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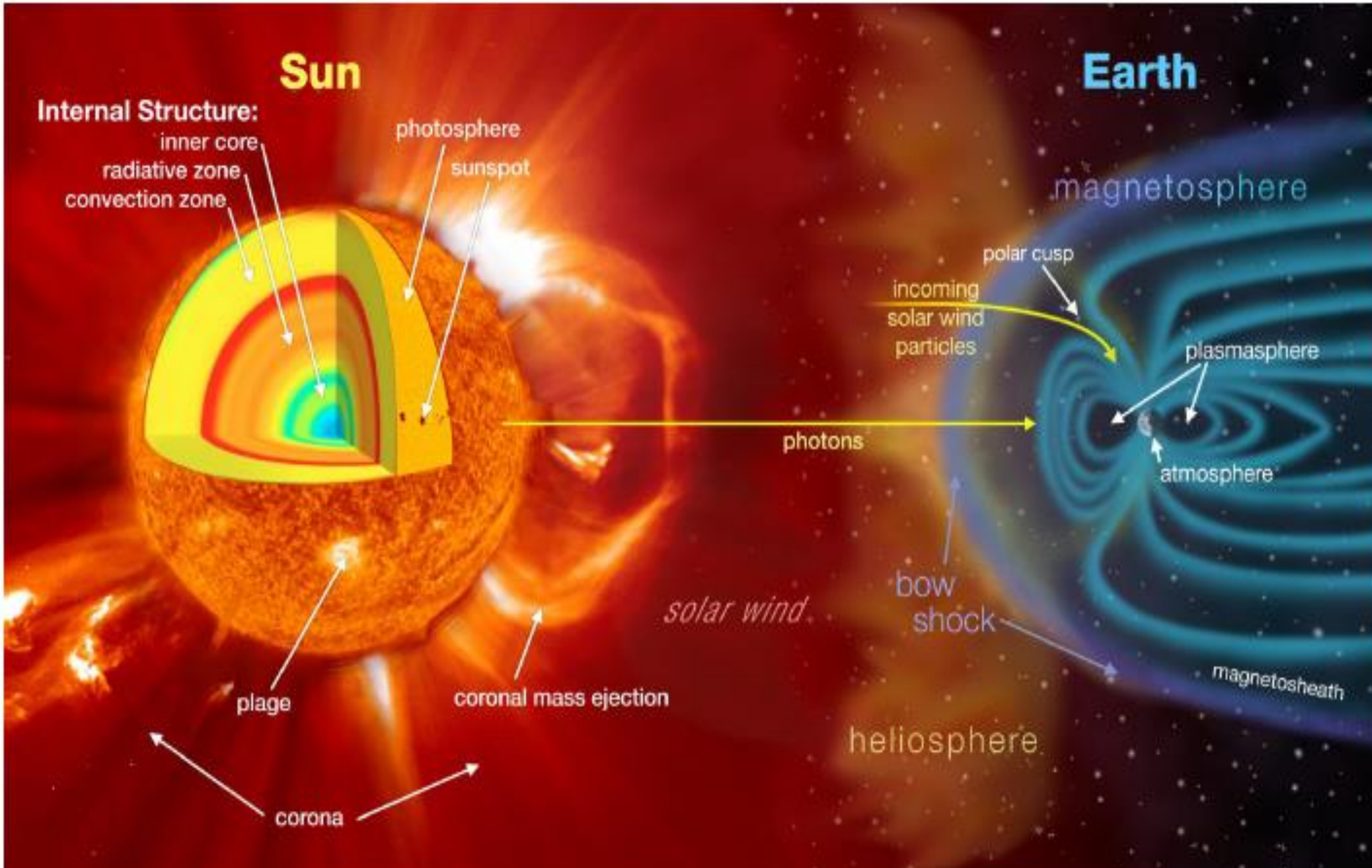
IONOSPHERIC ELECTRIC CURRENT DISTURBANCE ASSOCIATED WITH GEOMAGNETIC STORM

OUTLINES

- INTRODUCTION
- SCIENTIFIC ANALYSIS
- DISCUSSION OF THE RESULT
- CONCLUSION

Origins of Space Weather

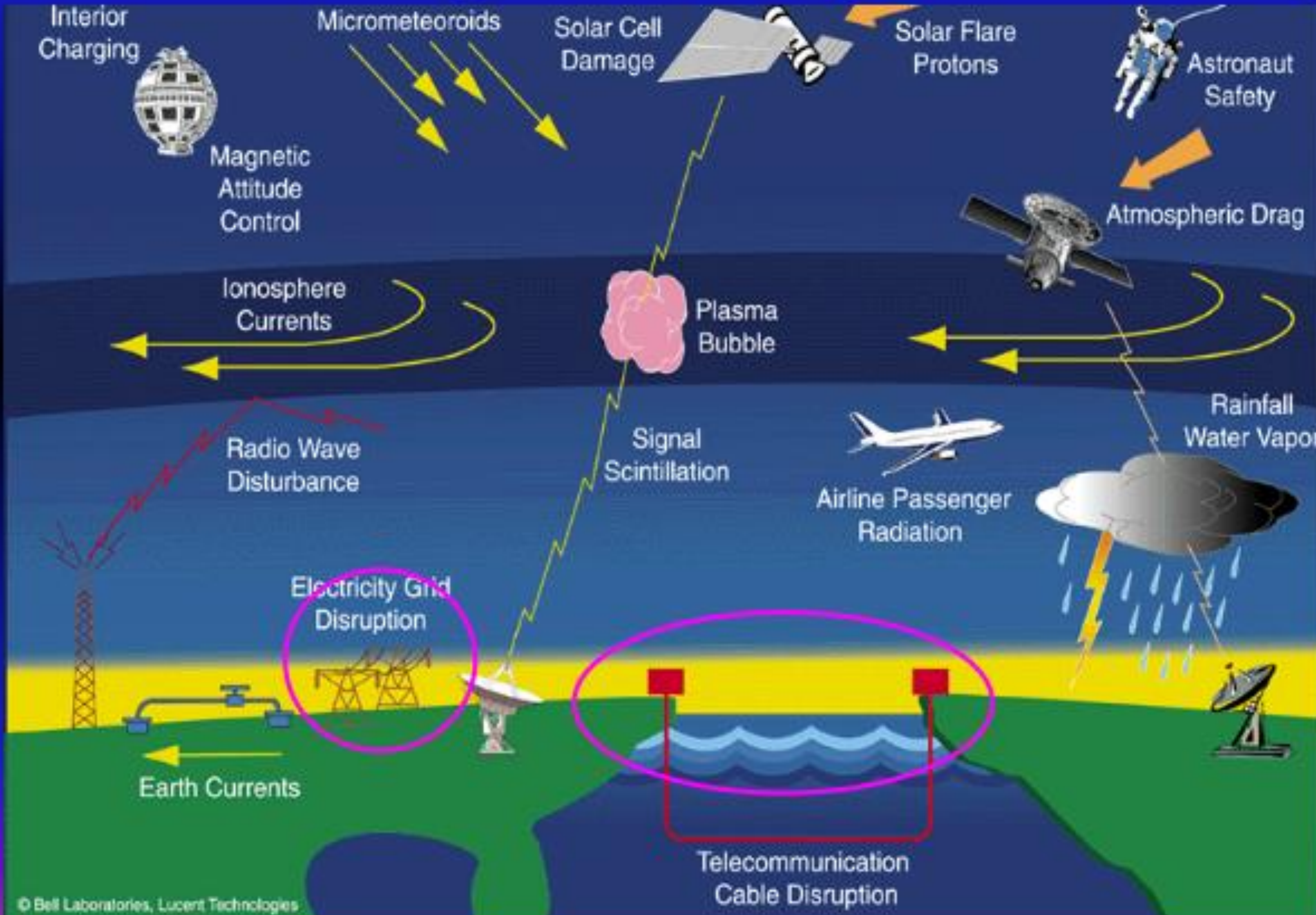


Space Weather

- **The US National Space Weather Programme defines space weather as: Conditions on the Sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health**

Why do we care about Space Weather?

Space Weather Impacts: Society and Technology

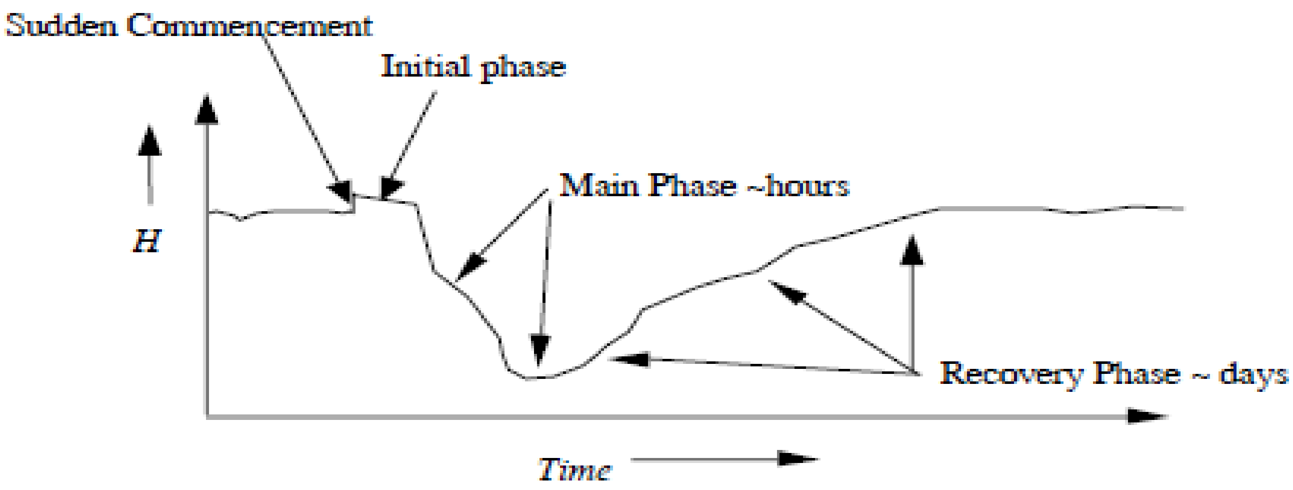


What can be done about it?

1. Quantify physics, dynamics, and behavior of Sun-Earth connected system through the range of conditions occurring in the 11 year solar cycle.
- Obtain improved measurements.
- Better understand Sun-Earth disturbances.
- Understand the solar cycle for long-range forecasting & assessing solar role in climate change.
2. Design predictive models for the system that:
- Demonstrate understanding of physics.
- Design software for prediction of space weather.
3. Minimize impact of space weather on technology and human space flight.
- Examine space environmental conditions vs location, time in solar cycle.
- Develop improved techniques for space weather predictions including Solar energetic Particle Events and their impact on humans in

Magnetic Storms

- Dst is a measure of the deviation of H (north-south) component of the magnetic field near the Earth's equator from a long term average
- The diagram below represents an ideal magnetic storm, which has all four phases.
  - The main phase is the defining feature of a storm. The main phase represents ring-current injection, which results from a southward IMF and the resultant strong convection.
  - Some storms have no sudden commencement.
  - Some storms have a sudden commencement but no initial phase: in that case, the main phase begins immediately after the compression.
  - The recovery phase is due to loss of ring-current ions as a result of charge exchange with the neutral exosphere.



Introduction

- Ionospheric electric current flow in a horizontal layer at an altitude between 100 and 150 km concentric with Earth surface.

- Ionospheric electric currents are observed during both quiet and disturbed solar wind conditions.

- The quiet ionospheric currents represented as Sq currents are produced by the motion of the ionized ionospheric particles across the planetary magnetic field.

- A diurnal variation of the geomagnetic field is observed by a magnetic station fixed on Earth and rotating through this current system.

- The disturbed ionospheric current represented as S_D are observed in conjunctions with auroral activity at high latitudes.

- The auroral ionospheric conductivity becomes enhanced when energetic particle is deposited into the auroral ionosphere

- **The equatorial ionosphere is perturbed during geomagnetic storm as a result of disturbed equatorial electric field. The ionospheric electric field plays a dominant role on the dynamics, distribution of ionization, and generation of plasma waves in the low-latitude and equatorial thermosphere.**

- **There are two major disturbance processes as far as this region is concerned. These are: the prompt penetration of the magnetospheric electric field, PPEF (Vasyliunas, 1970) and the disturbance dynamo electric field, DDEF (Blanc and Richmond, 1980).**

- **These mechanisms generate significant disturbances of electric fields and currents responsible for the terrestrial magnetic field disturbance in equatorial ionosphere, with different timescales, during and** after **the magnetic storm.**

- **Both processes are responsible for the perturbation in the ionospheric electric field captured by ground-based magnetometers.**

Intro.... Cont.

- **Disturbance dynamo electric field occurs as a result consequence of the energy input into high latitude ionosphere. This interaction results in joule heating and collision interaction that drive disturbance thermospheric winds towards the equation creating DDEF**

- **Transmission of a disturbance electric field dynamo DDEF, by the disturbed atmospheric motions in the dynamo layer also due to Joule heating in the auroral zone [Blanc and Richmond, 1980]**

- **DDEF occur after the energy input at high latitude, commonly during the later phase of the geomagnetic storm and has the opposite direction to the electric field (Santos et al., 2016).**

- **The ionospheric dynamo operates when the upper atmospheric move the electrically conducting medium through the Earth's magnetic field creating EMF that drives current and causes electric polarization charges.**

- **The purpose of ionospheric dynamo theory is to predict disturbance of ionospheric electric field and current associated with the response of the global thermospheric circulation to storm time heating at different latitude.**

Intro……cont.

- **The term electric field penetration refers to a phenomenon that disturbed electric field, which has external origin, appears in the mid- and low latitude ionosphere of the Earth. The disturbed electric field is usually called penetration electric field or prompt penetration electric field PPEF.**

- **In case of Earth, the mid and low latitude ionosphere connects with the inner magnetosphere through closed magnetic field lines, an external electric field propagate across the field lines to reach the equator.**

- **The external origin may refer to either the outer magnetosphere or the solar wind, considering that the magnetospheric electric field is ultimately driven by the solar wind.**

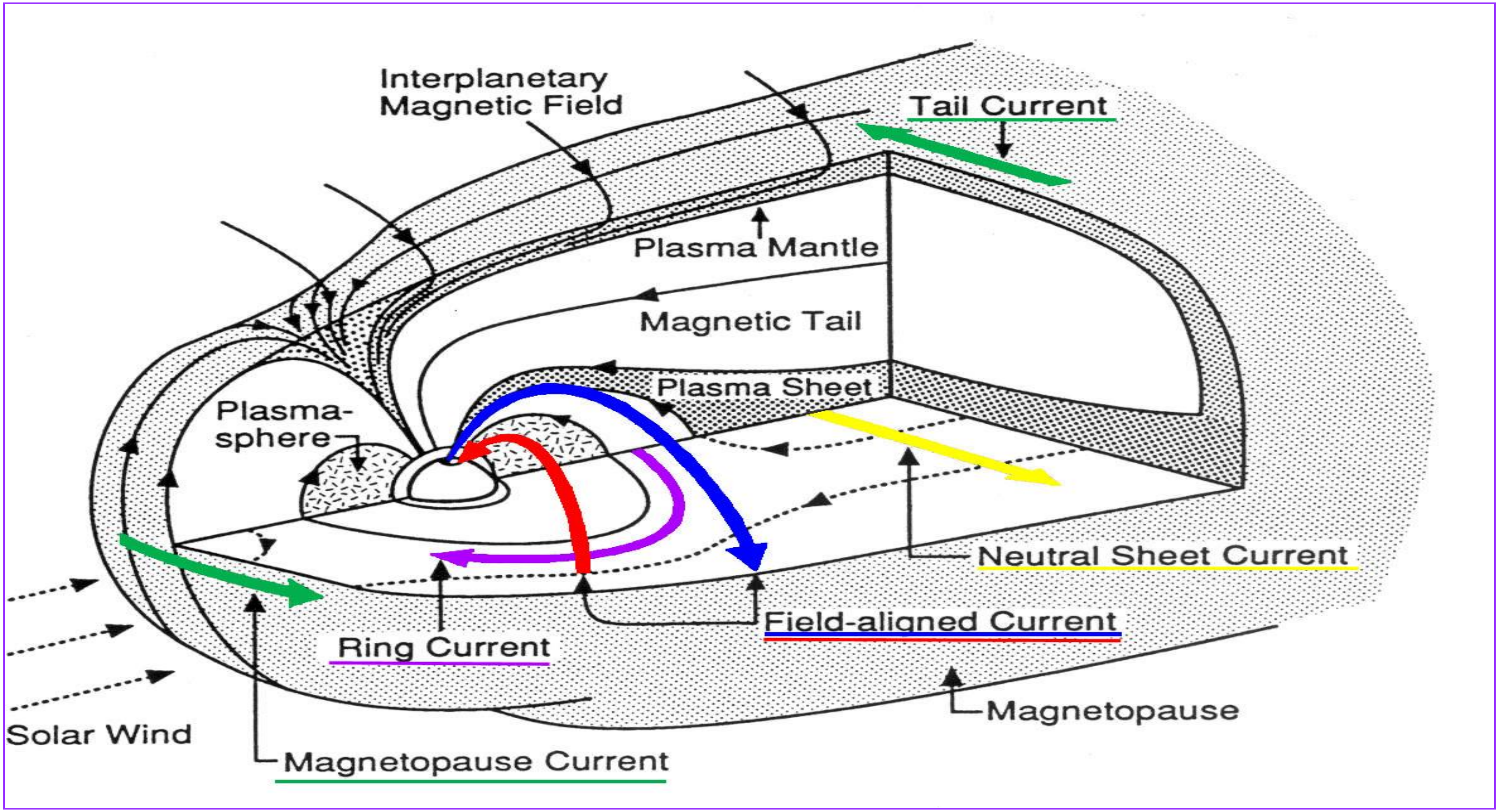
- **The magnetic signature of the PPEF is the disturbance polar number 2 (DP2) current system (Nishida et al., 1996) while that linked with DDEF is the Ionospheric disturbance Dynamo, Ddyn (Mayaud, 1980; Le Huy and Amory-Mazaudier 2005).**

Intro….cont.

- **PPEF results from the transmission of magnetospheric convection electric field from high to low latitudes and occurs at the beginning of geomagnetic storms under IMF Bz condition (Vasyliunas, 1970).**

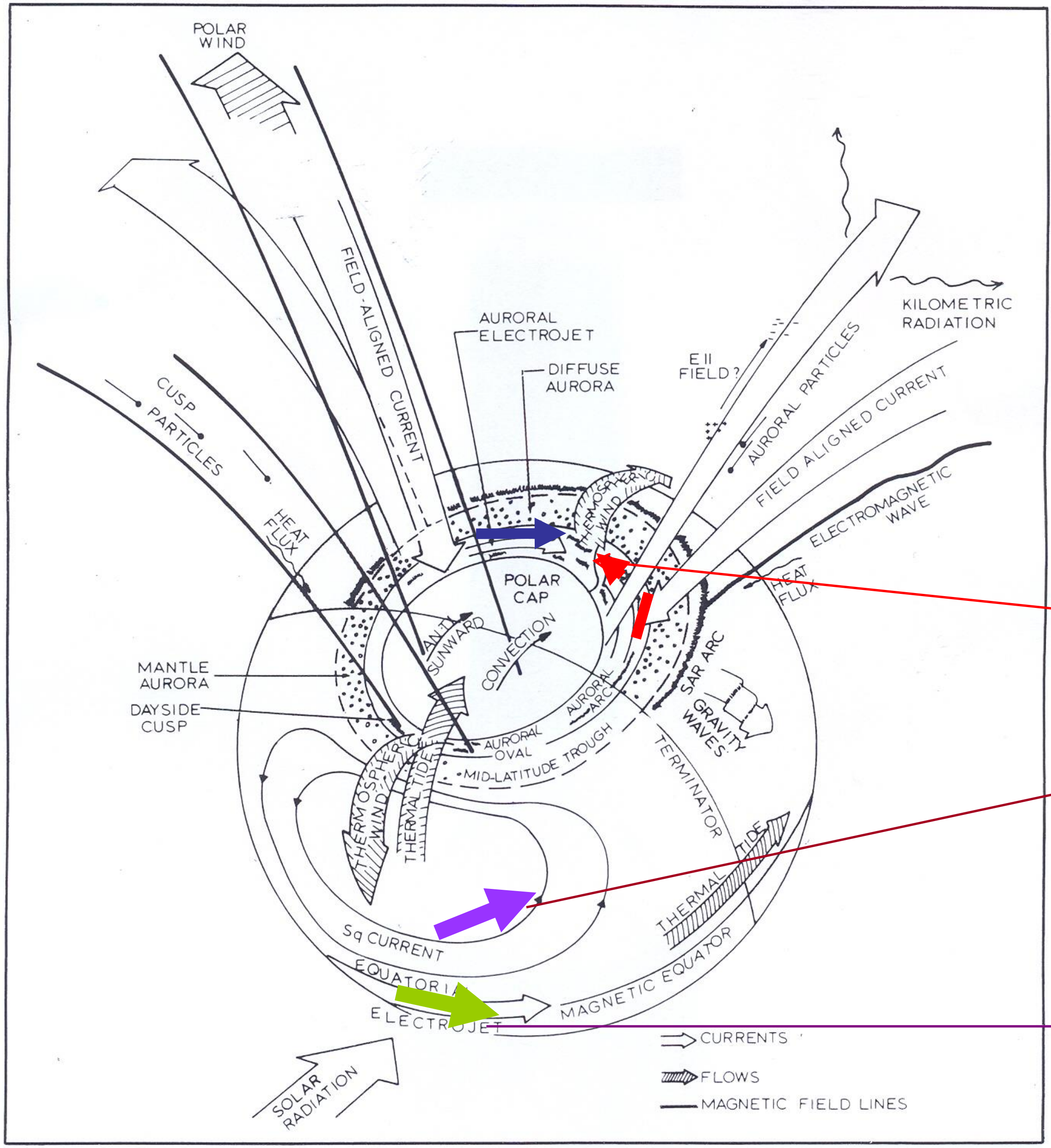
- **Huang et al. (2005, 2010, 2019) have shown that PPEF could last for some hours during prolonged magnetic activity and continuous southwards IMF Bz.**

- **The electric fields that contribute to the total PPEF are observed at equatorial latitudes, are the convection electric field and overshielding electric field (Fejer et al., 1979) which are active during the main phase and recovery phase of the storm, respectively (Kikuchi et al., 2008).**



The magnetosphere and the electric current systems in the magnetosphere

(Mazaudier, 2005)



IONOSPHERE
DI =
DP1 + DP2 +
D_{dyn}

Auroral

Auroral electrojets

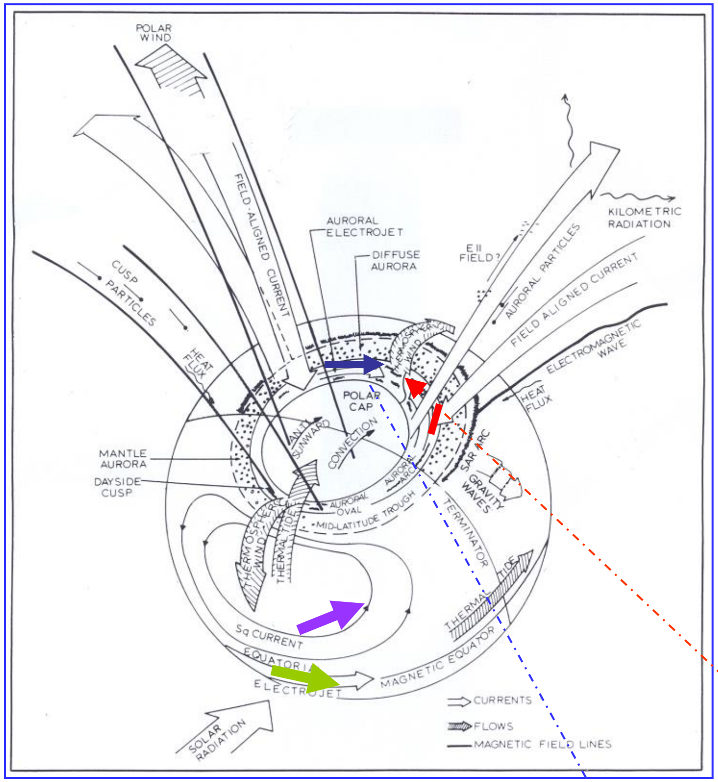
Middle latitudes

Sq/S_R

Equatorial latitudes

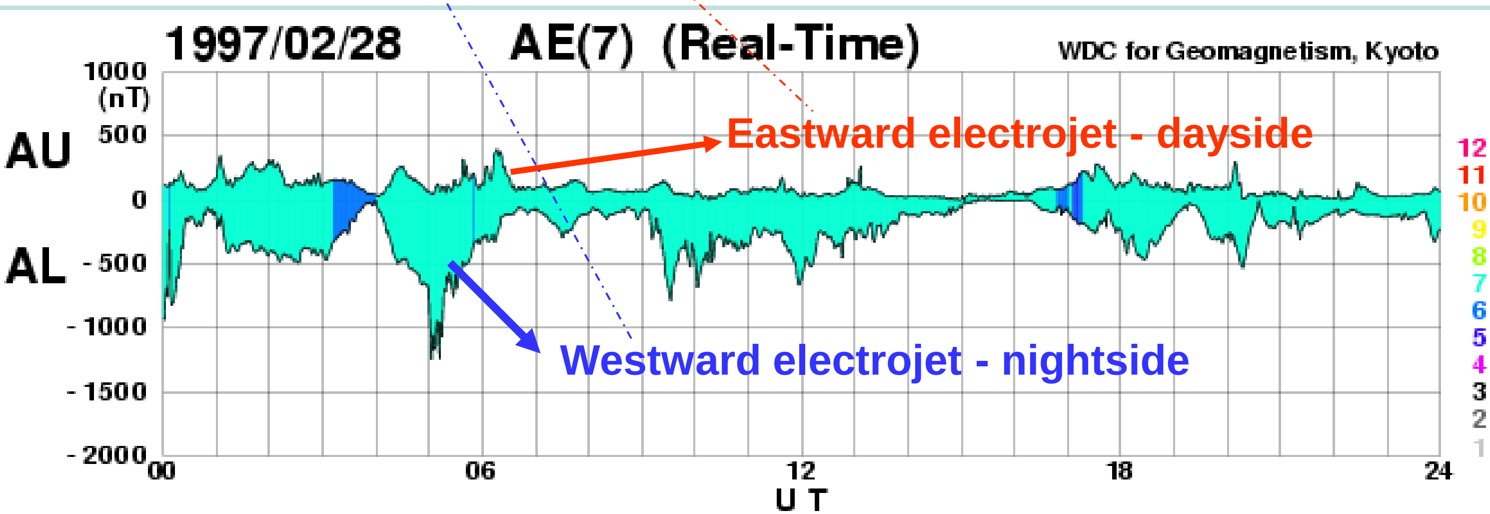
Equatorial electrojet

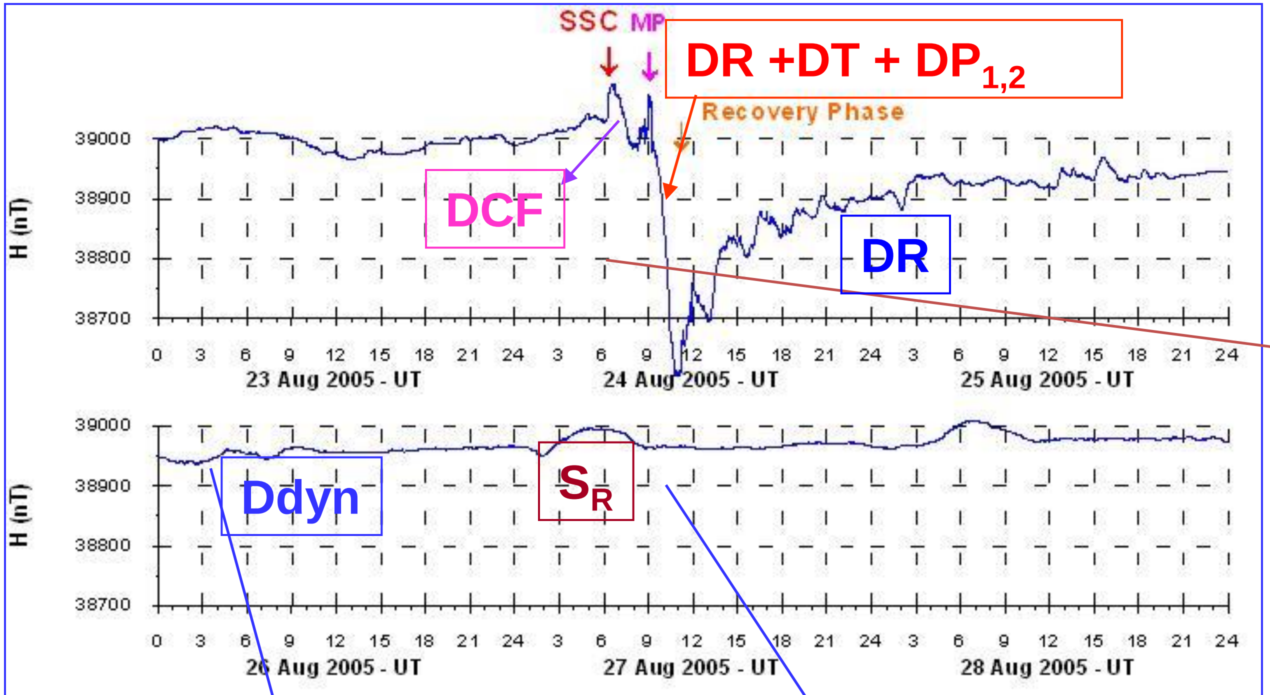
[Mazaudier, 2005]



Auroral indices

Auroral electrojets





Time variation of the H-component observed at Phu Thuy (Hanoi – Vietnam) from 23th to 28th August 2005

A knowlegde built during centuries

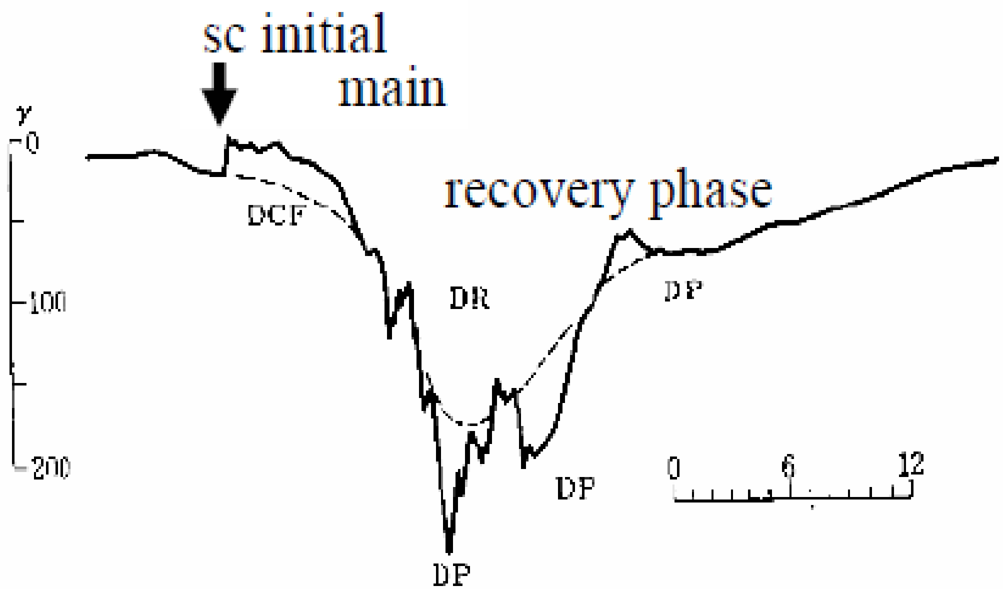
SOLAR WIND MAGNETOSPHERE DOMINATING

COUPLING SOLAR WIND MAGNETOSPHERE IONOSPHERE

RADIATIONS IONOSPHERE DOMINATING

Mazaudier, 2005

D = DCF + DR + DP



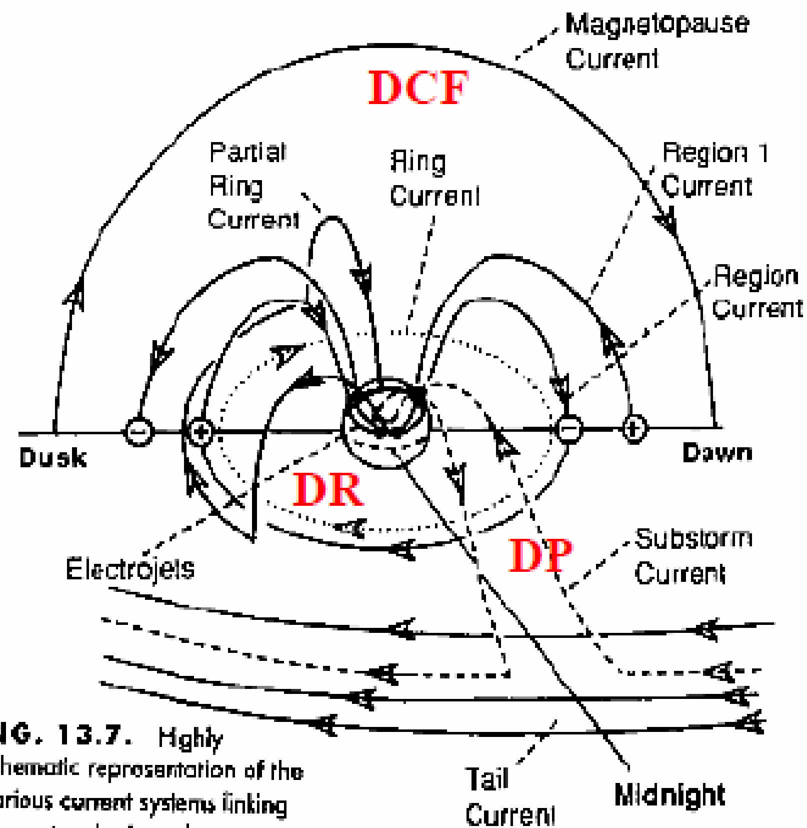


FIG. 13.7. Highly schematic representation of the various current systems linking magnetospheric and ionospheric currents and ultimately responsible for magnetic activity.

DCF : Disturbance of Chapman-Ferrao (Magnetopause) current

DR: Disturbance of Ring current

DP: Disturbance in Polar region (of substorm current)

Mazaudier, 2005

D = DCF + DR + DT + DI + DG

DCF : magnetic disturbance due to the Chapman Ferraro current

DR : magnetic disturbance due to the ring current

DT : magnetic disturbance due to the Tail currents

DI : magnetic disturbance due to the ionospheric disturbed electric current

DG : magnetic disturbance due to electric currents flowing in the ground related to external electric current systems.

Mazaudier, 2005

- **The ionospheric electric current disturbance (Diono) is obtained from Equation (1).**

- **$Diono = \Delta H$-S_R-DR (1)**

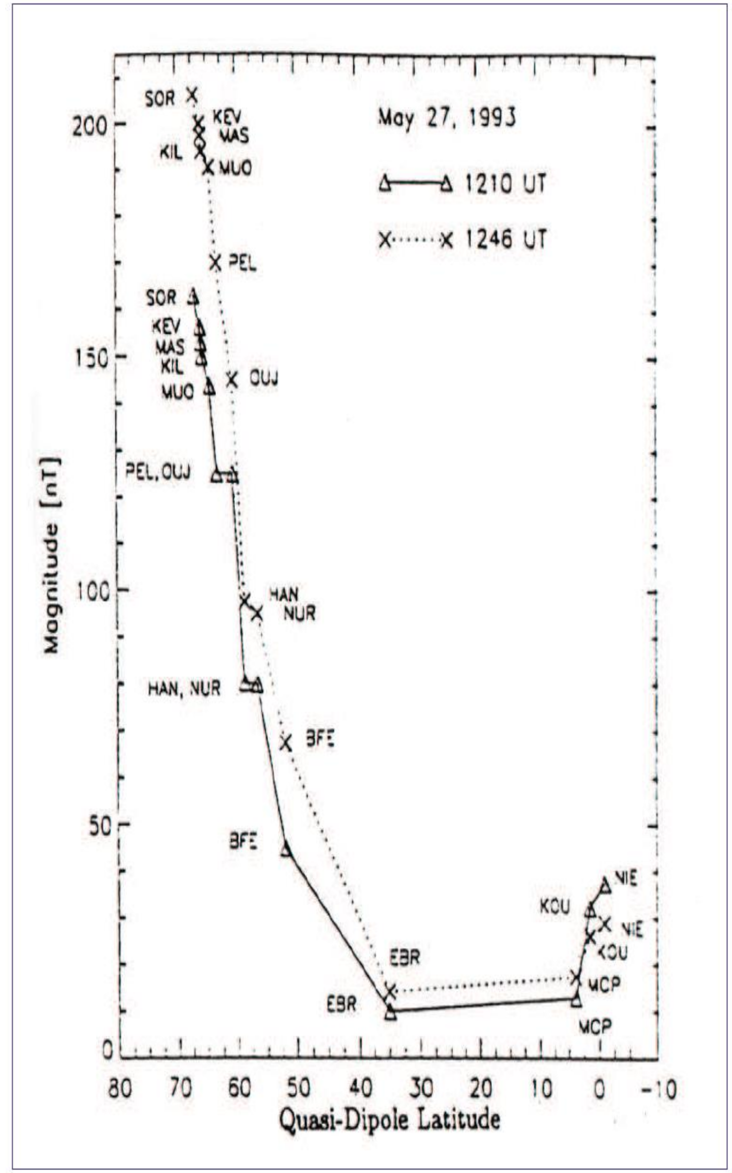
The daily regular variation of the geomagnetic field is represented S_R, ΔH is the change in the horizontal component of the geomagnetic field, the DR is the ring current, estimated from the Dst index and is the symmetric ring current during the observation period, see Eq. (2) below (Le Huy and Amory-Mazaudier, 2005).

- **DR= Dst cos(L) (2)**

where L is the geomagnetic Latitude

SCIENTIFIC RESULTS

- According to Wolf, 1970; Pellat and Laval, 1972; Senior and Blanc, 1984; Mazaudier et al., 1984; Spiro et al., 1988; Kobea et al., 2000; Peymirat et al., 2000, dealt with the direct penetration of the magnetospheric convection electric field from the polar region towards the equatorial latitudes .
- During the active phases of storms, the auroral electrojet are intensified by fields aligned currents. Subsequently, the auroral electrojet currents transfer thermal energy to the neutral gas via Joule heating and impulses through the ion-neutral momentum transfer.
- This process sets up gravity waves and equatorward thermospheric winds (Hadley cell between the poles and the equator) at F-region altitudes (Testud and Vasseur, 1969; Richmond and Robble, 1979).
- These winds extend from auroral zone to mid and low latitudes (Mazaudier et al., 1985) with a small return flow at the E-region altitudes around the equator (below about 120 km altitude)



The latitudinal profile of a magnetic disturbance observed on May 27, 1993 Kobea et al., 2000, JGR

- TEC was enhanced over two sectors at the beginning of the storm while it reduced after the main phase as a result of prompt penetration of electric field and disturbance dynamo electric field (DDEF), respectively.

- The magnetic effect of the disturbed ionospheric electric current showed oscillations and minima in response to prompt penetration of electric field, which further enhanced the equatorial ionization anomaly.

- The effect of DDEF estimated from the ionospheric disturbance dynamo manifested in the form of decrease in the amplitude of the horizontal component of the Earth magnetic field (H) several hours after the beginning of the disturbance and during the recovery phase.
- Consequently, ionospheric irregularities were suppressed over all stations in both sectors on 17 and 18 March due to westward DDEF. On the 19 March, however, there was a difference in the pattern of irregularities over both sectors
- (Amaechi et al. , 2018, JGR)

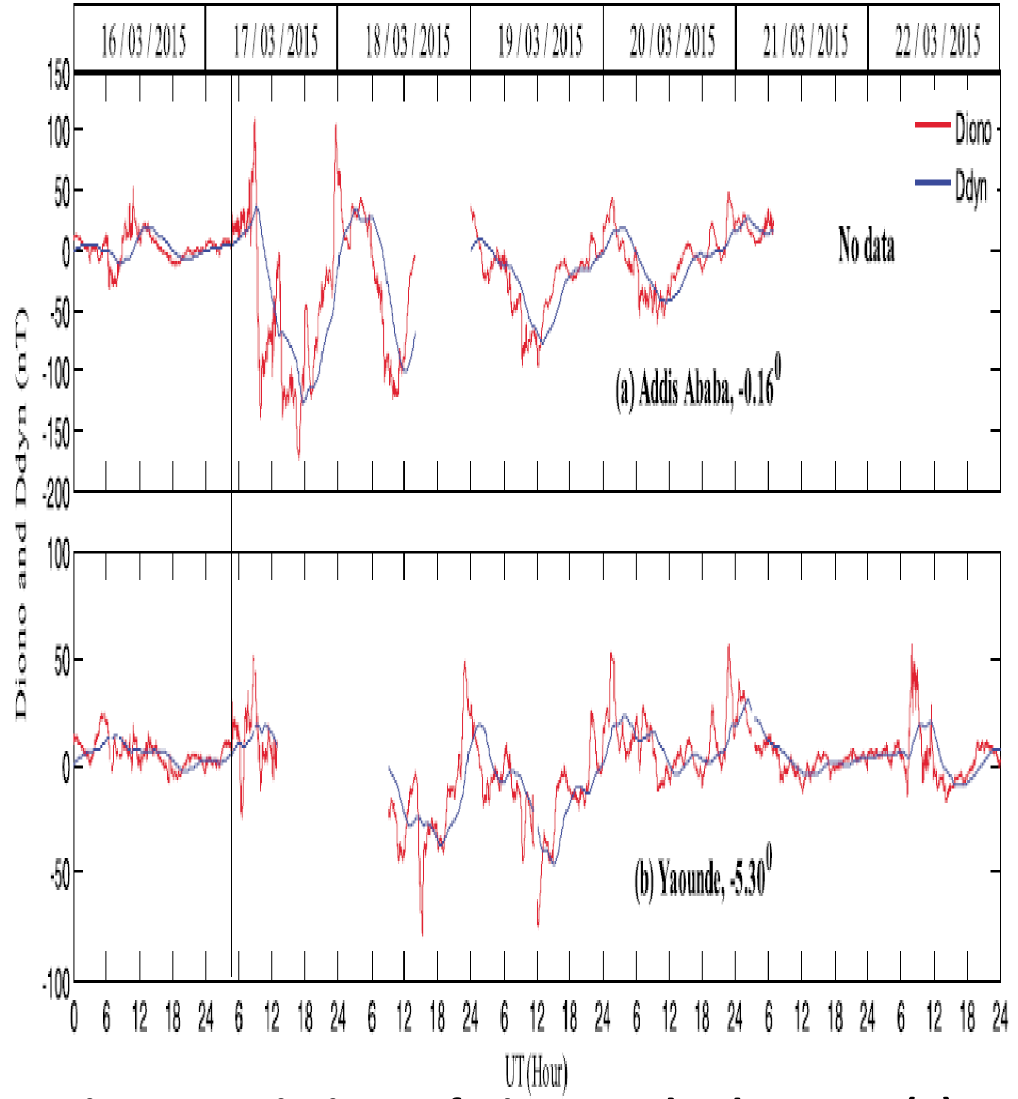
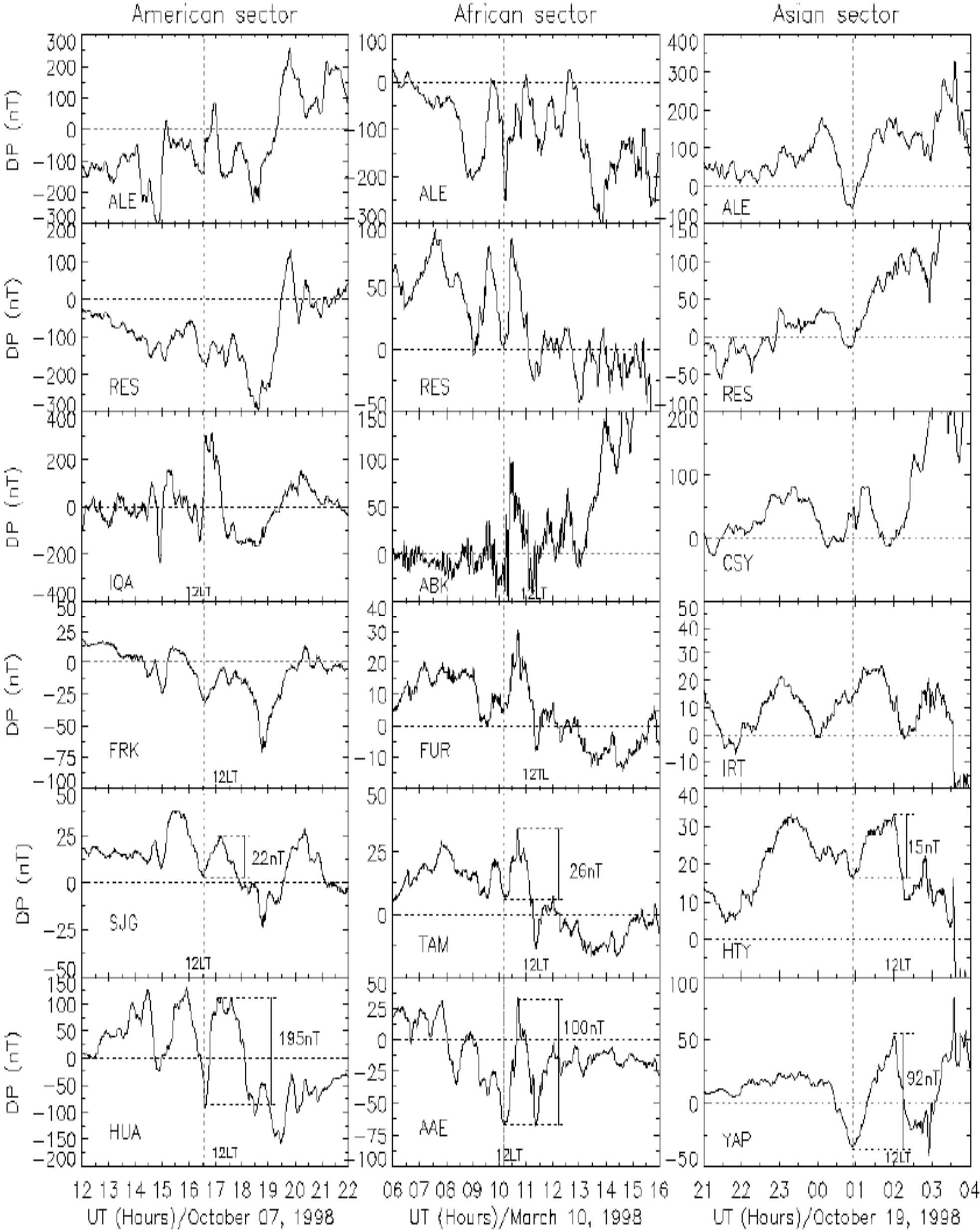


Figure: Variations of Diono and Ddyn over (a) Addis Ababa, and (b) Yaounde during March 16–22 March 2015. The vertical line shows the time of sudden storm commencement (Amaechi et al. , 2018, JGR)

- The Figure presents the time of H component disturbances (DP) from North polar cap latitudes to dip-equator during these magnetic storms.
- Over these three sectors, we observe increases of the DP simultaneously at the polar region, middle and low latitudes around 12:00 LT with considerably enhancement at the dip equator.
- The longitudinal variation of the enhancement ratio of the DP2 exhibits high values over the American sector compared to Asian sector and African sector which have lowest values
- The DP2 events are enhanced at the dayside dip-equator compared to low latitude due to the Cowling conductivity effect.



Variation of H-component disturbance (DP) from high latitude to dip-equator on 7 October 1998 (American sector), 10 March 1998 (African sector) and 19 October 1998 (Asian sector). Mene et al., 2011, Ann Geo.

Variation of ionospheric electric current disturbance using wavelet power spectrum approach

- Wavelet power spectrum (WPS) method was used to examine the variations of ionospheric electric current disturbance (Diono).

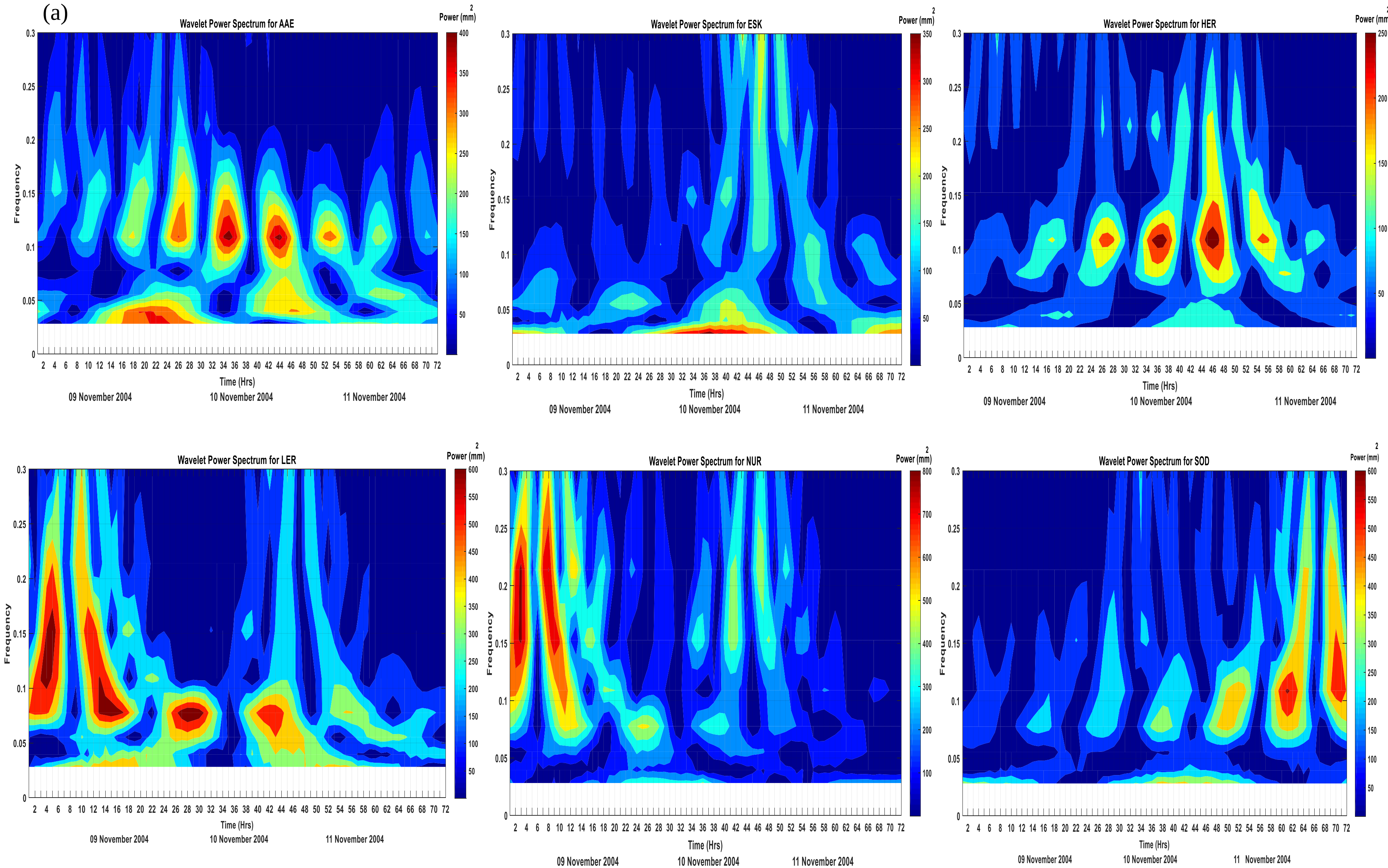
- WPS analysis for the evaluation of the time–frequency function of the Diono variation during the geomagnetic storm events on 9–11 November 2004 and 14–16 May 2005 at AAE, ESK, HER, LER, NUR and SOD.

- It was observed that the geomagnetic storms time are characterized by high wavelet coefficient and is more substantial at SOD, while minimum wavelet coefficients of ionospheric electric current disturbance observed at NUR, HER, ESK and AAE.

- The ionospheric electric current disturbance effect is amplified at ABK and SOD, NUR and LER on 14–16 May 2005. The equatorial ionosphere are disrupt during geomagnetic storms due to ionospheric electric current disturbance alongside with penetrating electric field from high latitude to lower latitude (Sastri et al., 2000).

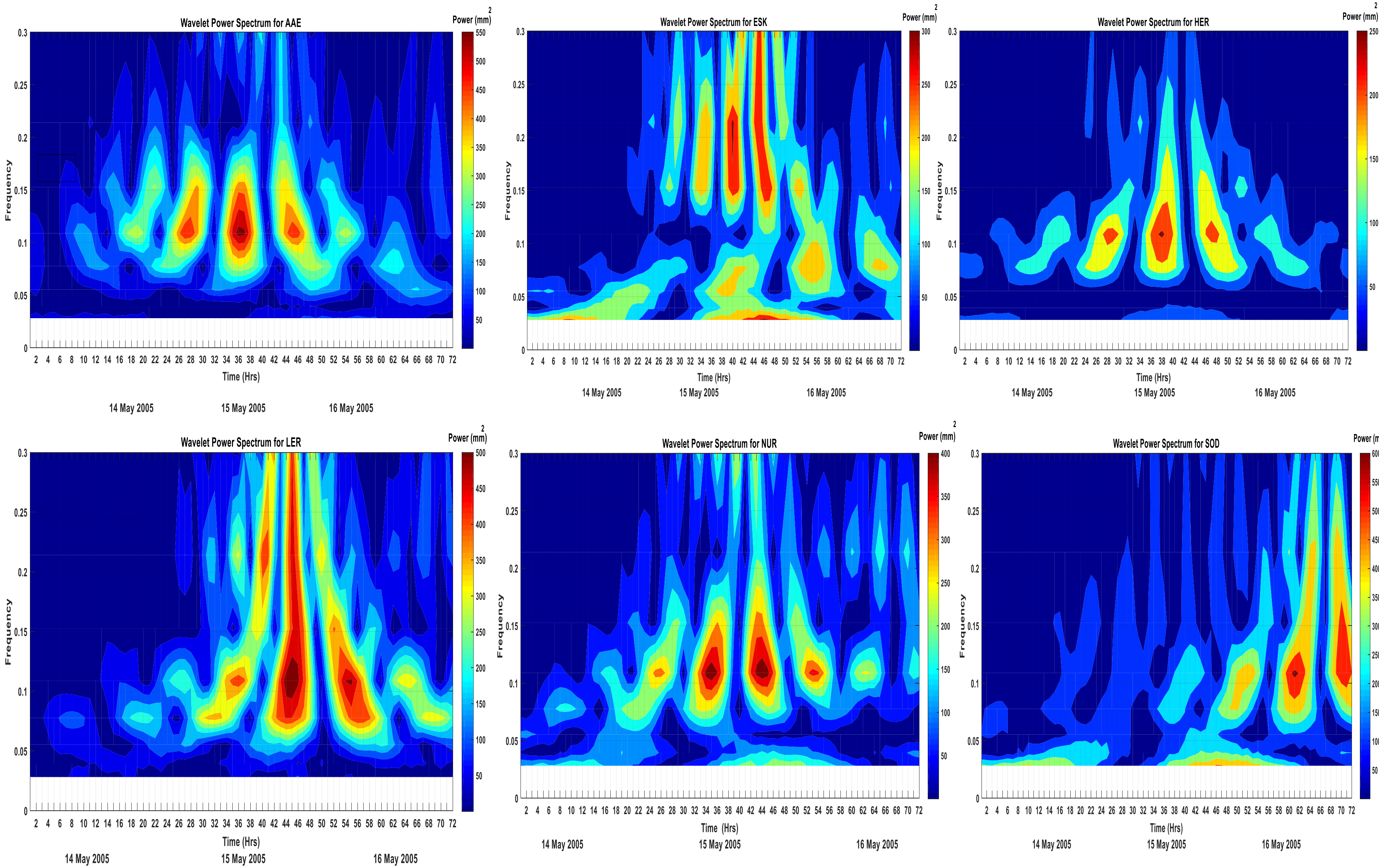
- It was observed that ionospheric electric current disturbance are noticed during daytime (eastward) and nighttime (westward) as shown on 9–11 November 2004 and 14–16 May 2005 respectively.

Falayi et al., 2022, ASR



Wavelet spectrum analyses of the ionospheric electric current disturbance on 14-16 May 2005 at AAE (b)ESK (c) HER (d) LER (e) NUR and (f) SOD.

Falayi et al., 2022, ASR



Wavelet spectrum analyses of the ionospheric electric current disturbance on 9-11November 2004 at AAE |(b)ESK (c) HER (d) LER (e) NUR and (f) SOD

Falayi et al., 2022, ASR

Result1

- WPS is a powerful techniques used to examine the significance of ionospheric electric current disturbance impact during coronal mass ejection on 9–11 November 2004 and 14–16 May 2005.

- The dominance of Diono at AAE using WPS was noticed during the daytime on 9 November and 10 November 2004.

- Similarly, the WPS was significant on 10 November at HER. This was due to the presence of westward disturbance electric field resulting from auroral heating of the high latitude during the geomagnetic activity of 8 November (Dst = 374 nT).
- On 10 November, however, eastward prompt penetration electric field conditioned by the southwards IMF Bz dominated the spectrum during the daytime. Eastward PPEF is known to enhance the regular daytime eastward dynamo electric field (Fathy et al., 2014).

- It is important to also note the contribution of substorm electric field which are eastward especially on 10 November when IMF Bz had a large southward amplitude (Fejer et al., 2021).

- Stations located at higher latitudes (ESK, NUR, LER and SOD) show higher energy wavelet coefficient of Diono with high frequencies, due to the existence of ionospheric currents at high latitudes during geomagnetic storm.

- The mid and low latitude stations display low energy wavelet coefficient with low frequency. The WPS of the geomagnetic data shows the actuality of the temporary fluctuations throughout the geomagnetic storm period.

- These fluctuations might be related to the PPEF and DDEF as suggested by Younas et al. (2020). The ionospheric electrodynamics and the neutral wind circulation are significant in the storm reaction of the ionosphere.

- The ionospheric disturbance dynamo produced electrodynamic disturbances as a result of dynamo action of equatorward propagating neutral wind flows and circulation changes driven by intensified energy and momentum deposition into the high latitude ionosphere during geomagnetic storm time.

Phase space reconstruction from time series data

- **The nonlinear time series (chaotic) method was established to obtain qualitative and quantitative information from the time series.**
- **The nonlinear equation is used to describe the complex behavior of dynamic systems.**
- **The dynamic variable relates the qualities of the system and their time transformations in nonlinear form.**

- **Ionospheric electric current disturbance was subjected to nonlinear dynamics of the time series analysis for the computation of average mutual information (AMI) and estimation of the false nearest neighbor (FNN) to determine chaoticity using the Lyapunov exponent (Falayi et al., 2020b; Ogunjo et al. 2021).**

- **To obtain dynamical attributes of a system the space phase reconstruction with embedding dimension (m) and the time delay (s) are necessary, for the ionospheric electric current disturbance time series data.**

- Lyapunov exponent (LE) is an essential quantifier for dynamical structure for nonlinear time series. The LE describes the trajectories when it diverges or converges.
- Eckman and Ruelle (1985) established that when the exponents are zero or negative it implies that trajectories converge, the system remains unsteady and when the system is chaotic, the Lyapunov exponent is positive.
- We applied the techniques used by Rosenstein et al. (1993) to compute the Lyapunov exponent values for ionospheric electric current disturbance at AAE, ESK, HER, LER, NUR and SOD.
- he Lyapunov exponent of Diono values was calculated and analysed for different storm time from 9 to 11 November 2004 and 14–16 May 2005 at different stations.

Falayi et al., 2022, ASR

9–11 November 2004

Station Codes	Embedding dimension	Lyapunov exponent
AAE	5	0.33
ESK	4	0.42
HER	3	0.26
LER	4	0.27
NUR	5	0.18
SOD	5	0.34

14–16 May 2005.

Station Codes	Embedding dimension	Lyapunov exponent
AAE	7	0.60
ESK	7	0.47
HER	5	0.35
LER	7	0.35
NUR	5	0.35
SOD	4	0.27

RESULT2

- **The chaotic behavior of ionospheric electric current disturbance was investigated using nonlinear time series method to phase space reconstructions and Lyapunov exponents.**

- **The low geomagnetic stations display high values of LE during 9–11 November 2004 and 14–16 May 2005 of the geomagnetic storm from Tables above.**

- **The low values of Lyapunov exponent might be as result of the internal dynamics restructuring during geomagnetic storm.**

- **The minimum value of chaoticity in the ionosphere during geomagnetic storms shows a period evolution from maximum values during the quiet phase to minimum values during storm phase which might be as result of the variation of the ionosphere by the arrival of high solar wind during the geomagnetic storm period (Unnikrishnan et al., 2006; Unnikrishnan 2010; Unnikrishnan and Ravindran, 2020; Rabiu et al., 2014)**

Cont.......RESULT2

- **The dynamics structure of the ionosphere is complex displaying irregular fluctuations, determined by geomagnetic field variation.**

- **This varies significantly with time and geographical locations (polar, auroral, sub-auroral, mid-latitudes and low/equatorial regions).**

- **Wilkinson (1995) established that the geomagnetic disturbance is associated with ionospheric effect.**

- **The ionosphere varies everywhere as noticed from geomagnetic observatories which appear chaotic during the geomagnetic disturbance (Fuller-Rowell et al., 1994; Consolini and Chang, 2001).**

- **The chaotic signatures of Diono may be influenced by the electrodynamics of the magnetosphere as a result of solar wind. The variability of the magnetosphere-ionosphere structures is the replication of the solar wind; engulf the Earth magnetosphere and prolongs nonlinearly.**

- **The solar wind as stochastic driver contributes largely in the production of geomagnetic disturbance in the Earth's magnetosphere as a result of coronal mass ejection that creates the geomagnetic storms.**

Conclusion

- **The WPS of the geomagnetic data displays the certainty of the temporary variations throughout the geomagnetic storm period.**
- **When the power drops substantially, Diono reduces as indicated by low coefficient and when the power is maximum, it denotes high coefficient of Diono.**
- **The chaoticity and dynamical complexity parameters used to evaluate Diono revealed that the magnetospheric dynamics are possibly impacted by some drivers associated with the perturbation in the magnetosphere mainly during the period of geomagnetic storm.**
- **The electrodynamics of the magnetosphere due to solar wind displays the occurrence of chaotic signature of Diono which dictates its nonlinear features.**
- **The dynamics of the ionospheric structure is complex, exhibiting irregular variabilities, determined by the variation of the geomagnetic field**

Thank you for your kind attention

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AGS

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ISEE

Institute for Space-Earth Environmental Research