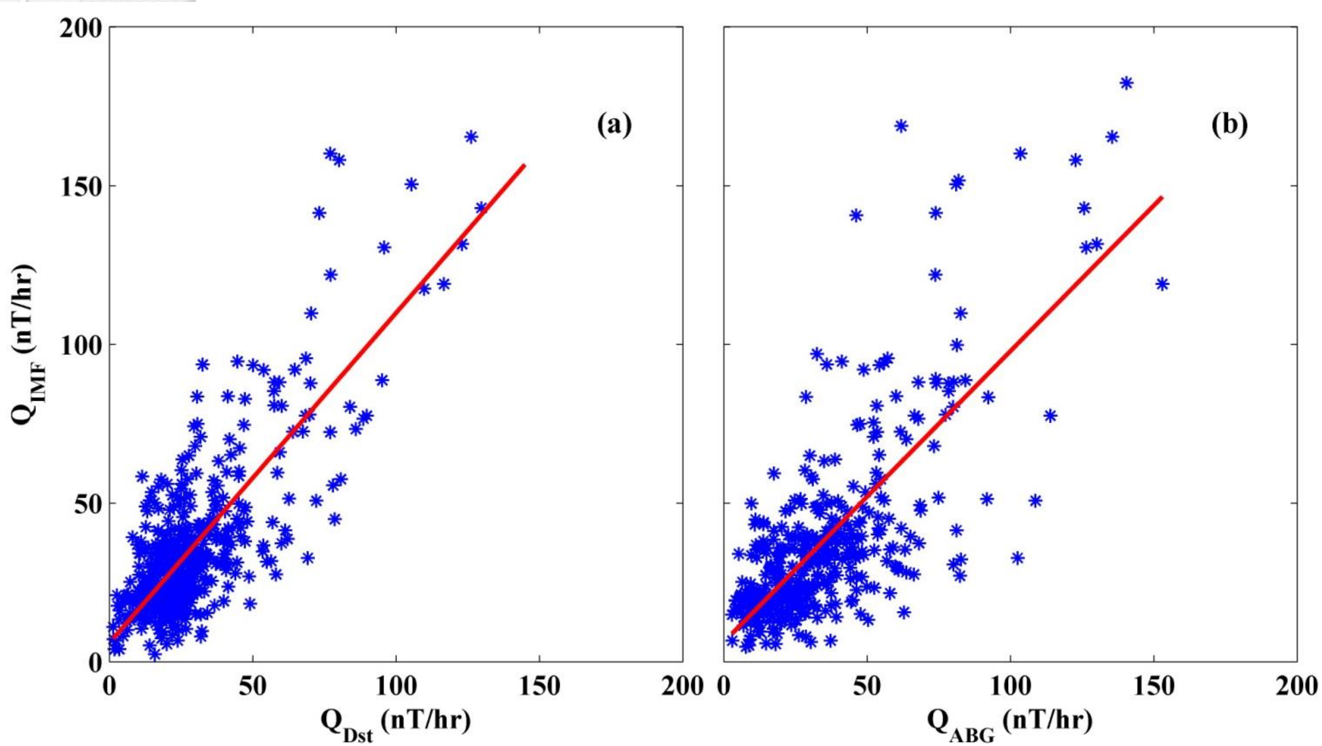
$$\frac{dDst}{dt} = Q_{Dst} - \frac{Dst}{\tau}$$

$$\frac{d\Delta H_{ABG}}{dt} = Q_{ABG} - \frac{\Delta H_{ABG}}{\tau} \quad (2)$$

Burton et al., 1975

Where Q is the input energy and τ is the decay constant

Relationship between Q_{Dst} and Q



$$Q = \alpha V_{sw} B_s$$

where α = -1.5×10^{-3} nT/s(mV/m)$^{-1}$ Vsw and Bs is the solar wind velocity and Magnetic field

(Burton et al., 1975)

$$Q = 1.04 * Q_{Dst} + 5.87$$

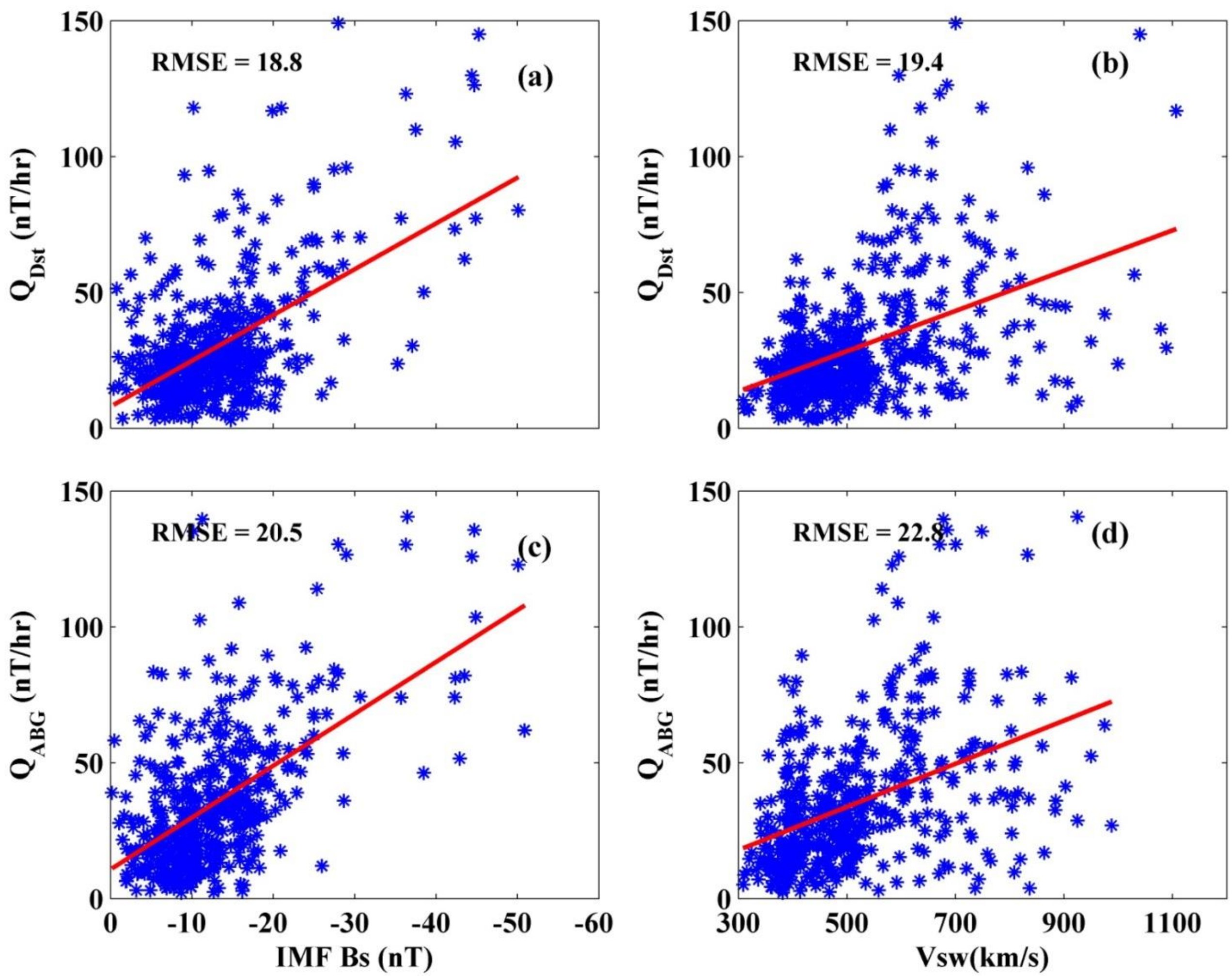
$$Q = 0.92 * Q_{\Delta H_{ABG}} + 6.12$$

We can write Q in terms of IEFy

$$IEFy = 0.19 * Q_{Dst} + 1.08$$

$$IEFy = 0.17 * Q_{\Delta H_{ABG}} + 1.13$$

Q_{Dst} / Q_{ABG} with Vsw and Bz for all values of Bz/Vsw



Kumar, S., B. Veenadhari, S. Tulasi Ram, R. Selvakumaran, S. Mukherjee, R. Singh, and B. D. Kadam (2015), *Estimation of interplanetary electric field conditions for historical geomagnetic storms,J. Geophys. Res. Space Physics, 120, doi:10.1002/2015JA021661.*

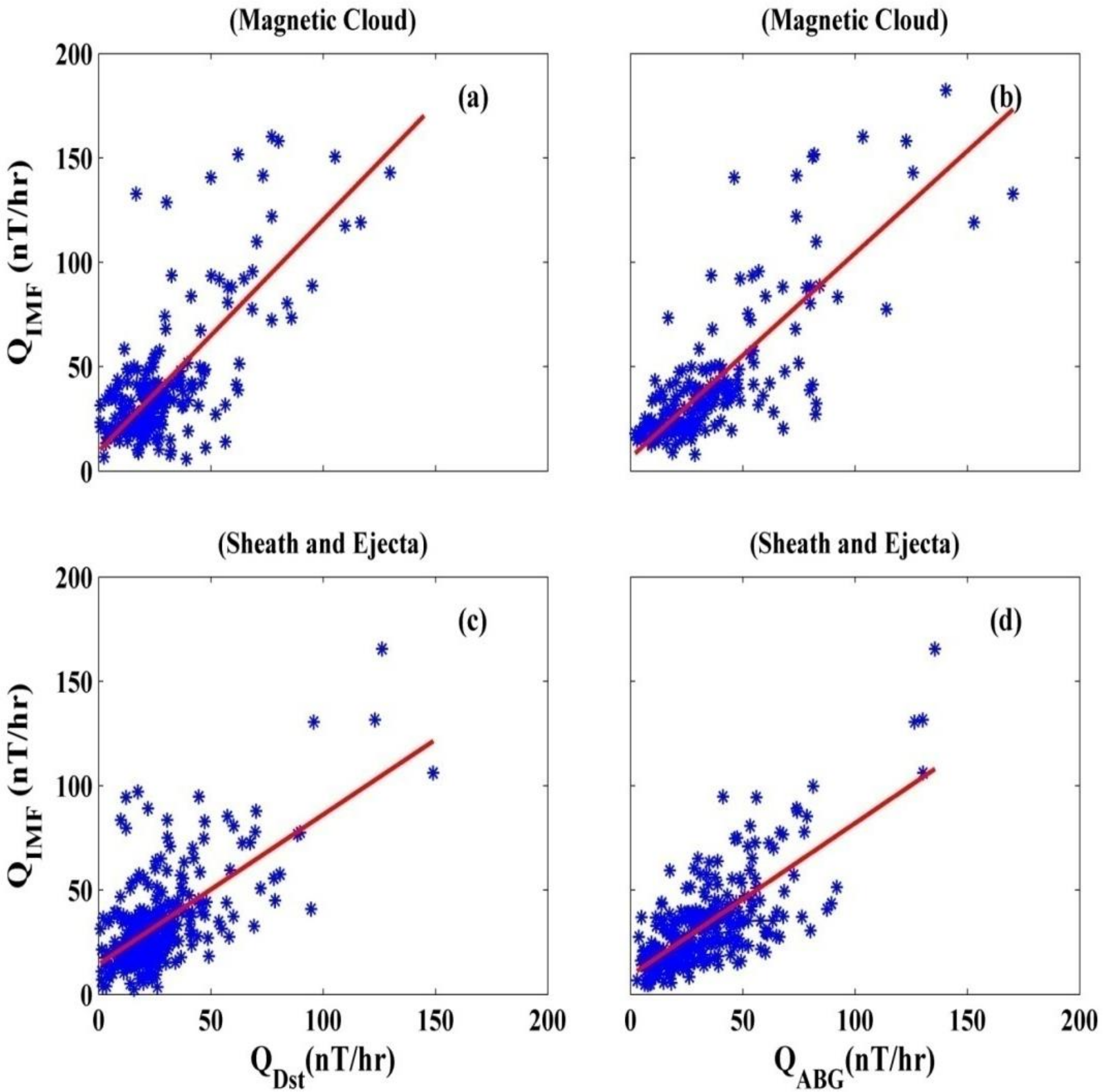
✓ **Echer et al., [2008] studied the interplanetary cause and conditions that led to intense(Dst≤ -100nT) geomagnetic storms during solar cycle 23 (1996-2006) and they found that the storm drivers varies with the phase of the solar cycle.**

Table 2 Interplanetary Structures That Caused Intense Geomagnetic Storms Per Year During Cycle 23

Year/IP Structure	CIR	sMC	Sh+MC	Sh	nsMC	nonMC	Sh+nonMC	nonMC+HCS	Sh+HCS	S.compr MC	nonMC+CIR	Complex	Total
1996	1	-	-	-	-	-	-	-	-	-	-	-	**1**
1997	-	1	2	1	1	-	-	-	-	-	-	-	**5**
1998	1	2	1	2	-	1	-	1	1	1		1	**11**
1999	-	1	-	1	-	1	-	-	-	-	1	1	**5**
2000	1	4	3	1	-	2	-	-	-	-	-	1	**12**
2001	-	2	3	6	1	1	-	-	-	-	-	-	**13**
2002	4	2	2	4	1	-	1	-	-	-	-	-	**14**
2003	1	2	1	3	-	-	-	-	-	-	-	-	**7**
2004	1	3	2	2	-	2	-	-	-	-	-	-	**10**
2005	3	3	-	2	1	1	-	-	-	-	-	-	**10**
2006	-	2	-	-	-	-	-	-	-	-	-	-	**2**
Total	**12**	**22**	**14**	**22**	**4**	**8**	**1**	**1**	**1**	**1**	**1**	**3**	**90**

CIR: corotating interaction region;
MC: ICME that shows the signature of a magnetic cloud;
sMCs: MC preceded by a fast shock;
nsMC: MC not preceeded by a fast shock;
Sh+MC: sheath field followed by a magnetic cloud;
Sh: sheath field;
nonMC: ICME that does not shows the signature of a magnetic cloud;
HCS: crossing of the heliospheric current sheet;
S compr MC: magnetic cloud compressed by shock.

The relationship between the Q_{Dst}/Q_{ABG} with Q_{IMF} for different interplanetary structures



Date	M P onset (LT)	M P Range[a] (nT)	Σ IEFy Estimated (mV.m-1.h)
02/09/1859	11	1600	273
12/10/1859	17	915	355
18/10/1859	9	415	260
04/02/1874	19	220	67
02/10/1882	14	350	102
03/04/1883	14	371	86
14/06/1891	10	173	41
13/02/1892	10	607	95
20/07/1894	14	513	102
13/03/1989[b]	02(UT)	572	275

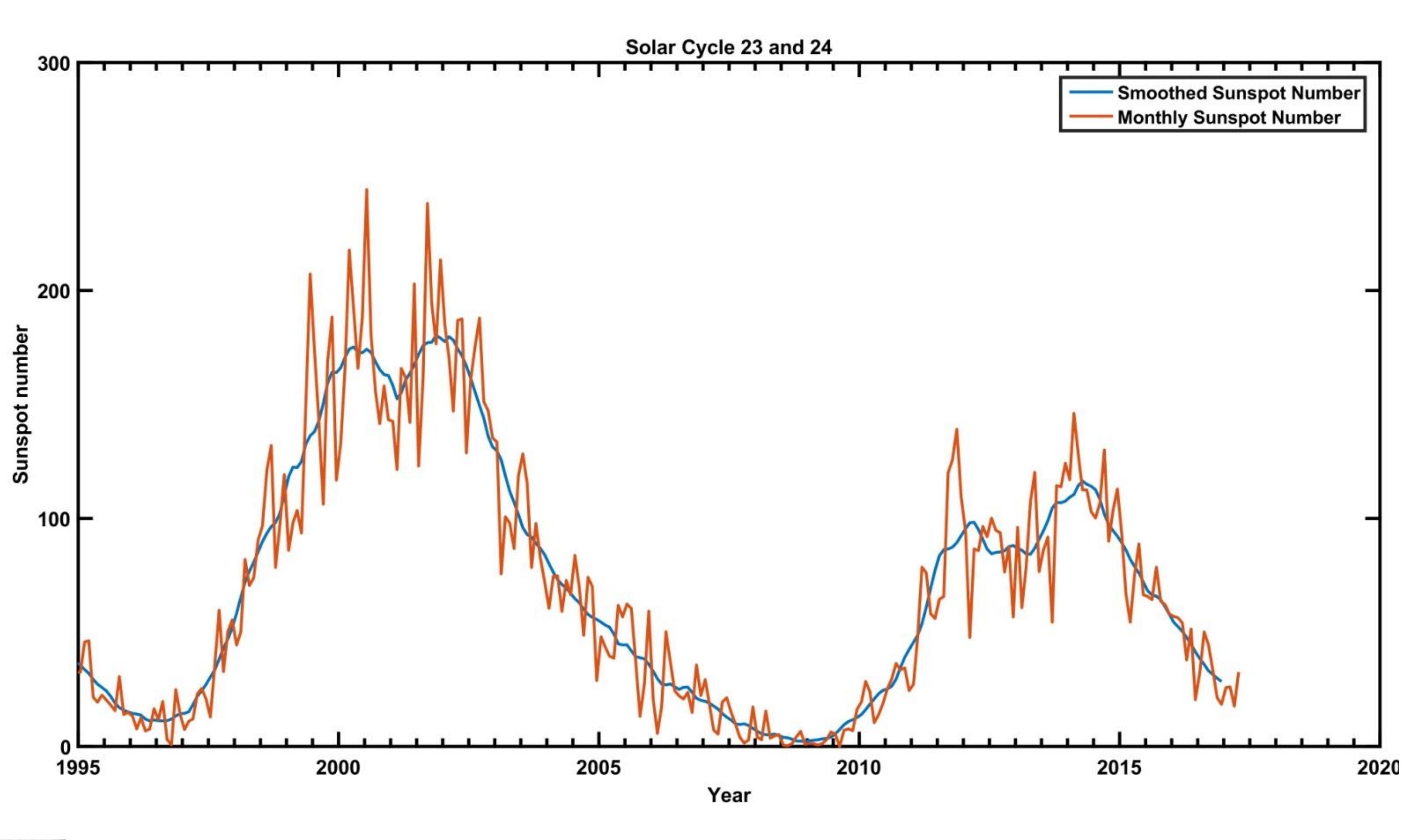
- List of intense historic magnetic storms recorded at Colaba with main phase onset, range and estimated time integrated interplanetary electric fields using ΔH_{COL}.

[a] *The Main phase range is the difference between maximum and minimum of H.*

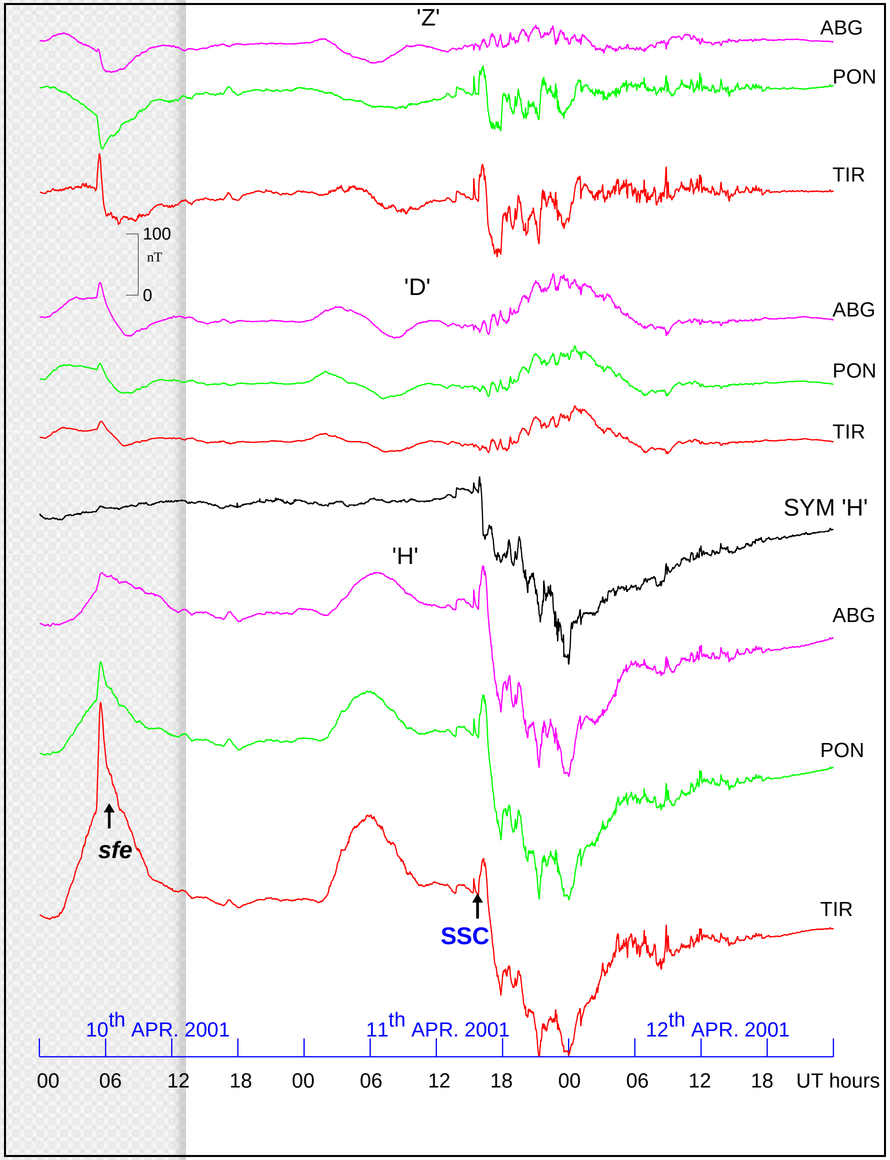
[b] *For March 13,1989 storm Dst index is used and time is in UT*

Space weather events of solar cycle 23

Solar activity of cycle 24 following the deep minimum between cycle 23 and cycle 24 is the weakest one since cycle 14 (1902–1913). Geomagnetic activity is also low in cycle 24.



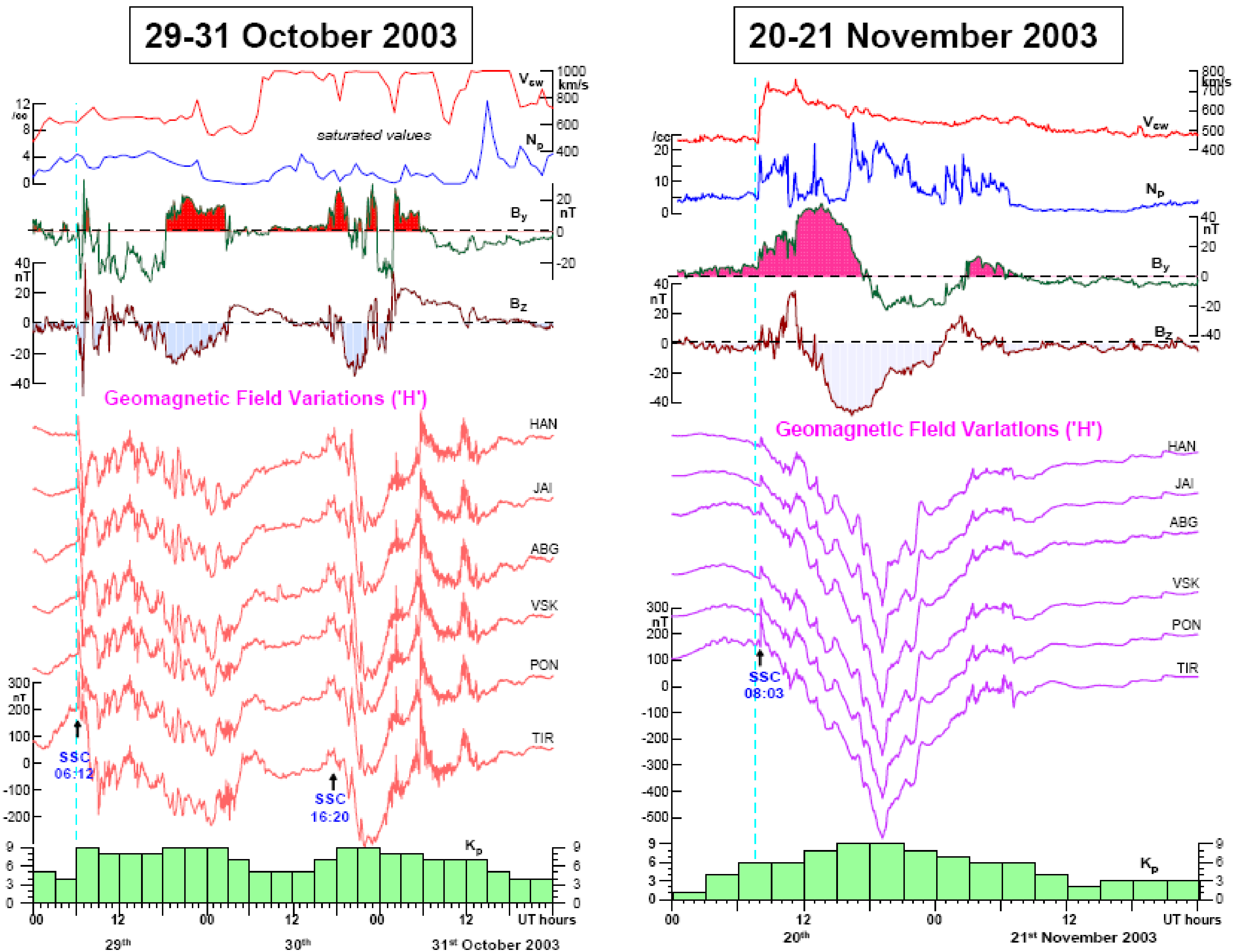
Geomagnetic variations on consecutive days at three magnetic observatories reflecting the solar conditions



10 April 2001 : X2.3 Solar flare (sfe) at 05:25 UT modified the ionospheric current and affected the magnetic field within a few minutes.

11 April : Pre-noon Quiet day condition prevails showing a steady geomagnetic field.

11-12 April : Effect on the ground magnetic variation following the flare and earth directed Halo CME on 10 April, which impacted the earth's magnetosphere almost 34 hours after the solar burst.



29-31 October 2003
20-21 November 2003
saturated values
Vsw
km/s
Np
/cc
By
nT
Bz
Geomagnetic Field Variations ('H')
HAN
JAI
ABG
VSK
PON
TIR
SSC 06:12
SSC 16:20
SSC 08:03
Kp
UT hours
29th
30th
31st October 2003
20th
21st November 2003

A series of powerful solar flares and associated geoeffective Coronal Mass Ejections (CMEs) travelling at 2000km/s drove shock fronts that impacted the Earth's magnetic field consecutively on 29 and 30 October, resulting in intense geomagnetic disturbances during 29–31 October.

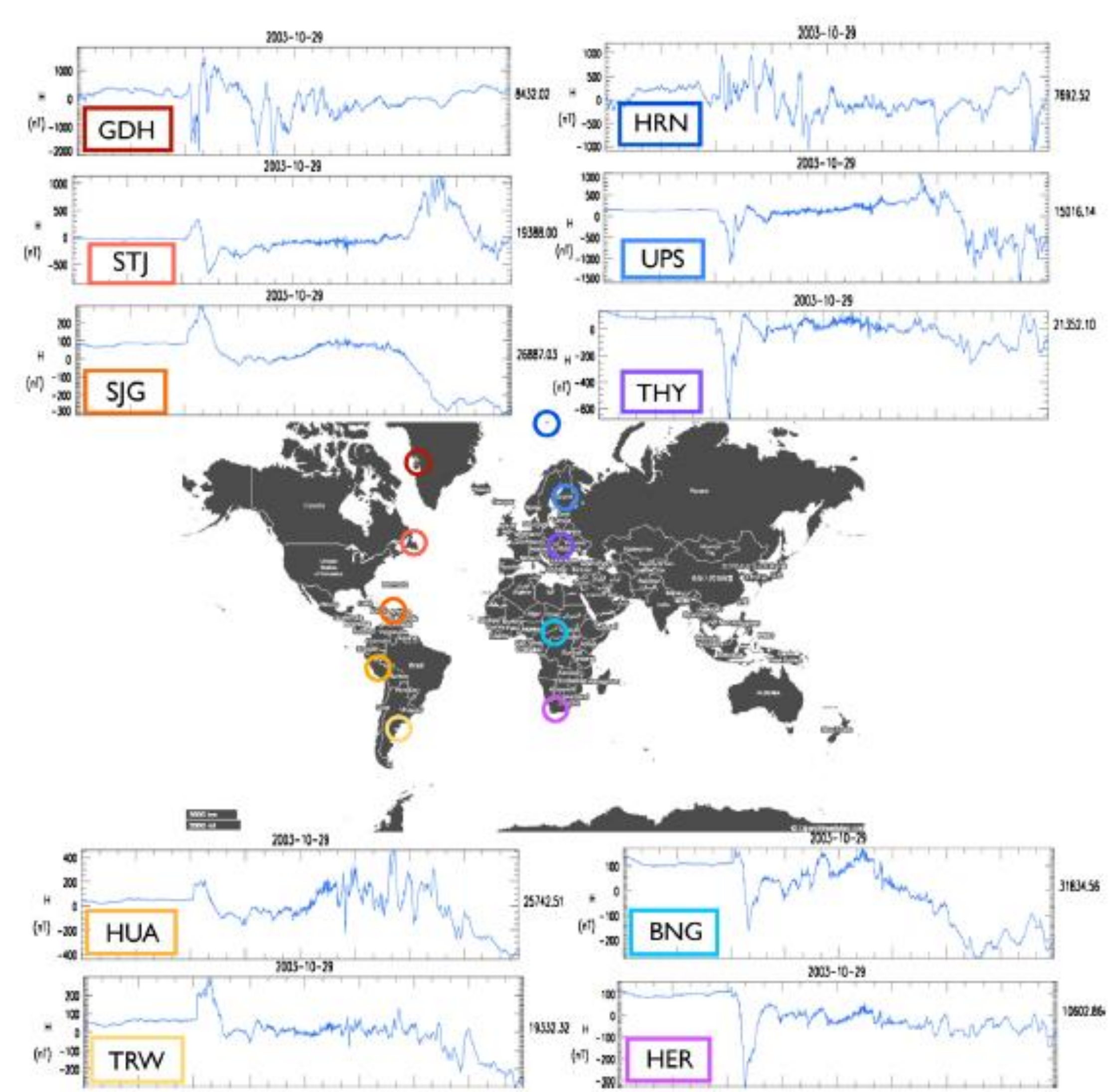
Another intense geomagnetic storm activity occurred during 20–21 November, resulting from a solar flare that had an associated geoeffective CME travelling at a speed of 1100 km/s.

Digital ground magnetic field measurements from the equatorial and low-latitude locations in the Indian longitude zone, in conjuction with the interplanetary solar wind and magnetic filed parameters, are used to study the characteristics of these storms.

Maximum magnitude of the total magnetospheric energy injected into the magnetosphere during the mainphase of the three major storm amounts to approximately 4.5×10^{13}, 3.6×10^{13}, 2.8×10^{13} W.

(Veenadhari et al., JASTP, 2006)

Geomagnetic response from high and middle latitude magnetic observatories



The disturbance in the Southern hemisphere is significantly smaller than in the Northern one for any latitude considered.

However, at longitudes close to 10, the disturbances in the Northern hemisphere do not decrease from high to low latitudes, resulting in an extreme disturbance of almost 800 nT at Tihany (THY, geographic latitude 4599).

The northern-southern asymmetry remains at this longitude. The above examples evidence that global indices are not adequate to quantify the geomagnetic disturbance according to its hazard.

Map showing H records along two main longitudes: 300 and 10. The profiles of the H component are clearly different at different locations on 29 October 2003. Offset values are shown at the right of each panel. *(Cid et al, 2014)*

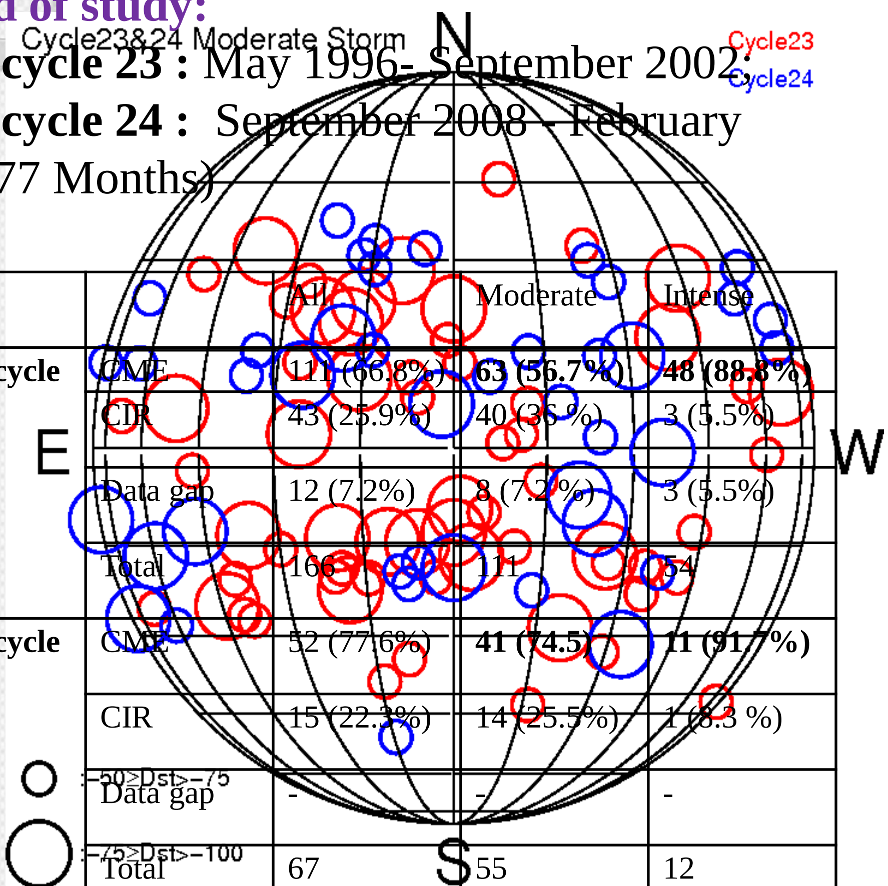
On the reduced geoeffectiveness of solar cycle 24: a moderate storm perspective

Objective: Reduction in geoeffectiveness has anything to do with the occurrence of moderate storm.

Period of study:

Solar cycle 23 : May 1996- September 2002;

Solar cycle 24 : September 2008 - February 2015(77 Months)



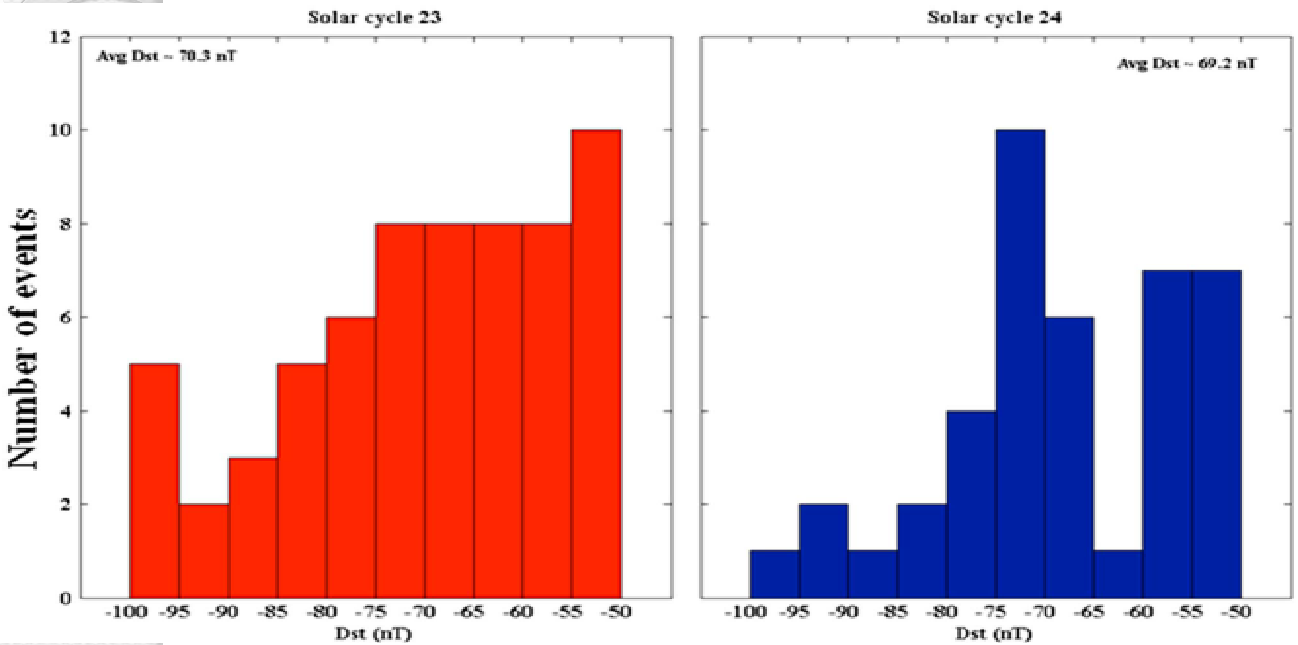
		All	Moderate	Intense
Solar cycle 23	CME	111 (66.8%)	**63 (56.7%)**	**48 (88.8%)**
	CIR	43 (25.9%)	40 (36 %)	3 (5.5%)
	Data gap	12 (7.2%)	8 (7.2%)	3 (5.5%)
	Total	166	111	54
Solar cycle 24	CME	52 (77.6%)	**41 (74.5)**	**11 (91.7%)**
	CIR	15 (22.3%)	14 (25.5%)	1 (8.3 %)
	Data gap	-	-	-
	Total	67	55	12

Solar source location of moderate storms occurred during SCs 23 and 24.

The size difference in the circle indicates the strength of the Dst produced, and the range is mentioned in the figure.

Red indicates the source location of SC 23, and blue denotes the cycle 24.

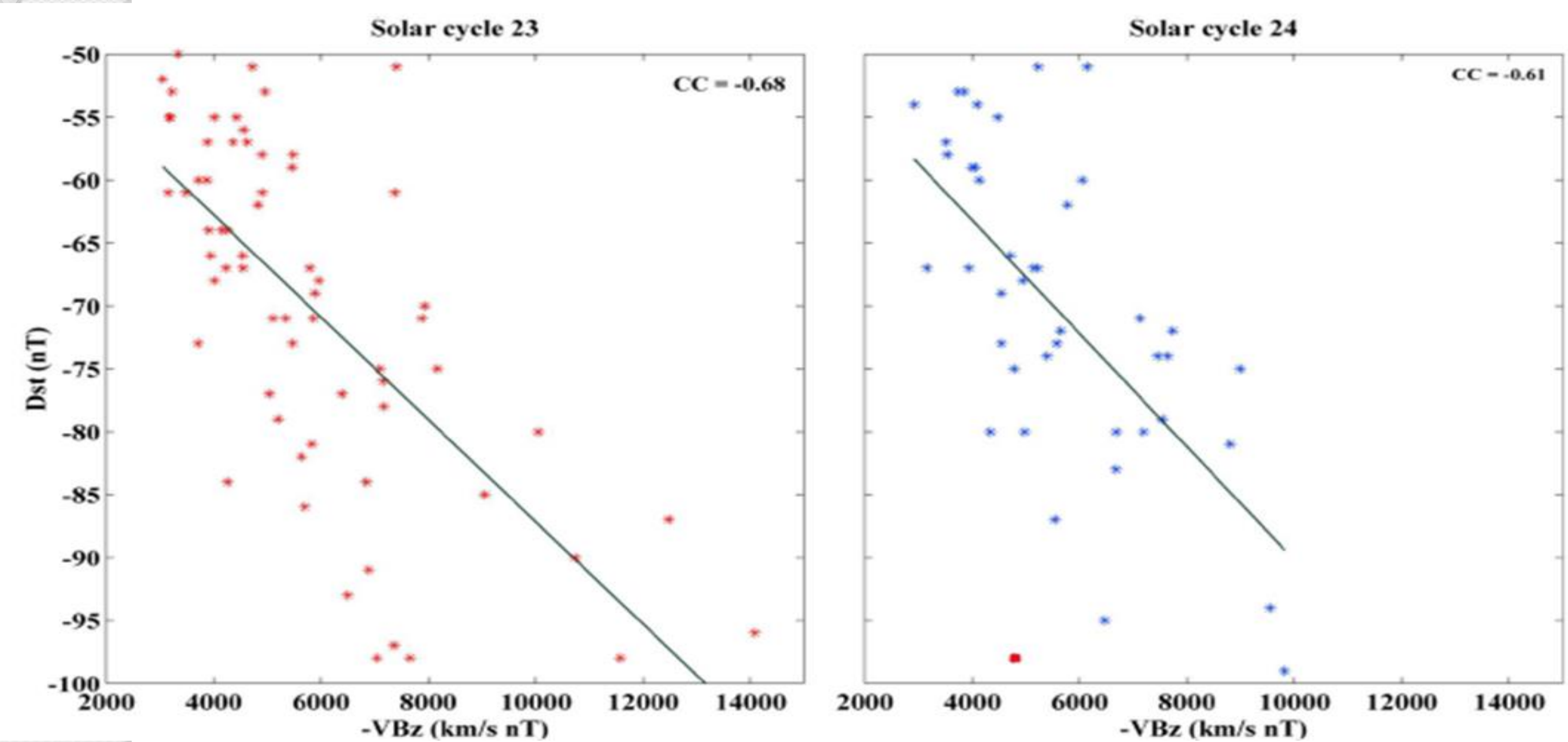
Distribution of Dst value



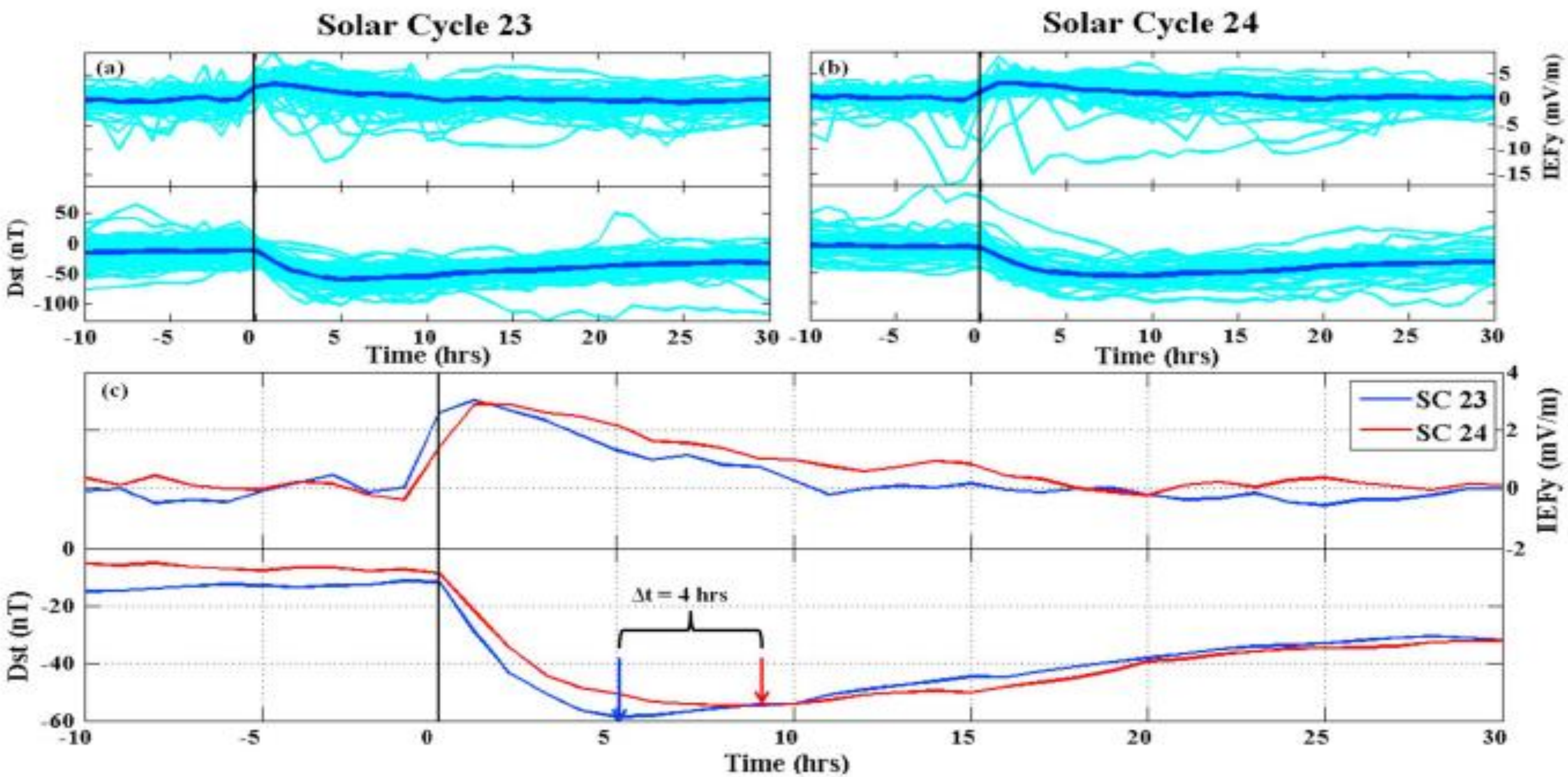
- Average Dst values for the two cycles are comparable (~70 nT), and though there is nearly 40% reduction observed in number of events, the average values are the same.

The 95% confidence intervals of the means overlap (73.33 and 66.87 nT for cycle 23 and 73.15 and 65.65 nT for cycle 24), again suggesting no significant difference between the distributions.

Interplanetary and Magnetospheric for moderate storms



- The geomagnetic storm process of converting solar wind energy to ring current energy did not change which is consistent with the work by Gopalswamy et al. [2015].

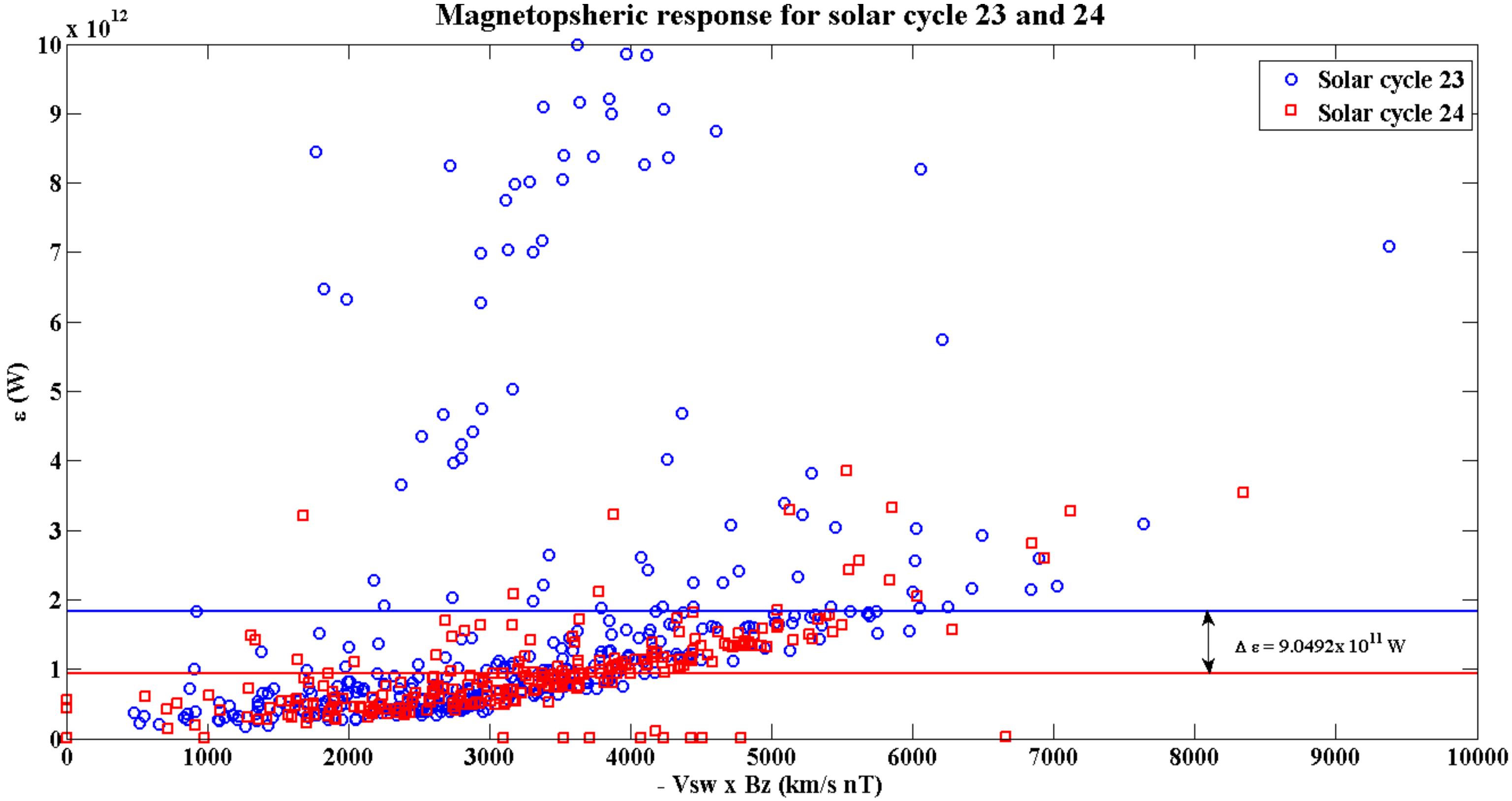


Average minimum Dst

Cycle 23 : -58.7 nT

Cycle 24 : -54.9 nT

Delay in Dst minimum suggests that although the average IEFy is similar, the response of the magnetosphere and the rate of ring current injection is rapid for cycle 23



➢The Ɛ is estimated to be 1.83 x 10^{12} W for cycle 23 and 9.93 x 10^{11} W for cycle 24. So the average energy transfer is larger by 9.05 x 10^{11} W for cycle 23 than in cycle 24.

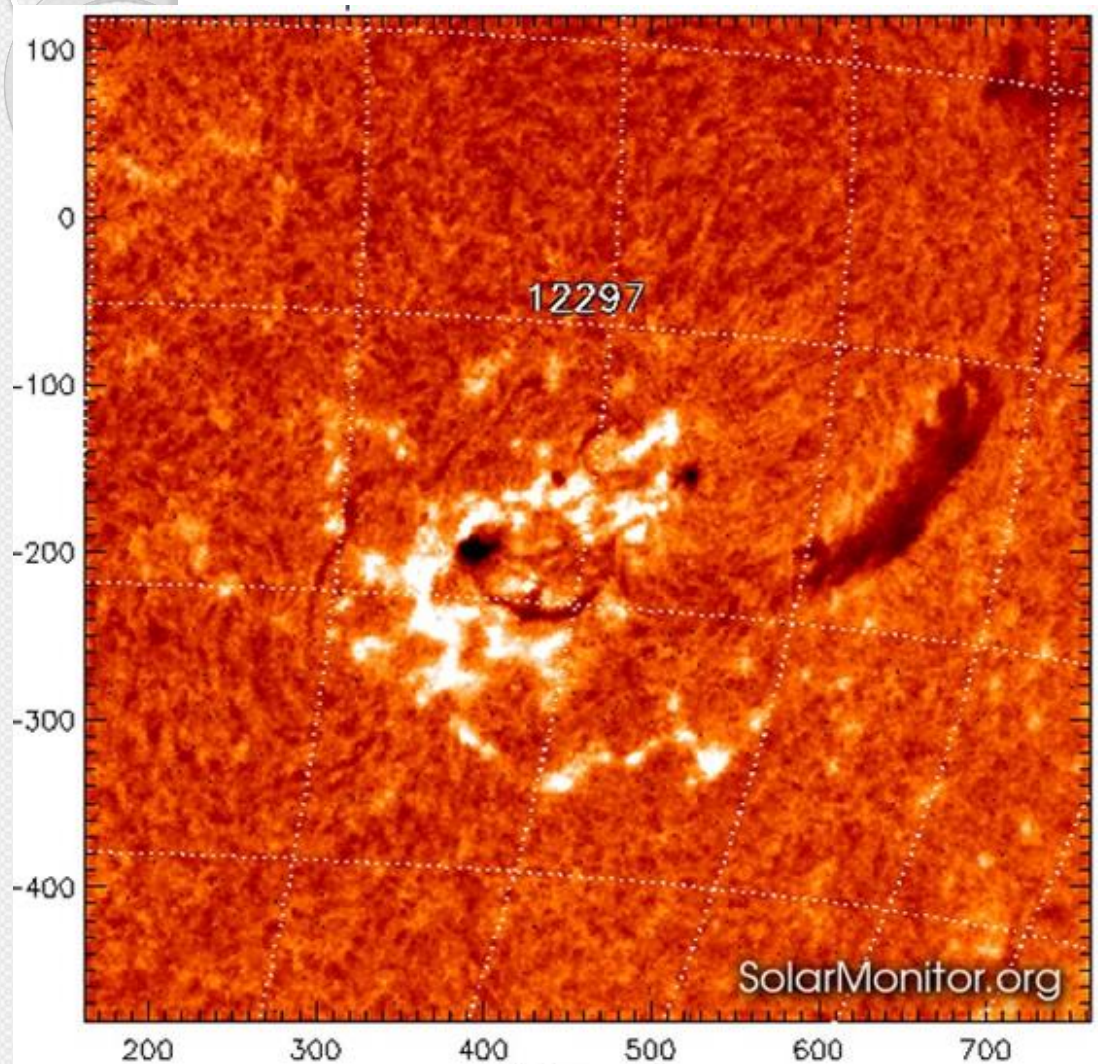
Reason for reduced geoeffectiveness in cycle 24 is mainly due to

✓**Anomalous expansion of CME expansion**

✓ **Less magnetopsheric energy transfer in cycle 24.**

R.Selvakumaran , B.Veenadhari , S.Akiyama, Megha Pandya , N.Gopalswamy, S. Yashiro, Sandeep kumar, P. Mäkelä , H. Xie, On the reduced geoeffectiveness of solar cycle 24: a moderate storm perspective, *JGR , Space physics, 121, doi: 10.1002/2016JA022885*

Intense Geomagnetic storms of solar cycle 24



C9.1 Solar flare

Flare location : S22^{o}W29^{o}

Flare timing

Starting time : 1:15 UT

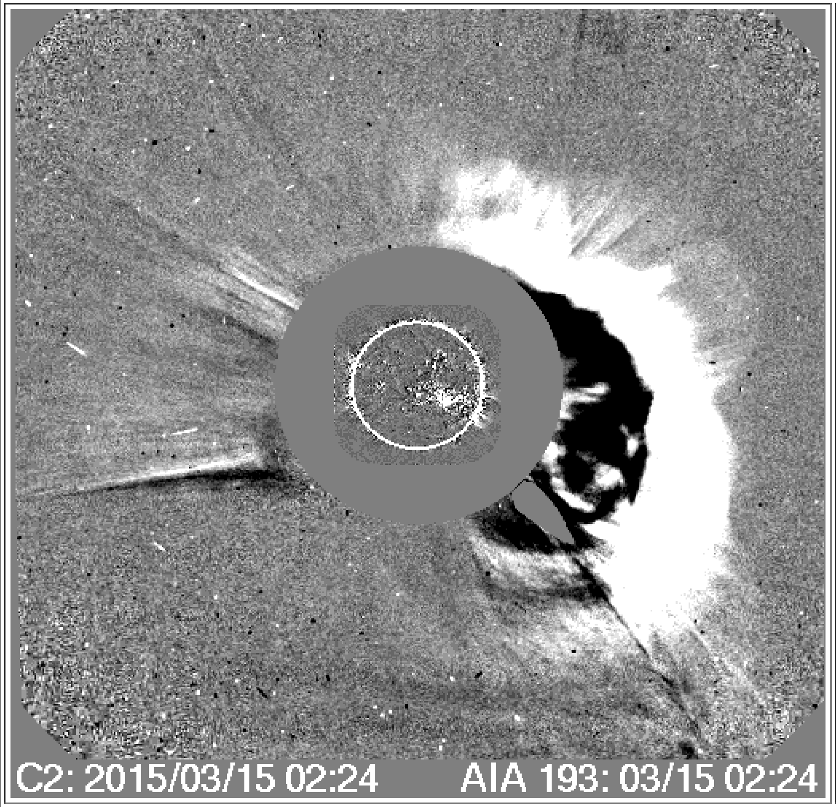
Peak time : 2:13 UT

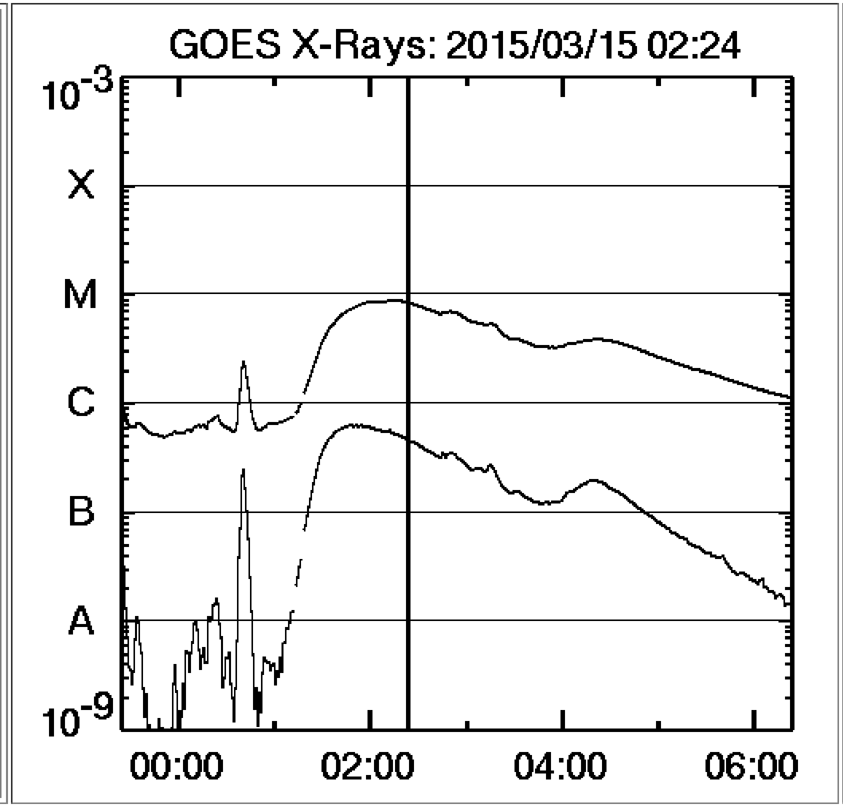
CME time : 02:10

Speed at 1 A.u : 683

Dst = −223 nT

Halo-CME eruptions on 15th March 2015 of St. Patrick storm





Speed of this CME is estimated to be ~668 km/s

Sheath + MC – The first step was associated with the sheath, whereas the second step was associated with MC

HALO- CME

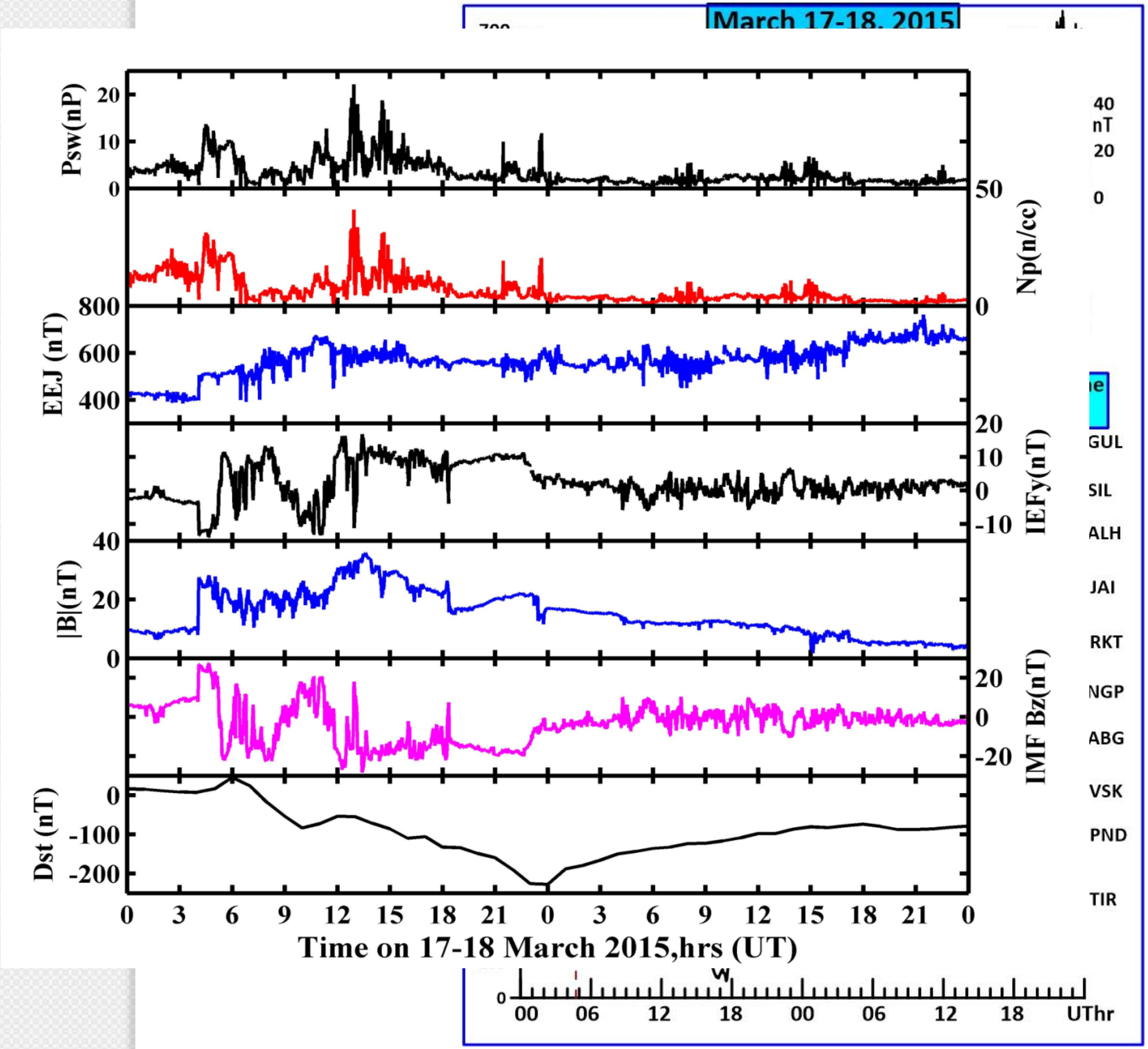
↓

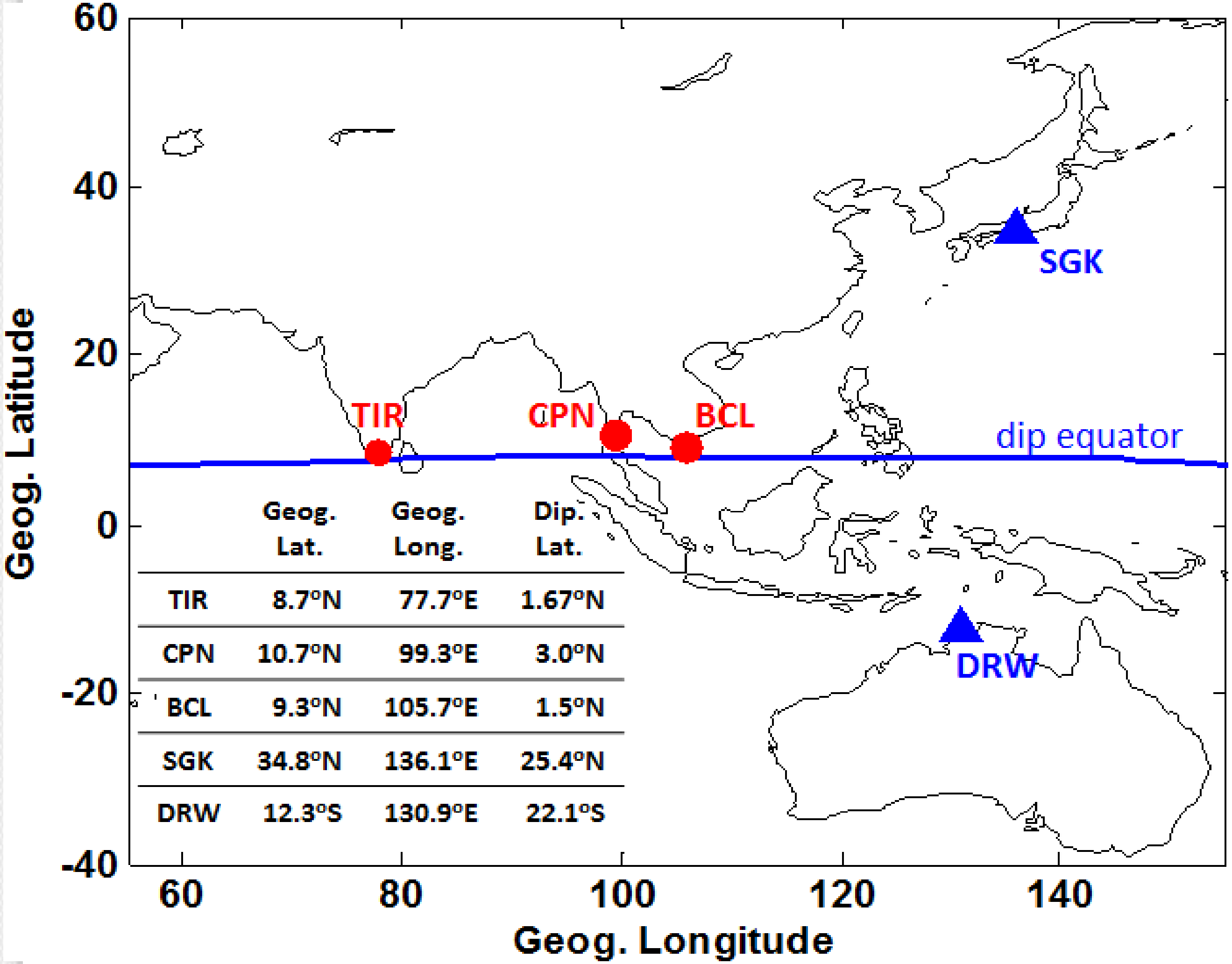
Centered S24°W38°

↓

IP shock at 3:59 UT (17 March 2017)

Geomagnetic storms of 17 March, 2015





	Geog. Lat.	Geog. Long.	Dip. Lat.
TIR	8.7°N	77.7°E	1.67°N
CPN	10.7°N	99.3°E	3.0°N
BCL	9.3°N	105.7°E	1.5°N
SGK	34.8°N	136.1°E	25.4°N
DRW	12.3°S	130.9°E	22.1°S

Geographic locations of Ionosondes and Fabry-Perot Interferometers (FPIs) used in this study. The geographic coordinates and dip latitudes are indicated in the figure.

Dusk side enhancement of equatorial zonal electric field response to convection electric fields during the intense geomagnetic storm of March 17, 2015.

- ✓ The equatorial zonal electric field response to prompt penetration of eastward convection electric fields (PPEF) is investigated at dusk to pre-midnight sector at closely spaced longitudinal intervals.
- ✓ A chain of three ionosondes at Tirunelveli (India), Chumphon (Thailand) and Bac Lieu (Vietnam) were employed in conjunction with in-situ ion-density observations from C/NOFS and SWARM satellites to closely examine the relative amplitudes of equatorial zonal electric field perturbations from dusk to pre-midnight sectors and their impact on the development of equatorial plasma bubble (EPB) irregularities.
- ✓ A rapid uplift of equatorial F-layer to above ~550 km and subsequent development of range spread-F is observed over Tirunelveli which is located at dusk sector

Tulasiram et al., JGR Space Physics, 2015

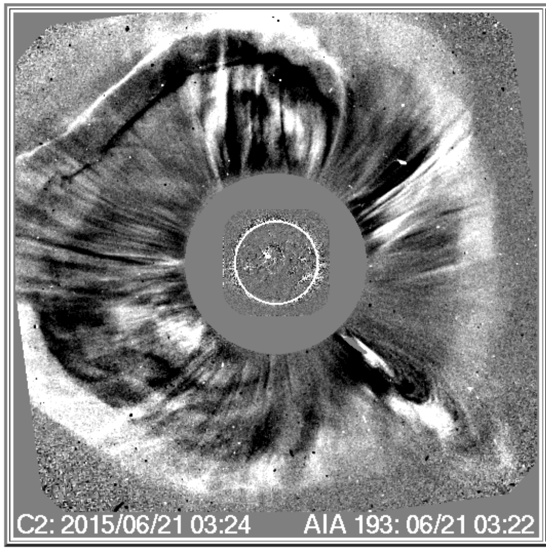
21- 24 June 2015 - Geomagnetic storm

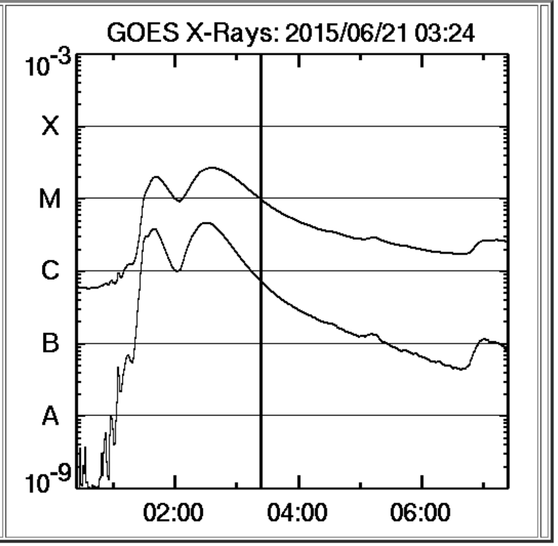
Source :
AR 12371
Multiple CME

18th June : 1200 km/s – M3.0 flare N13°E45° - resulted in SC on 21st June

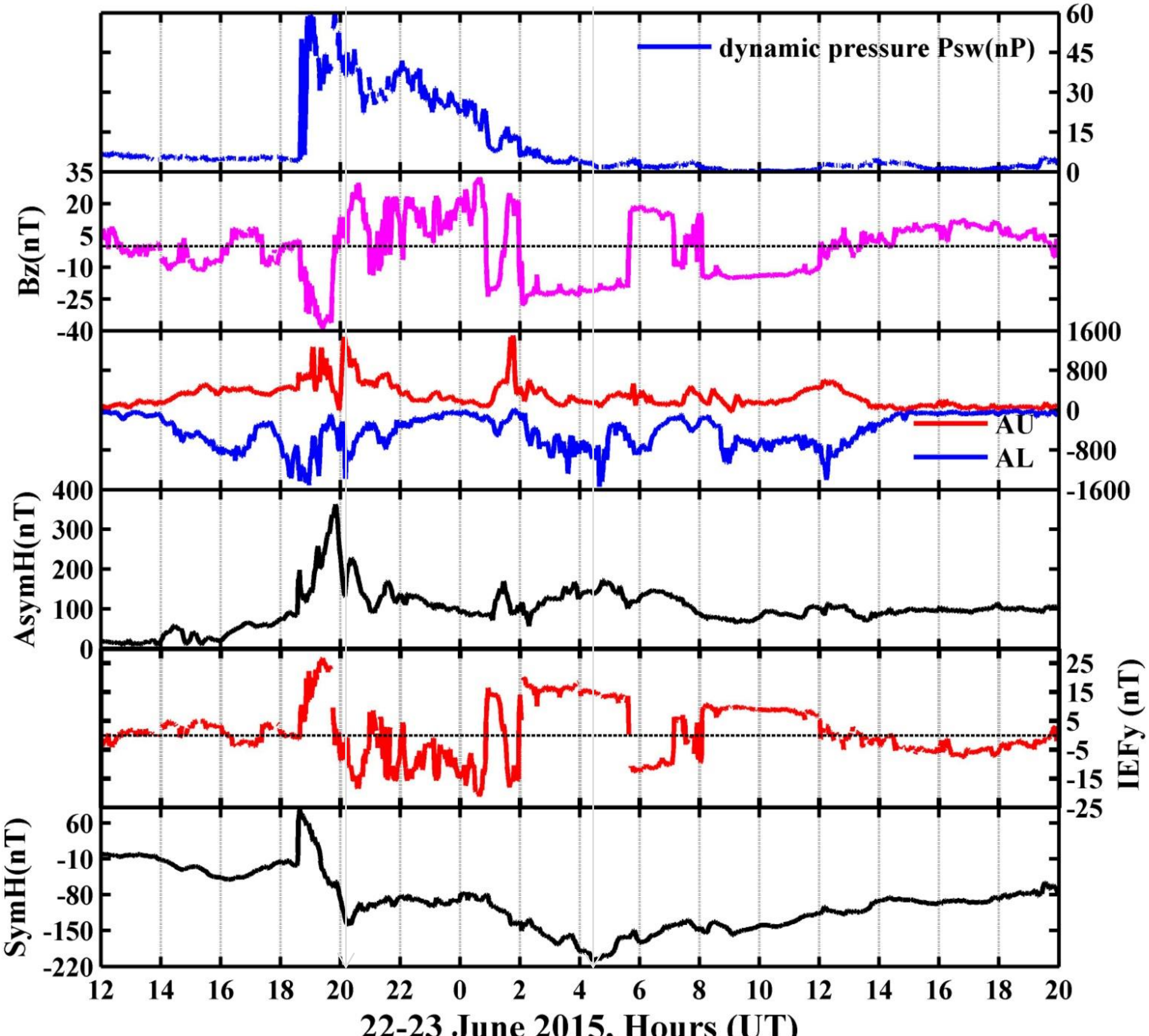
CME of about 1300 km s−1 associated with an M2.0 flare from N12°E13° peaking at 01:42 UT on June 21. The June 21 CME appeared as a single halo event in the coronagraph images and a near head-on collision with the Earth was expected

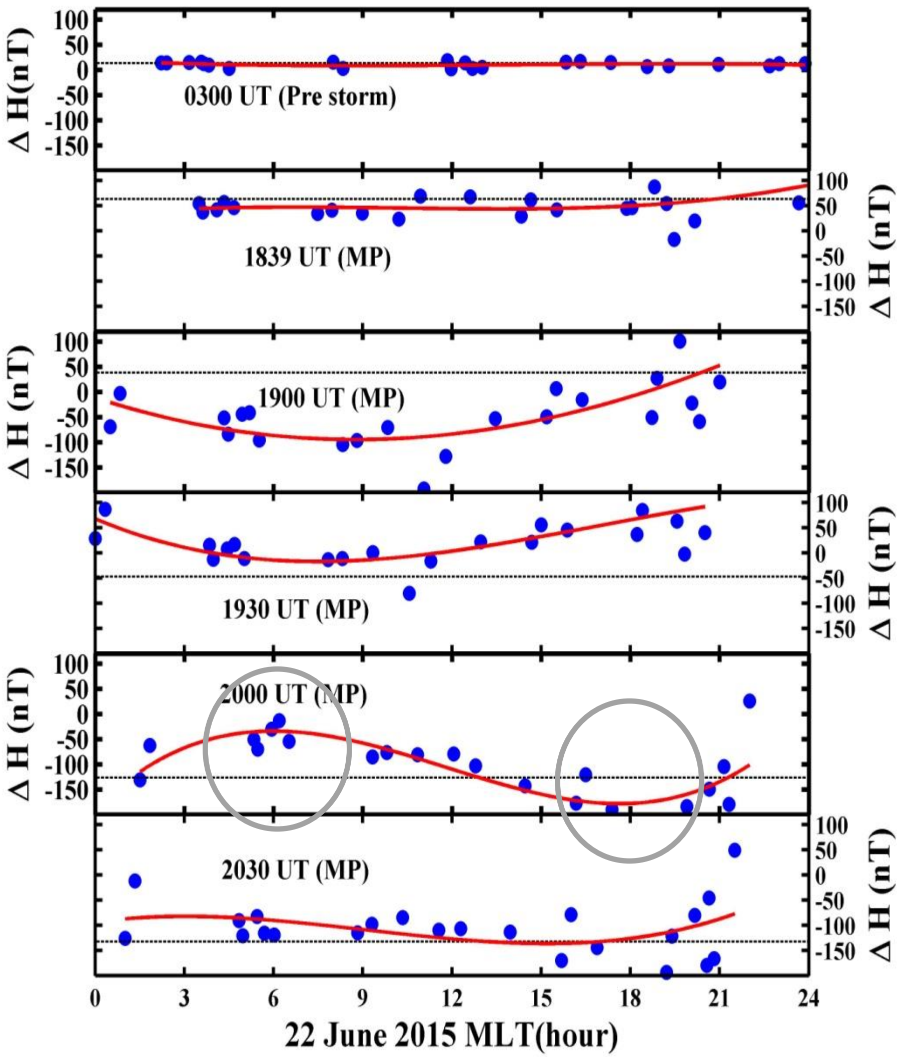
ICME : Sheath + MC

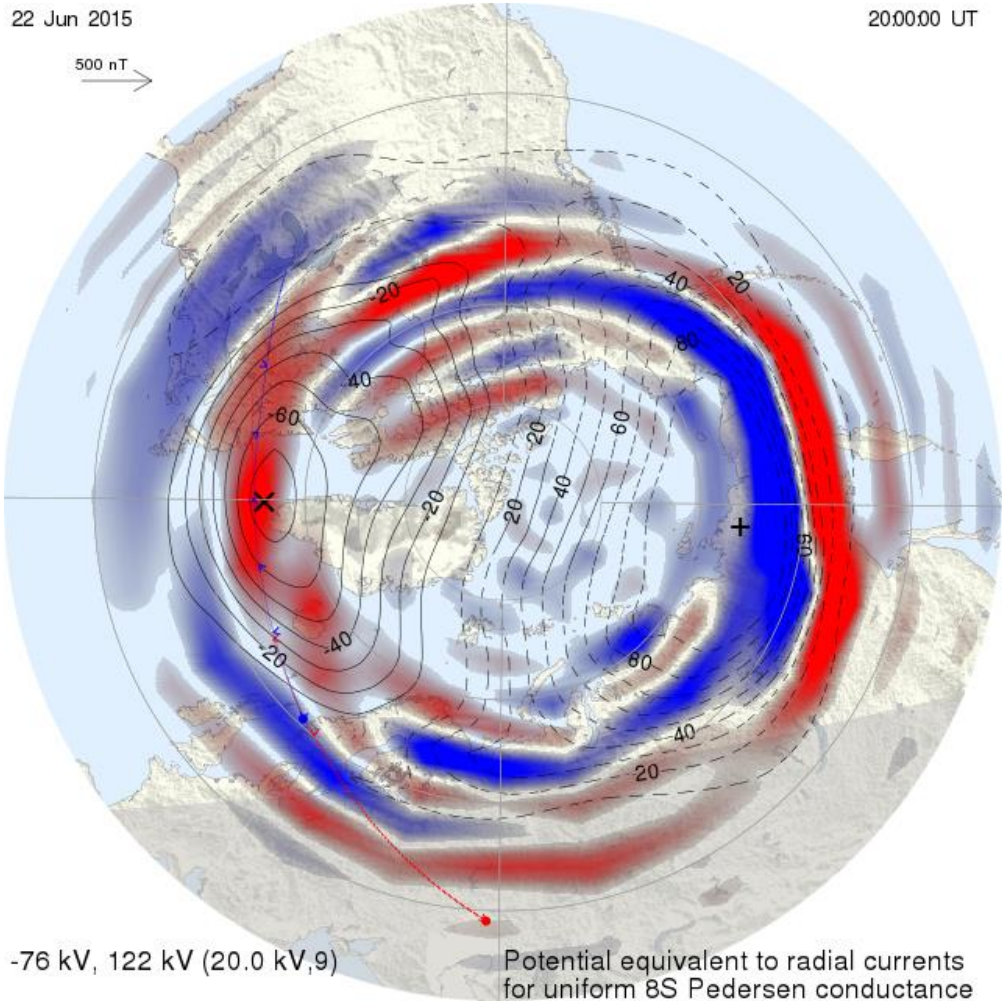




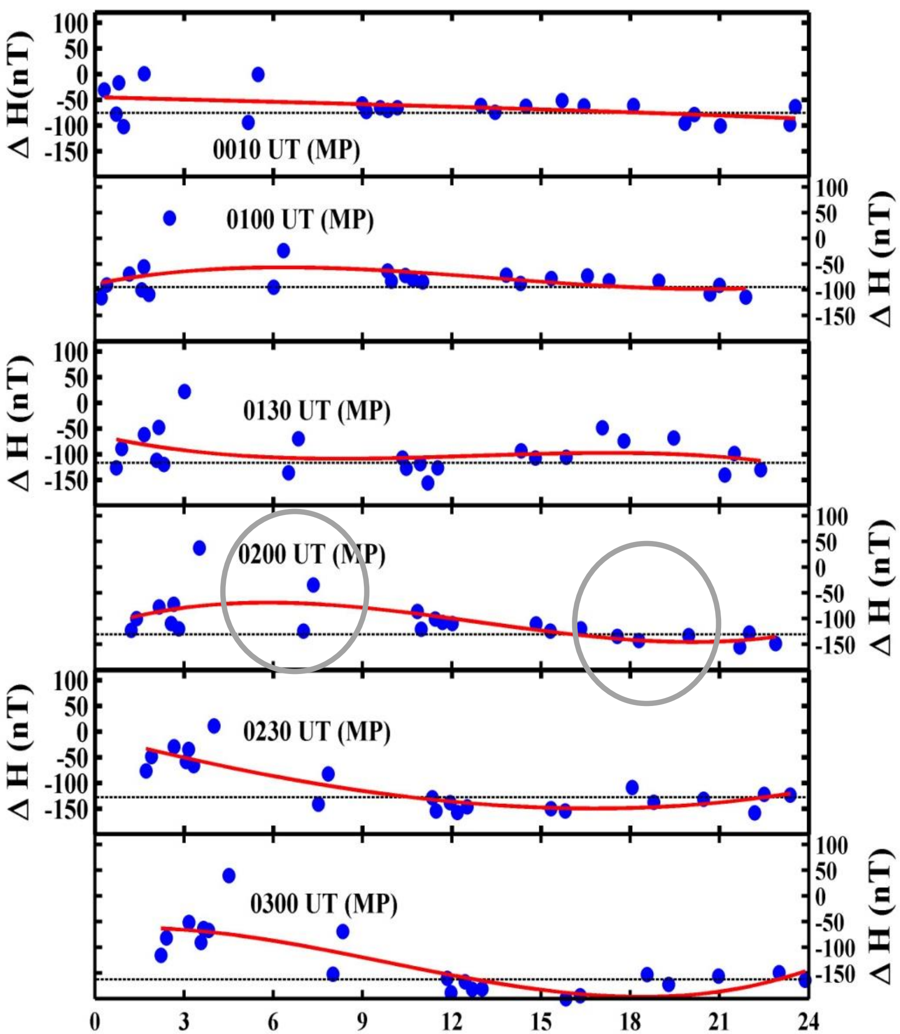
22-23 June 2015

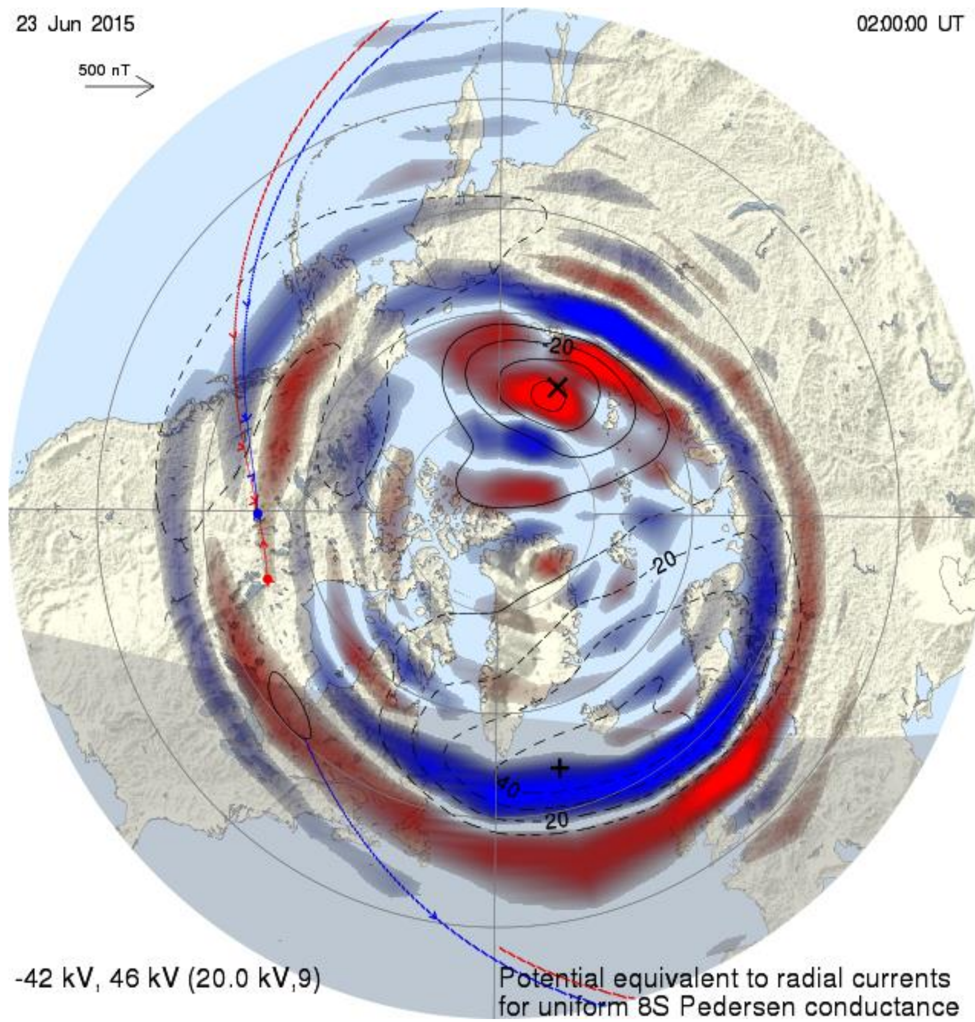






Around 2000 UT there was a northward turning of IMF Bz.





23 June 2015

On 23 June 2015 around 0200 UT there is sharp southward turning of IMF Bz.

Summary

- The study of old magnetic storm records are more important and the knowledge will be very much required for predictability of similar intensity events in future.

- The past occurrence of the intense magnetic storms will be helpful to understanding the physical processes involved in the phenomena.

- Some intense events of Solar cycle 24 are analysed for the signatures of PPEFs and PRC signatures from ground magnetic data.

- Reason for reduced geoeffectiveness in cycle 24 is mainly due to Anomalous expansion of CME expansion and Less magnetopsheric energy transfer in cycle 24.

Indian AWESOME VLF observation sites
Setup in 2007-08 under IHY/UNBSSI program (2007 – 2017)

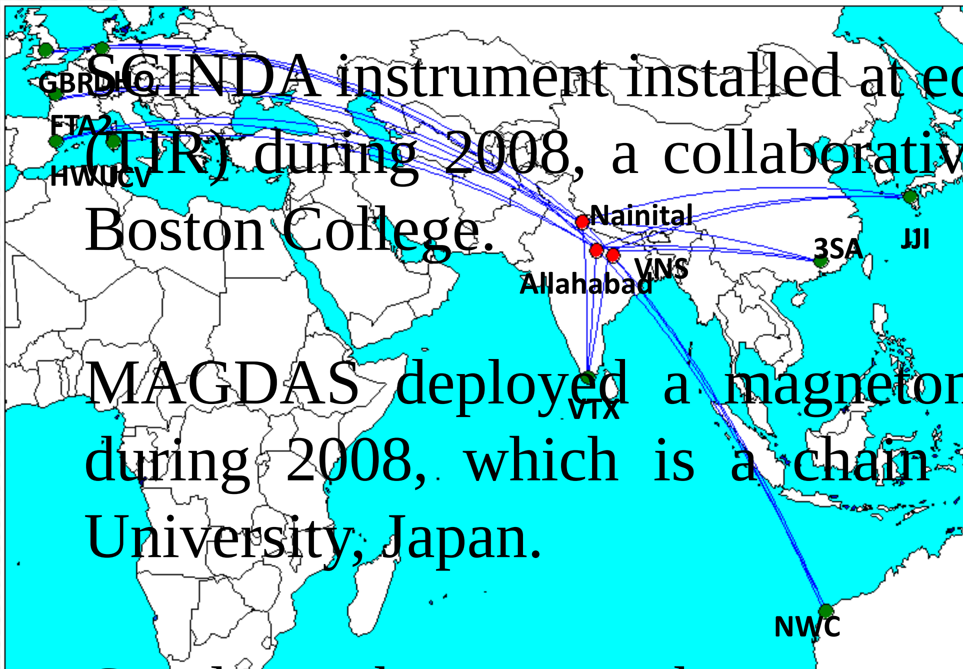
Rajesh Singh, B. Veenadhari, A.K. Maurya, R. Selvakumaran, Sneha, G, Venkatesh

IIG Setup Three New VLF stations under collaboration with Stanford University for the studies of Ionosphere & Magnetosphere using Lightning Discharge Generated VLF Waves

Allahabad (Lat.16.49 N Long.155.34 E)

Varanasi (Lat. 15.41 N Long. 156.37 E)

Nainital (Lat.20.48 N Long.153.34 E)



SCINDA instrument installed at equatorial station Tirunelveli (TIR) during 2008, a collaborative project between IIG and Boston College.

MAGDAS deployed a magnetometer at Tirunelveli (TIR) during 2008, which is a chain of MAGDAS by Kyushu University, Japan.

Good number research papers published by collaborative scientists

Objective:

Study of phenomena like:

- Radio atmospheric
- Whistlers
- VLF emissions
- Lightning induced electron precipitation (LEP)
- Cosmic gamma-rayflares
- Solar flares
- Geomagnetic storms
- Earthquake precursors

- AWESOME in operation since last 10 years (2007 – 2017)

-More than 30 publications

-- 2 Ph.Ds awarded

Thank you

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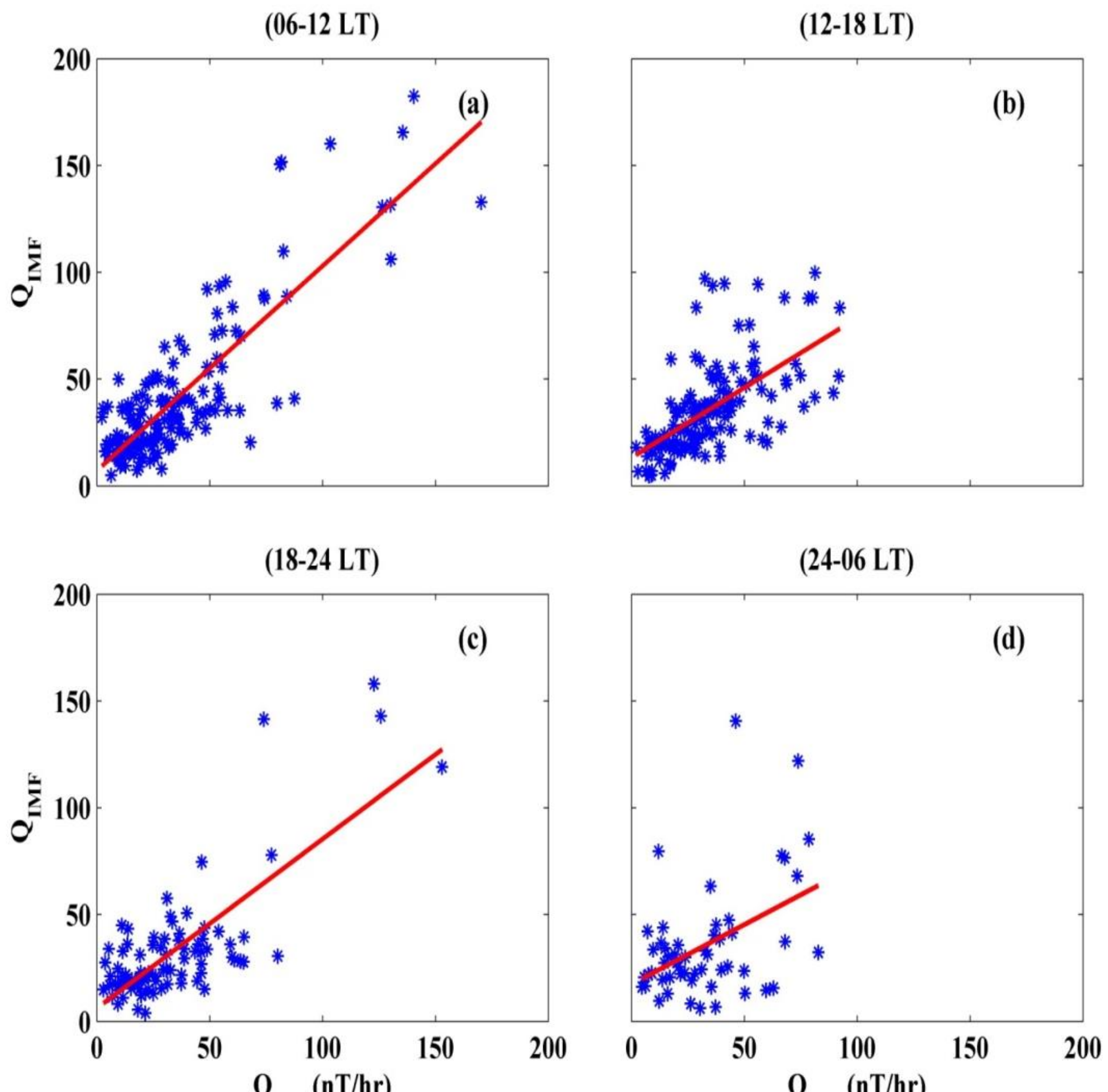
Good number publications by collaborative scientists

Table 1. The details of ground geomagnetic stations in India.

Station/Code	Geographic Latitude	Geographic Longitude	Geomagnetic Latitude	Geomagnetic Longitude	Dip. Latitude
Tirunelvelli (TIR)	8.7 N	77.8 E	0.17 S	149.97 E	0.96
Trivandrum (TRD)	8.48	76.95	0.31 S	149.1	0.73
Ettaiyapuram (ETT)	9.17	78.0	0.28 N	150.2	1.54
Kodaikanal (KOD)	10.23	77.47	1.39 N	149.78	2.86
Pondicherry(PON)	11.92	79.92	2.86	152.33	4.82
Hyderabad(HYD)	17.42	78.55	8.45	151.5	11.62
Visakhapatnam(VSK)	17.68	83.32	8.34	156.09	11.77
Alibag (ABG)	18.62	72.87	10.17	146.15	13.31
Nagpur(NGP)	21.15	79.08	12.12	152.32	16.20
Ujjain(UJJ)	23.18	75.78	14.43	149.39	18.83
Silchar(SIL)	24.93	92.82	15.02	165.6	20.62
Jaipur (JAI)	26.92	75.80	18.15	149.80	23.48
Sabhawala (SAB)	30.37	77.80	21.41	152.02	27.78
Hanle(HAN)	32.76	78.95	23.69	153.32	30.81

WDC Mumbai : http://www.wdciig.res.in/index.asp

Variation of Q_{ABG} with Q_{IMF} for different local time intervals.



To calculate the average H we have used the following method

$$\Delta \mathrm{H} = \frac{H - Hq}{\cos(\psi)}$$

$$where(\psi) = magnetic\_latitude$$

$$Hq = Quiet\_day$$

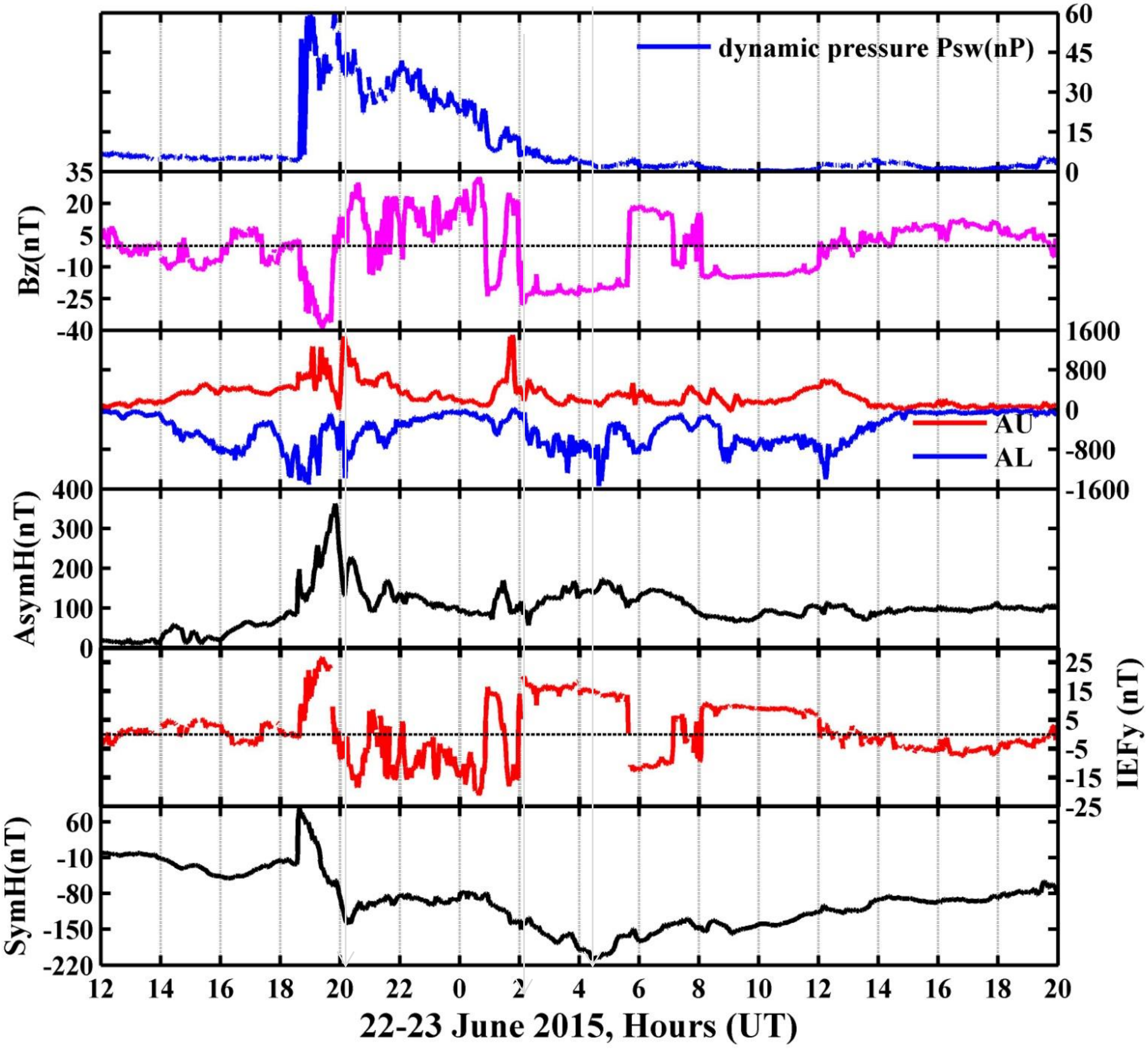
$$\Delta \mathrm{H}m = \frac{1}{N}\sum_{n=1}^{N} \Delta H$$

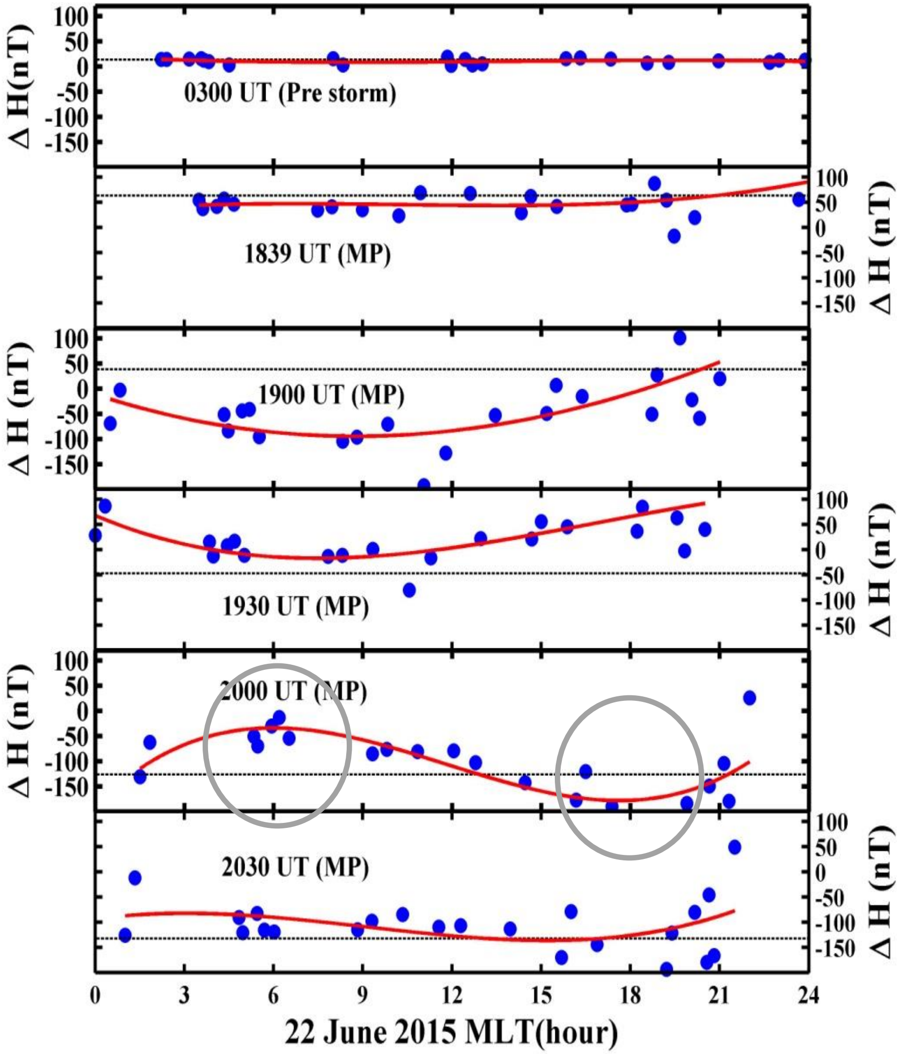
$$n = number\_of\_stations$$

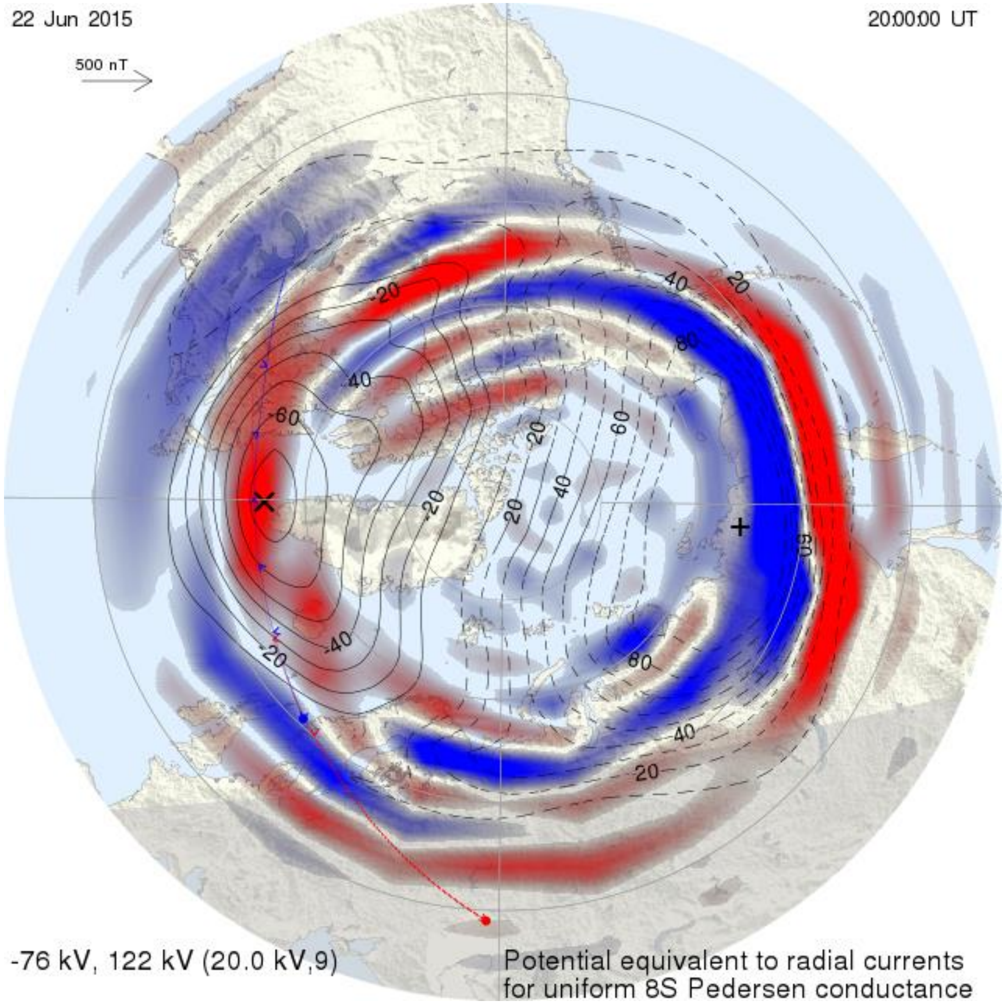
$$N = total\_no.\_of\_stations$$

$$\Delta \mathrm{H}m = Average\_H$$

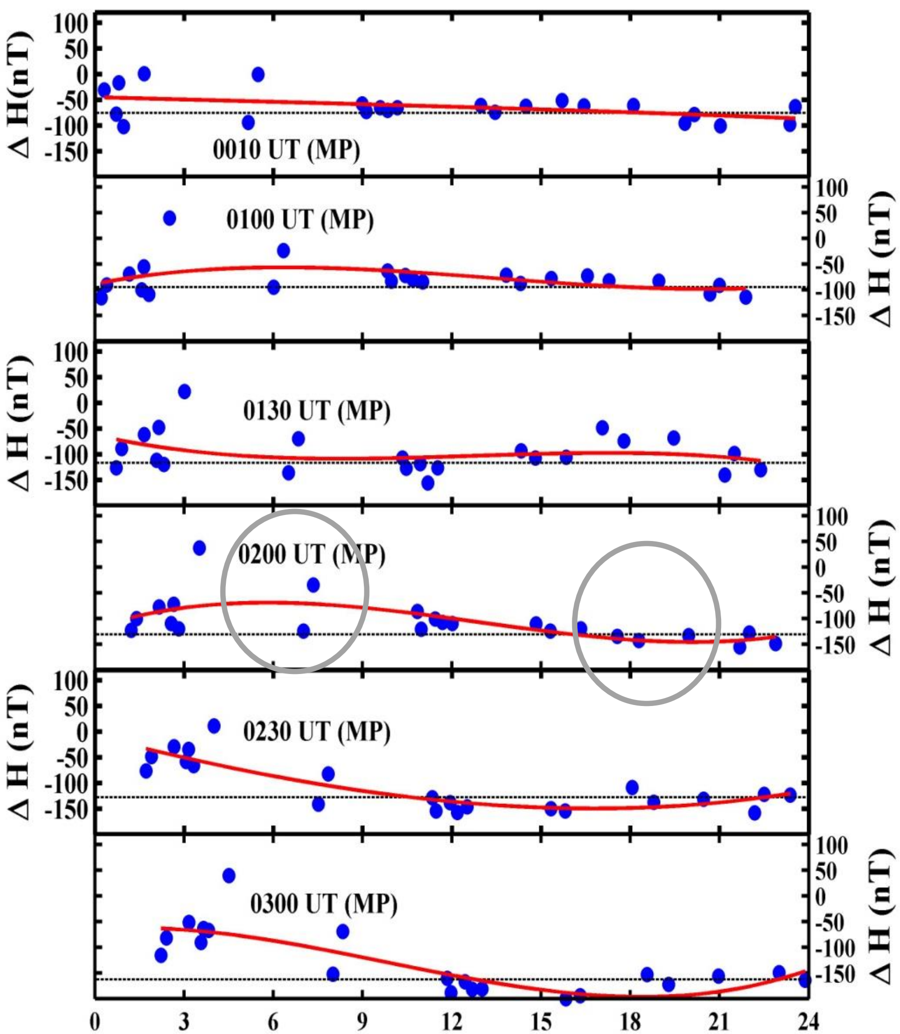
22-23 June 2015



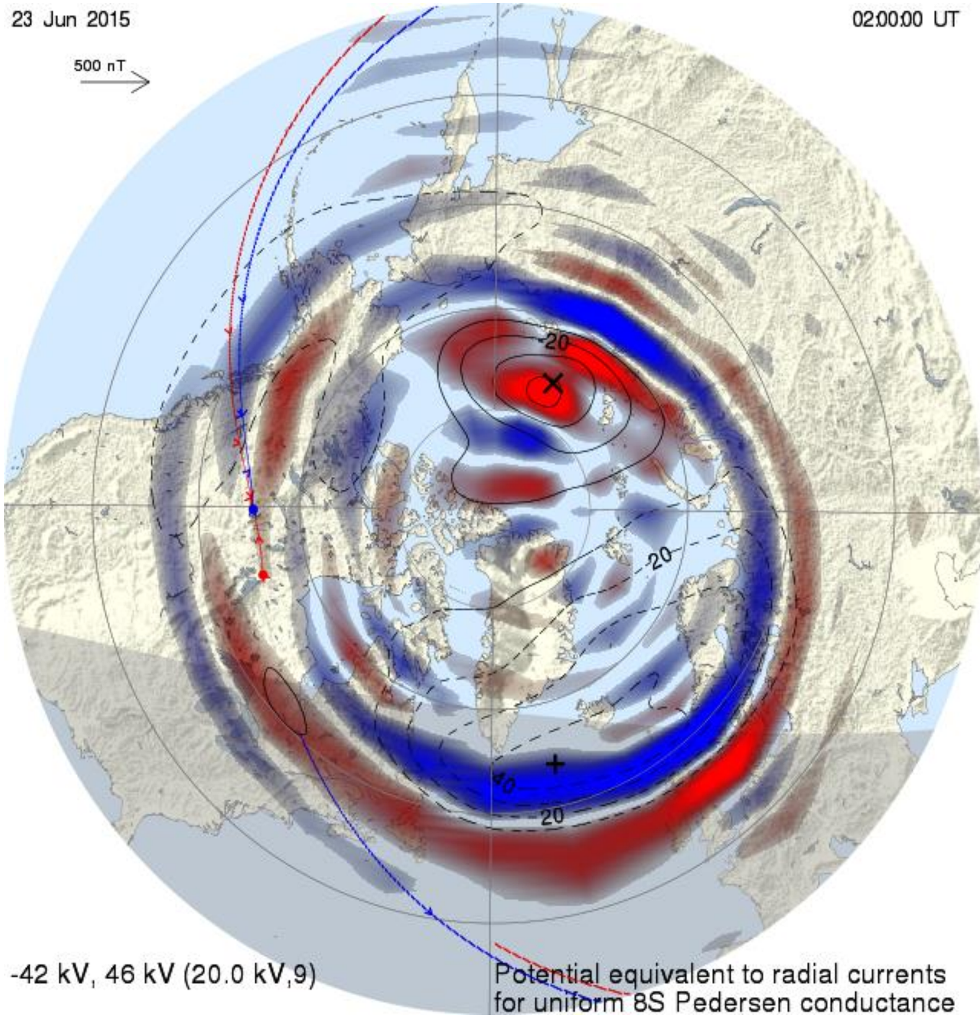




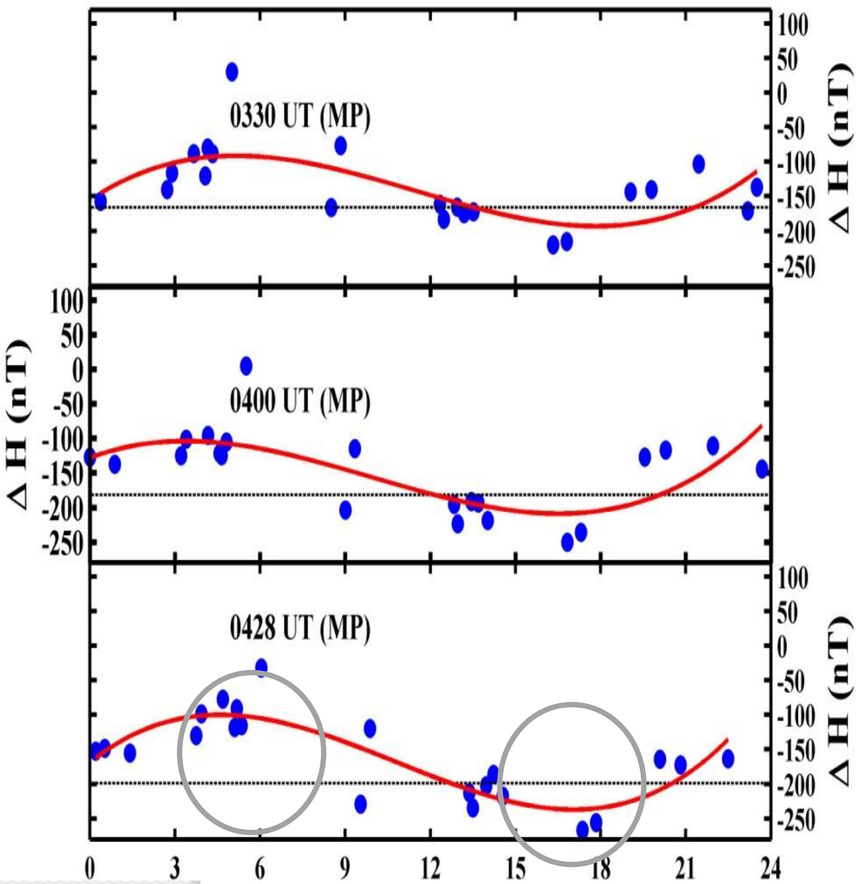
Around 2000 UT there was a northward turning of IMF Bz.

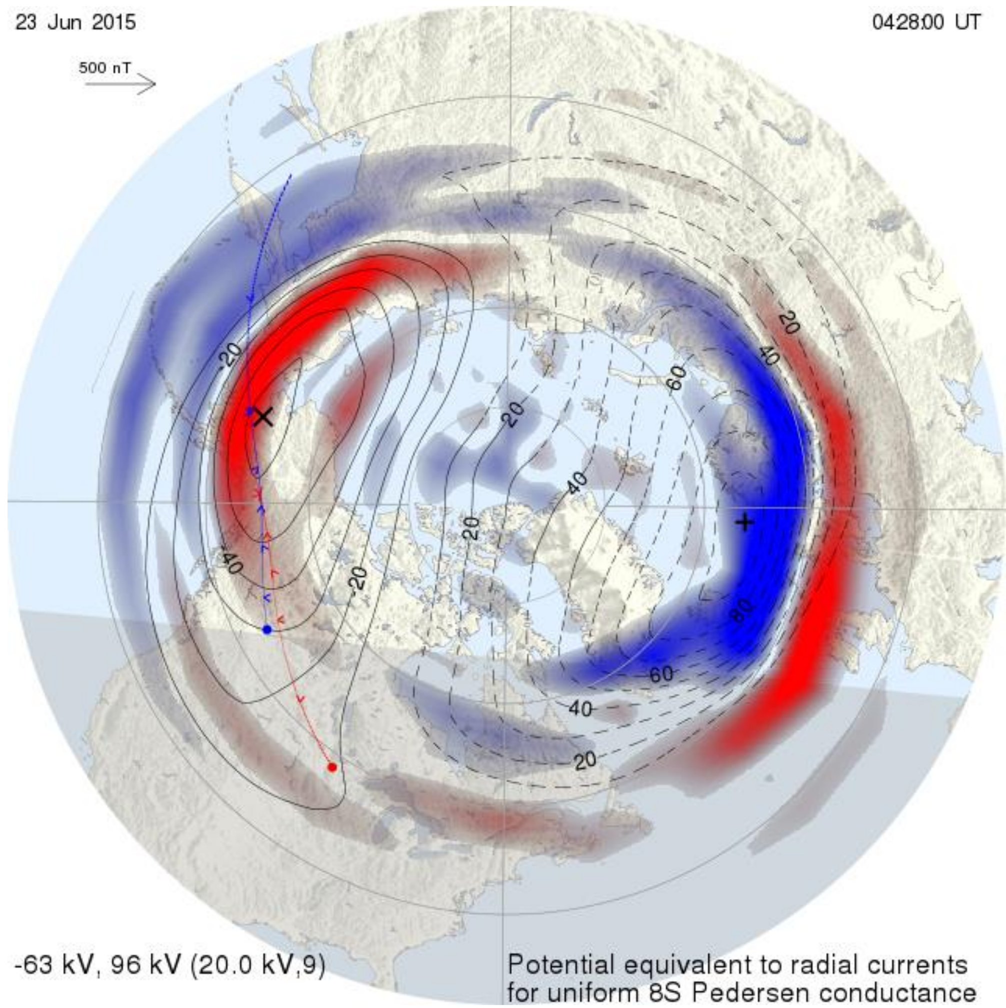


23 June 2015



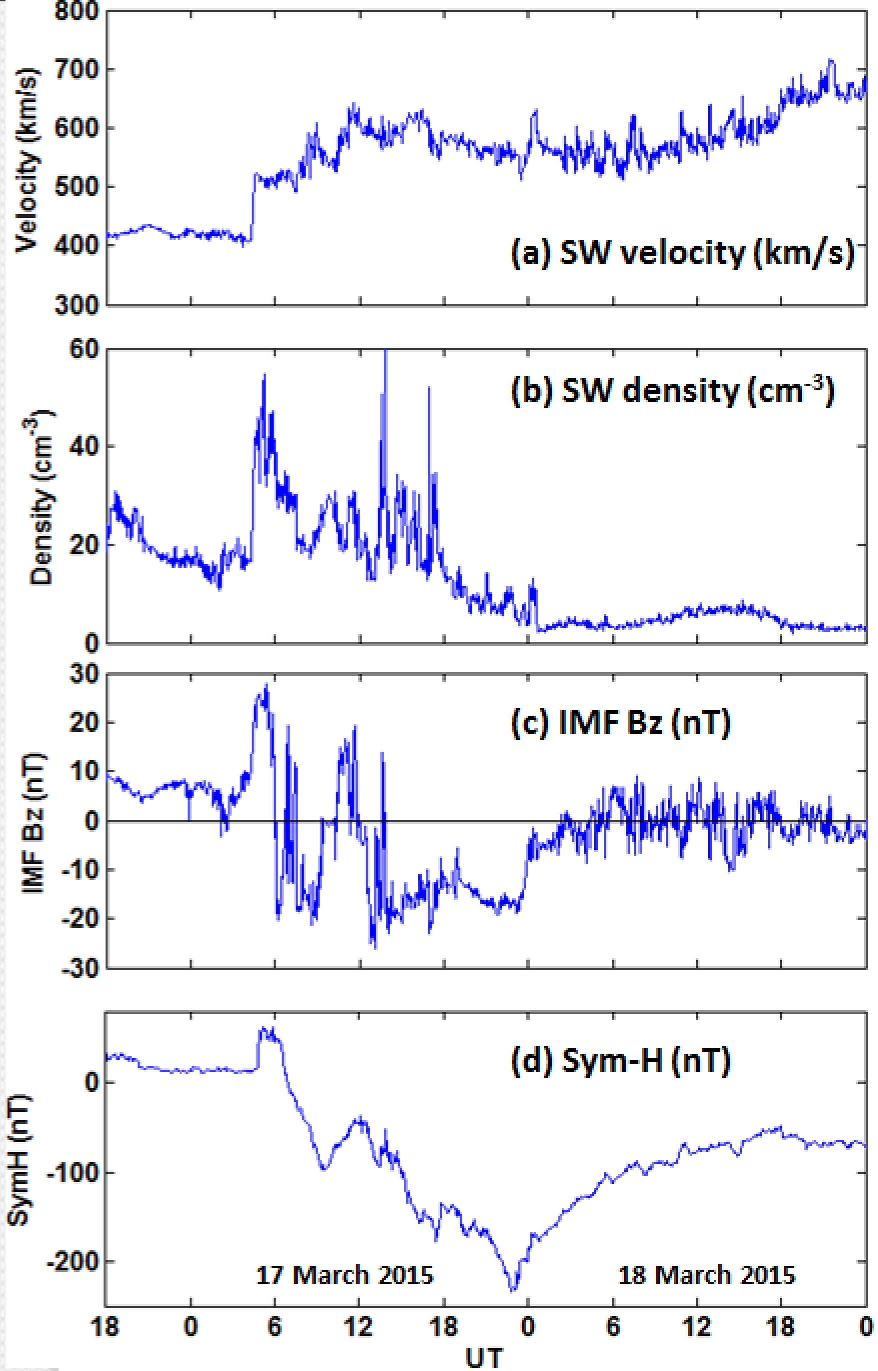
On 23 June 2015 around 0200 UT there is sharp southward turning of IMF Bz.





23 June 2015

On 23 June 2015 around 0428 UT we have southward IMF Bz. From 0200-0600 UT we have long southward IMF Bz. We have strong Dawn-Dusk asymmetry.



Temporal variations of (a) solar wind velocity, (b) solar wind density, (c) z-component of interplanetary magnetic field (IMF Bz) (d) Sym-H index.

16 December, 2015 – Geomagnetic storm

Source :

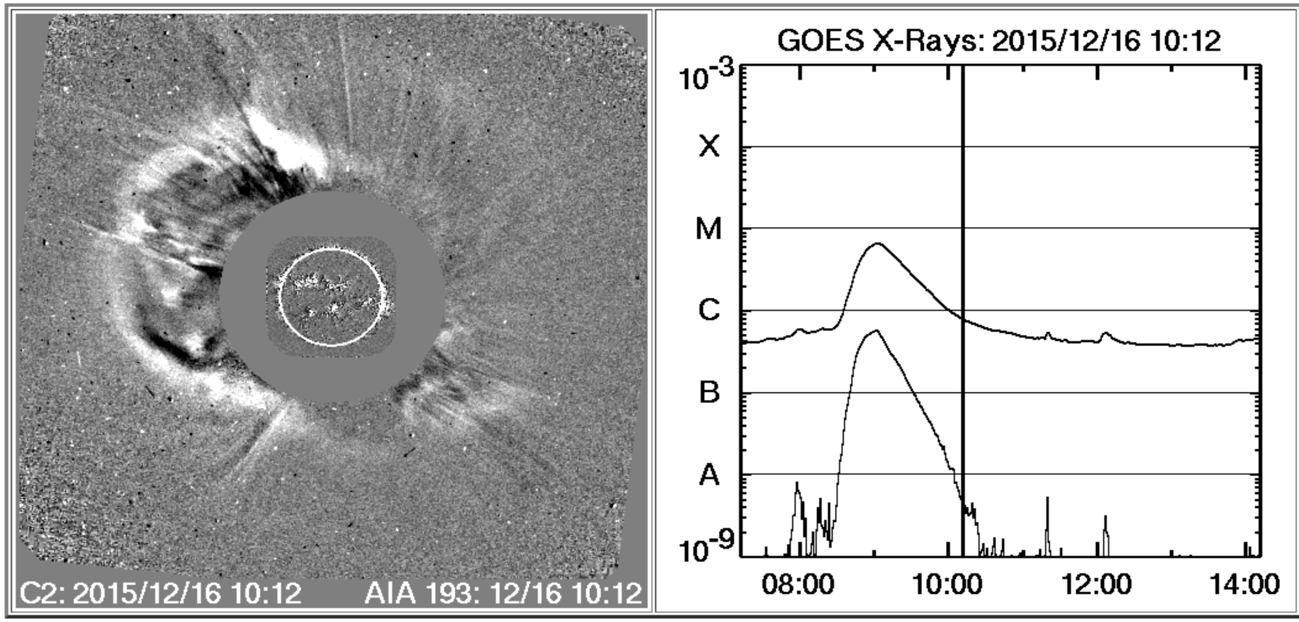
Double halo CME

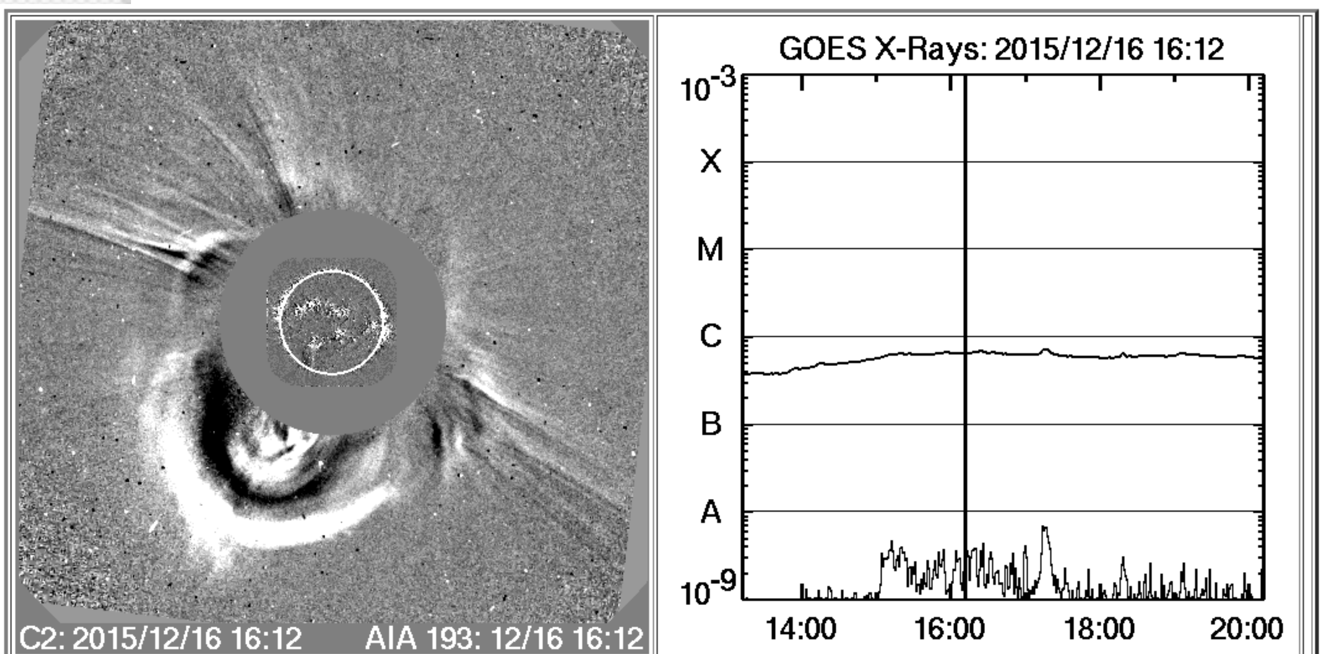
16th Dec, 2015

S13°W04°

S23 ° E18 °

Flare : C6.6





ICME : MC

Continued…..

- The study of old magnetic storm records are more important and the knowledge will be very much required for predictability of similar intensity events in future.

- The past occurrence of the intense magnetic storms will be helpful to understanding the physical processes involved in the phenomena.

- Knowing the physical processes causing solar flare or magnetic storms , then the high energy tail distributions could be found.

- Also reasons for the saturation mechanisms

- Also, need to define a new indices for extremely large storms, where the ring current intensity is sharp and intense.

- These statistics can be used to infer probabilities extreme events, solar flares, geomagnetic storms.