GEOMAGNETIC STORMS AND THE EQUATORIAL IONOSPHERE

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OBJECTIVES

- Understand the peculiarities of the equatorial regions of the ionosphere
- Appreciate geomagnetic storm as a manifestation of extreme space weather
- Understand how the equatorial ionospheric region respond to geomagnetic storms
GUIDELINES

- Introduction : The Ionosphere
- Equatorial ionosphere and its peculiarities
- Space weather and geomagnetic storms
- Geomagnetic storm effects and response of the equatorial ionosphere
- Summary/Conclusion
- References
INTRODUCTION: THE IONOSPHERE- FORMATION AND STRUCTURE
# The Ionosphere: Structure

<table>
<thead>
<tr>
<th>Layer</th>
<th>Approximate Elevation</th>
<th>Major Component</th>
<th>Importance</th>
<th>When Present</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topside F</td>
<td>&gt; 450 km</td>
<td>O+</td>
<td>Domain of line of sight propagation</td>
<td>Always</td>
</tr>
<tr>
<td>Plasmasphere</td>
<td>&gt; 1200 km</td>
<td>H+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>F1: 140 - 200 km</td>
<td>F1: O+, NO+</td>
<td>Main &quot;reflection&quot; region</td>
<td>Always - stronger during daytime</td>
</tr>
<tr>
<td></td>
<td>F2: 200 – 450 km</td>
<td>F2: O+, N+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>90 - 140 km</td>
<td>O2+, NO+</td>
<td>Lower frequency &quot;reflection&quot; region</td>
<td>Always - but very weak at night</td>
</tr>
<tr>
<td>D</td>
<td>60 – 90 km</td>
<td>NO+, O2+</td>
<td>Main absorption region</td>
<td>Daytime only</td>
</tr>
</tbody>
</table>
THE IONOSPHERE: APPLICATIONS

- Sky wave propagation
- Line of sight propagation of HF radio waves
**Equatorial Ionosphere**

- As a result of the magnetic effect due to (i) the earth crust and (ii) ionospheric currents, the earth behaves like a permanent dipole magnet.

- The influence of the field due to this magnet on electric charges in the ionosphere leads to the geomagnetic description and delineation of the ionosphere.

- Hence, the ionosphere bounded ± 20 degrees around the geomagnetic equator is referred to as the Equatorial ionosphere.
The equatorial ionosphere demonstrates great departures from the other regions of the ionosphere which have unusual influences on radio propagation within the region.

- The presence of **equatorial electrojet** (strong electric current flowing) within the E-region ± 3 degrees of the equator which creates the so-called **fountain effect** is the major defining factor in region.
EQUATORIAL LATITUDE: PECULIARITIES

As a result of the constraints imposed on electric charges by the magnetic field, the conservation equations are complicated by the magnetic field geometry that must be incorporated in them.

PLASMA MOTION: Consider the continuity equation

\[
\frac{dN}{dt} = q(z, \chi) - L(N) - \text{div}(N \cdot \mathbf{v})
\]  

... (i)

Here:

\[
\text{div} (N \mathbf{V}) = N \text{div} \mathbf{V} + \mathbf{V} \cdot \text{grad} N
\]  

... (ii)

\[
\mathbf{V} = V_E + V_W + V_D
\]  

... is plasma velocity ... (iii)

where

\[
V_E = \frac{(EXB)}{B^2}
\]  

... (iv)

\[
V_W = \frac{(U \cdot B)B}{B^2}
\]  

... (v)

where \(\mathbf{B}\) is horizontal in orientation, thus \(\mathbf{B} = \mu \mathbf{H}\)

\[
V_D = \text{gravity} + \text{derivatives of plasma conc} + \text{Temp along magnetic field}
\]  

... (vi)

➢ The grad (advection) term is more important as the drift of plasma essentially depends on it.
➢ The horizontal plasma motion due to this term plays a good role in shaping the equatorial ionosphere

Rishbeth, 2000
**Equatorial electrojet: Development**

- In the dayside ionosphere, the neutral wind sets up a polarization electric field pointing in the eastward direction.
- At the equator, the effect of this field results in the $\mathbf{E} \times \mathbf{B}$ upward drift of electrons which generates a negative charge at the top and a positive charge at the bottom of the E-region.
- The resulting electric field prevents further upward drift of electrons, instead they get propelled westward by the eastward electric field.
- This westward movement of electrons constitutes an eastward electric current known as the **Equatorial electrojet** ([www.goemag.us](http://www.goemag.us)).
**Equatorial Latitude: Peculiarities**

- The equatorial electrojet generates a *drift of electrons* to high height in the ionosphere at equatorial latitudes that are forced to diffuse pole-ward along the geomagnetic field lines.

This process generates a trough at the geomagnetic equator and crests of electron density at ±15-20° that characterize the meridional variations of the maximum electron density in the ionosphere (NmF2), defining the so-called "equatorial ionization anomaly".

Radicella, 2009
EQUATORIAL IONOSPHERE: PECULIARITIES

As a result of the above, equatorial ionosphere exhibits a departure from the normal undisturbed ionosphere found in mid-latitude.

**Departure of equatorial ionosphere includes:**
- i. irregular structures in E-layer: sporadic E (Es)
- ii. equatorial ionisation anomaly (EIA),
- iii. post-sunset irregularities; EPB, ESF, Scintillation etc.
- iv. winter anomaly,
- v. noontime bite-out ...etc.

**These departures are brought about by:**
- (a) the nearly horizontal inclination of the geomagnetic field and its influence on plasma motion,
- (b) the daily magnetic range which indicates the strength of the daytime ionospheric electric (Sq) current, and which is related to the ambient electric field and
- (c) the day-to-day variability of the electrojet, which determines the extent of both the noon time ‘bite-out’ in the electron density and the latitudinal trough of the EIA.
**EQUATORIAL IONOSPHERE: PECULIARITIES**

Latitudinal and Longitudinal differences in the features of equatorial ionosphere:

- The entire equatorial region of the ionosphere share a common feature and prevailing phenomena such as nighttime irregularities, EIA, etc.
- These features exhibit both latitudinal (magnetic dip angle) and longitudinal differences. So that as we move from one longitude (latitude) to the other one may observed some variations in these features.
- Thus, the equatorial features of the Brazilian sector may show some variations from that of African sector etc.
**Space weather** is the conditions in space that change from time to time.

A flow of charged particles called the "solar wind" constantly streams outward from the sun. The speed and pressure of this "solar wind" change all the time. Changes in radiation, the solar wind, magnetic fields, and other factors make up space weather.

Irregular or extreme space weather is brought about whenever there are solar storms leading to the release of solar flares, coronal mass ejection (CMEs) which interact with and modify the IMF.

Factors that determine regular space weather include:

i. Extent of solar radiation
ii. Solar wind i.e. stream of energetic particles from the sun
iii. The interplanetary magnetic field (IMF) strength and direction at any point in time.
GEOMAGNETIC STORMS: MECHANISM

➢ Geomagnetic storm is a manifestation of extreme space weather.
➢ Geomagnetic storms result when high-speed plasma injected into the solar wind from coronal mass ejections or coronal holes impinges upon the earth’s geomagnetic field.

During geomagnetic storms, energetic particles from solar flare and coronal mass ejection (CME) find their ways into the earth’s magnetosphere and eventually causing thermosphere/ionospheric storms.

Storm Drivers:
geomagnetic storms are driven by two major drivers:
• Coronal Mass Ejections (CMEs) and
• Co-rotating Interactive regions (CIR)
# Geomagnetic Storms: Mechanisms

<table>
<thead>
<tr>
<th>CME-driven Storms</th>
<th>CIR-driven Storms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generated by</td>
<td>Generated by</td>
</tr>
<tr>
<td>(i) CME sheaths, (ii) magnetic clouds and (iii) ejecta</td>
<td>(i) the associated recurring high-speed streams</td>
</tr>
<tr>
<td><strong>They cause:</strong></td>
<td>Have</td>
</tr>
<tr>
<td>(i) denser plasma sheets, (ii) strong ring currents, (iii) great auroras and (iv)</td>
<td>(i) longer duration, have (ii) hotter plasmas (leading to stronger spacecraft</td>
</tr>
<tr>
<td>dangerous geomagnetically induced current</td>
<td>charging), and (iii) produce high fluxes of relativistic electrons.</td>
</tr>
<tr>
<td>CME-driven storms pose more of a problem for Earth-based electrical systems</td>
<td>CIR-driven storms pose more of a problem for space-based assets</td>
</tr>
</tbody>
</table>
GEOMAGNETIC STORMS: CATEGORIES AND PHASES

GEOMAGNETIC STORM CATEGORY
- Sudden commencement
- Gradual commencement
- Sporadic
- Recurrent (caused by coronal holes)
- Does not necessarily depend on solar activity

Phases of Geomagnetic storms

Indices of geomagnetic storms

<table>
<thead>
<tr>
<th>Storm intensity</th>
<th>Kp-definition</th>
<th>Dst-definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Big</td>
<td>$8 \leq Kp \leq 9$</td>
<td>$Dst \leq 200nT$</td>
</tr>
<tr>
<td>Intense</td>
<td>$Kp = 7$</td>
<td>$-200nT \leq Dst \leq -100nT$</td>
</tr>
<tr>
<td>Moderate</td>
<td>$5 \leq Kp \leq 6$</td>
<td>$-100nT \leq Dst \leq -50nT$</td>
</tr>
</tbody>
</table>
Geomagnetic Storms: Mechanism

Physical mechanisms for solar wind energy transport into the magnetosphere include:

i. **magnetic reconnection** between southwardly directed interplanetary magnetic field (I.M.F'), Bz and magnetospheric dayside fields.

ii. **enhanced reconnection** of fields on the night side with the concomitant deep injection of plasma sheet

iii. **formation of the storm time ring current** which has between 5-10% efficiency during storm time.
GEOMAGNETIC STORM MECHANISM: MAGNETIC RECONNECTION

- Magnetic reconnection is the breaking and rejoining of magnetic field lines in a highly conducting plasma.
- Reconnection converts magnetic energy into kinetic energy, thermal energy and particle acceleration energy.
- It is often very fast and accompanied by efficient particle acceleration and changes in magnetic topology.
- Magnetic reconnection occurs in two locations:
  - At the dayside magnetopause when solar wind plasma reconnect with magnetospheric plasma and
  - At the night side i.e. magnetotail in response to magnetic energy building up in lobes due to solar wind driving.
- Reconnection depends on the orientation of interplanetary magnetic field (IMF): southward IMF being more geoeffective than northward IMF.
**Geomagnetic Storms Mechanism: Disturbance Time Ring Current**

- The ring current is carried by energetic charged particles flowing toroidally around the earth, and creating a ring of westward electric current, centred at the equatorial plane and extending to geocentric distances of about 2Re to about 9 Re.

- Although this current has a permanent existence due to natural properties of charged particles in the geospace environment, it becomes more intense during geomagnetic storms.

- Changes in the ring current are responsible for global decrease in the Earth’s surface magnetic field, which is the defining feature of geomagnetic storms (Daglis, 2001). These changes are measured by the indices such as Dst, Kp, Ap etc.

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EQUATORIAL IONOSPHERE AND GEOMAGNETIC STORMS

The physical and dynamic state of the upper atmosphere gets altered on a global scale during the main and recovery phases of storms due to deposition of energy and momentum to the high latitude upper atmosphere and its redistribution to other regions of the globe through various physical processes.

Irrespective of the type or category of geomagnetic storm, it affects all the attributes of the equatorial ionosphere causing variability of different magnitudes in all the regions i.e. E, F1 and particularly the F-region.

Also, all the three phases of geomagnetic storms have their signatures on the profile of the equatorial ionosphere.

Parameters affected by geomagnetic storms include: h’F, foE, foF1, foF2, B1, Bo, NmE, NmF1, NmF2, hmF2, TEC, M(300)F2, EPB, ESF, EIA e.t.c.

Impacts of geomagnetic storms can be grouped into two categories: (i) Bottomside - E and F1 regions, and F2/F region and (ii) Topside /entire ionosphere.
MECHANISM OF GEOMAGNETIC IMPACT AT EQUATORIAL REGION

- **Thermospheric perturbation**: this causes the down- or up-welling of neutral species through constant pressure surfaces causing changes in the O/N2 ratio. The resultant effect is enhancement or depletion of electron density.

- **Effect of equatorward wind**: geomagnetic storms enhanced equatorward winds causing the lifting of ionization to greater heights, and if this takes place at a time when production is still on-going, it will produce enhancement in electron density.

- **Perturbation of the equatorial electrojet** by the prompt penetrating strong magnetospheric electric fields (PPEF) and the electric fields generated by the disturbance dynamo (DDEF) leading to changes in the ExB drift.

- **Vertical drift perturbation**: affect the development of irregularities and drives the fountain effect which determines the electron density distribution and thus EIA.
**Effect at Different Layers**

The effects of these impacts of geomagnetic storm is the resulting ionospheric storm in which there are perturbations of different degrees at different the layers of the equatorial ionosphere.

**Lower: E and F1 regions:**
- The two processes in operation within this region during geomagnetic storms are (i) intensified ionization due to enhanced flux of energetic particles and (ii) changes in the neutral composition (thermospheric storm).
- These two processes appear to balance up at the equatorial region.
- As a result the resultant effect is little or less pronounced deviation from quiet time values except in rear cases.
EFFECT AT DIFFERENT LAYERS

**Bottomside F-region**
- Ionospheric storm has the greatest bearing on the F-region where all the parameters e.g. NmF2, hmF2, foF2, Bo, B1 etc. of the region are subjected to different degrees of variability due to the fact that all the stormtime mechanisms are active within the region.
- Hence there can be enhancements or depletions in F-region parameters depending on which of the mechanisms is most prevalent.

**Effects on TEC**
- Total Electron Content also undergo perturbation during stormtime
- TEC can be enhanced or depleted during geomagnetic storms depending on the category and phase of storm.

**Effect on EIA**
- Strong EIA variability are observed under magnetically active conditions arising from the simultaneous impulsive action of eastward prompt penetration electric field and equatorward neutral wind

**Effect on Irregularity**
- Irregularities are either enhanced or suppressed by geomagnetic storms
EFFECT OF STRONG STORM ON HEIGHT(N) PROFILE AT ILORIN
Effect of storm on NmF2

Effect of Feb., 2010 storm on three stations, two equatorial and one outside the equator:: large deviations were observed in the equatorial region compared to the mid-latitude station.
Intense storm of 27 May-2 June, 2010 and effects of equatorial region

Diurnal variation of NmF2 over: (3a) Ilorin, (3b) Jicamarca and (3c) Hermanus, for Average Quiet day (dark dashed line) with the disturbed thick dark line) during the storm of 29, 30 May, 2010. The plot spans 27 May through 2 June, 2010.
Response of TEC at two stations to 6-11 March intense storm


Fig. 6. TEC variations at (a) Toro and (b) Ilorin during 6–11 March, 2012 events

Fig. 7. Percentage deviation in TEC during 6–11 March, 2012 events at (a) Toro and (b) Ilorin.
EIA is modified during storm

Figure 5. Altitude-latitude variations of electron density $N_e$ at 13:00 LT on 08 November 2004 ($F_{10.7} = 123$) modelled by SUPIM using (a) equatorward neutral wind and quiet time $E \times B$ drift and (b) equatorward neutral wind and $E \times B$ drift due to eastward PPEE. Positive latitude is north (after Balan et al., 2010). Unit of $N_e$ is $10^{16} \text{ cm}^{-3}$ in both (a) and (b).

Balan, 2018

Courtesy: Radicella, S. M, 2009
SUMMARY OF EFFECTS OF GEOMAGNETIC STORMS ON THE EQUATORIAL IONOSPHERE

Effects of geomagnetic storms at equatorial latitudes can be summarized as follows:

(i) Geomagnetic storms affect the entire ionosphere i.e. E, F1, F2 –layers and topside of the equatorial ionosphere.

(ii) There are three major mechanisms at play in the equatorial ionosphere during storm; and the effects of these mechanisms produce deviations in the electro-dynamics from the quiescent features.

(iii) Equatorial ionosphere responds to geomagnetic storms by either raising or lowering heights of electron densities with corresponding depletion or enhancement of electron densities within the profile.

(iv) Percentage deviation within the E and F1 region (100 – 200 km) during is usually small except in rare cases. The effects of geomagnetic storms become pronounced at the F2-layer heights of about 200 km and above. The effect increases progressively from around 200 km to the peak of the F-region.

(v) All categories and types of geomagnetic storms affect the equatorial ionosphere.

(vi) The plasma fountain become super fountain during geomagnetic storms leading to the EIA becoming strong due to both eastward prompt penetration electric field and storm time equatorward wind.
CONCLUSION

- The equatorial ionosphere is a peculiar region of the ionosphere exhibiting features different from other latitudes.
- The equatorial ionosphere owes its peculiarity to the horizontal inclination of the magnetic field.
- The drift of plasma is governed mainly by the advection component of the drift term with $\text{ExB}$ drift playing prominent role.
- Geomagnetic storm is a manifestation of extreme space weather.
- Geomagnetic storms cause perturbation of the electric field thereby causing changes in the $\text{ExB}$ drift of plasma leading to the modification of the equatorial ionosphere.
Adeniyi, Jacob O; Isaac A. Adimula; Babatunde O. Adebisin; Bodo W. Reinisch; Olusola A. Oladipo; Olayinka Olawepo; and Kiyohumi Yumoto (2014). Quantifying the EEJ current with ground-based ionosonde inferred vertical e x b drifts in the morning hours over Ilorin, West Africa. Acta geophysica vol. 62, no. 3, pp. 656-678 doi: 10.2478/s11600-014-0202-0


Thanks
for your attention