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Equatorial Ionization Anomaly(EIA): Unraveling The Phenomenon of Ionospheric Disturbance

[1] Mustapha Abbas [2]Abdullahi Mohammed, [3]Dangana Abubakar Idris,
[4]Abubakar Umar & [5]Yusuf Arzika Koko

[1] Department of Physics, Kebbi State University of Science and Technology Aliero, Kebbi State
[2,3,4,5] Department of Physics F.C.E Kontagora
Arzikayusuf1@gmail.com

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ABSTRACT: *The Equatorial Ionization Anomaly (EIA) refers to a prominent irregularity in the distribution of ionization density within the ionosphere, situated near the magnetic equator, with two distinct crests at around ±150 in magnetic latitude- where ionization densities are significantly higher - and a trough at the magnetic equator in the F2 layer. This irregularity in ionization density has garnered considerable attention from researchers and scientists due to its complex underlying mechanisms and its significance on both the space and ground based communication facilities. This paper aims to explore the mechanisms and characteristics of the EIA, its impacts on communication and navigation systems, and various models that contribute to our current understanding of this enigmatic phenomenon. It also delves into spatio-temporal variability of the EIA, and finally proffers clarification on some misconception on the subject matter of the equatorial ionization anomaly.*

KEYWORDS: The Equatorial Ionization Anomaly; Ionosphere; Equator

INTRODUCTION

The equatorial ionization anomaly (EIA) is a well-known ionospheric phenomenon with two crests at around ±150 in magnetic latitude and a trough at the magnetic equator in the F2 layer (Balan et al., 2018). Its formation is generally explained by the uplift of the ionization to the higher altitudes in the equatorial region through E×B drifts, and the downward plasma diffusion along the magnetic field lines to the low latitudes aside the magnetic equator. This is the so-called equatorial plasma fountain effect, which is also modulated by neutral winds and compositions (Dang et al., 2016). Understanding the EIA's characteristics and behaviors contributes not only to advancing fundamental scientific knowledge but also to improving technological applications that rely on ionospheric interactions. As we continue to explore and study this intriguing phenomenon, we uncover its relevance in shaping our understanding of the dynamic space environment surrounding our planet.

The Ionosphere

The ionosphere is the partially ionized region of the Earth's upper atmosphere. It extends from about 60 km to 1000 km. The main source of the ionization in the ionosphere is the solar radiations such as extreme ultra violate (EUV) and X-ray radiations (Dang et al., 2019). In addition to photoionization, collisional ionization due to particle precipitation from the magnetosphere is another source of ionization, in particular in the high latitude region. Once the plasma is produced by these processes, it undergoes chemical reactions with neutrals, diffuses due to the gravitational force and plasma pressure gradients, and is transported via neutral winds and electric fields under the influence of the Earth's magnetic field (Dang et al., 2016). Due to the altitude variations in the atmospheric neutral composition and the production rate with altitude, the plasma density in the ionosphere has a vertical layered structure, denoted by the D, E, and F layers (Shim, 2009).
As shown in Figure 1.1.

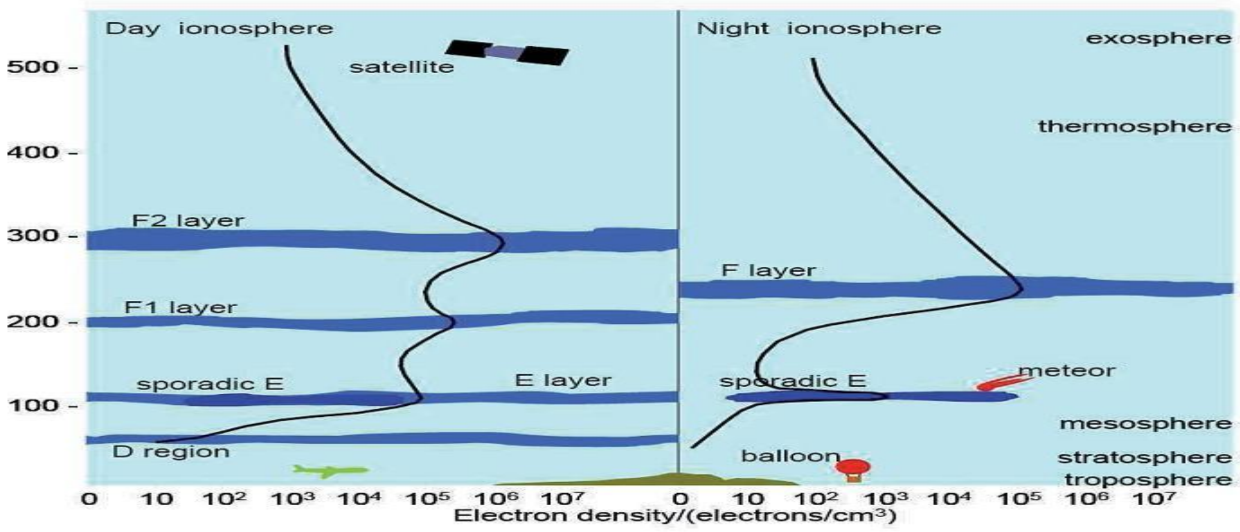

Figure 1.1 Day and Night Structure of the Ionosphere

Ionospheric and Equatorial Anomaly Modeling

In view of Samuel *et al.*, (2017) a representation of something that is often too difficult or impossible to observe or display directly is referred to as MODEL, although a model is justified by experimental test, it is only accurate in describing certain aspects of a physical system, while a theory is a carefully thought out explanation for observations of the natural world that has been constructed using the scientific method, which brings together many facts and hypotheses.

In order, not only to specify the ionosphere, but also to understand the Physics that controls the dynamics of the ionosphere, several ionospheric models have been developed over the last several decades. The ionospheric models can be broadly divided into three main categories, empirical, theoretical, and data assimilation models (Chapagain *et al*., 2011). Empirical models yield an average behavior of the ionosphere based on observational data. Therefore, empirical models are limited by the amount of data and the spatial and temporal coverage of the data that were used in their construction.

The table below summarizes some suggested models/theories used in an attempt to unveil the intriguing phenomenon called EIA

Table 2.0: Theories and Models that were suggested to explain the EIA (Eastes et al., 2023; Balan et al., 2024)

AUTHOR/YEAR	THEORY / MODEL	NATURE
Mitra,1947	Diffusion theory	Plasma diffuses along the geomagnetic field lines from the (otherwise) high density region at the equator to low density region at higher latitudes under the influence of gravity and pressure gradient forces,
Mitra, 1956	Electrodynamic drift theory	In addition to diffusion, upward ExB drift of plasma should also be important in causing the anomaly
Rishbeth, 1963	Rishbeth model	Diffusion is important but not sufficient. The combination of the drift and diffusion theories which generate the equatorial plasma fountain (EPF), on the other hand, was successful in explaining the observations
Hanson and Moffett, (1966)	Steady state model	Presented the first picture of EPF and IEA in the northern hemisphere from steady state model calculations using assumed upward ExB drift velocity (the drift velocity had yet to be measured)
Anderson, 1973	Anderson Model	showed the neutral wind modulation of EIA.

Hedin, 1991		Showed detailed pictures of the plasma fountain with and without neutral wind and their effects in producing and modulating EIA
Bailey and Balan, 1996	Plasmasphere - Ionosphere Model (SUPIM)	Incorporates measured values of ExB drift velocity and neutral wind velocity
Watanabe *et al.*, 1995	Ionosphere-plasmasphere model	Exploring EPF, EIA and ExB drift
Huba *et al*., 2000	Coupled thermosphere-ionosphere models(CTIM) model	EPF,EIA
Miyosh *et al.*, 2011	GAIA (ground-to-topside model of the atmosphere and ionosphere for aeronomy)	Exploring EPF, EIA and ExB drift
Abdu, 2016	Assimilative modeling	Understanding of the ionospheric weather variations and the electrodynamic processes underlying them
Balan *et al*., 2018	SUPIM model(Recent revision)	Validation/upgrading of SUPIM model
Eastes *et al.*, 2019	Gold NASA OBSERVATION	Global-scale Observations of the Equatorial Ionization Anomaly
Eastes *et al.*, 2022	Whole Atmosphere Community Climate Model-eXtended (WACCM-X)	Captures qualitatively an extra electron density (Ne) peak poleward of the southern equatorial ionization crest near sunset.

Equatorial Ionization Anomaly (EIA).

Equatorial Ionization Anomaly (EIA) was first discovered in 1938 by Namba and Maida, but was first recognized by Appleton (1946) as the Equatorial Ionization Anomaly (EIA) or Appleton anomaly (Abdul *et al.*, 2011). Since then, the research at the equatorial and low latitudes has become one of the hottest topics in the ionospheric community. During the past 2 decades, large amounts of ionospheric and thermospheric data from the ground-based and satellite-borne observations and also from the novel capability of three-dimensional numerical models stimulated the ionospheric weather studies (Dang et al., 2016).

The universal form of the equatorial and low-latitude region of the ionosphere is usually distorted with depletion of electron density over the geomagnetic equator and huge enhancements occurring around ±20° of the magnetic equator that corresponds to the EIA (Ogwala *et al.*, 2022). See figure 3.0.The low latitude ionosphere is known to exhibit several special features basically due to the horizontal orientation of the geomagnetic field at the geomagnetic equator. The special features include the equatorial electrojet, equatorial plasma fountain, equatorial ionization anomaly, equatorial plasma temperature anomaly equatorial temperature and wind anomaly, spread F and plasma bubbles, and the F3 layer. (Balan *et al.*, 2018).

When the sun shines over the equator, the ionospheric density was expected to vary from a maximum at the equator to a minimum at high latitudes. But when the density variation was measured (Appleton, 1946) it was found to exhibit an unexpected large structure with a trough around the equator, crests at near ±15° magnetic latitudes and crest-to -trough ratio of around 1.6 in daytime peak electron density (Nmax). This large structure known as the equatorial ionization anomaly (EIA) covers about half the global area in 24 hours, and position of the crests and crest- to-trough ratio vary with various geophysical conditions (Balan *et al.*, 2018).

Formation and Mechanism

The reason for the formation of the EIA structure is related to the equatorial fountain process, parallel pressure gradient and gravity. The electric field in equatorial regions is usually directed eastward during the day time. The electric field in combination with the nearly parallel geomagnetic field at the dip equator causes the plasma to be lifted upward by E × B drift (Figure 2.2).

The equatorial fountain process via the E × B drift tends to decrease the plasma density from the magnetic equator and move it to higher altitudes. The uplift of the plasma by the equatorial fountain process continues until the pressure gradient force field becomes strong enough. Then the plasma will be forced to move horizontally and downward by the horizontal pressure gradient and gravity along the magnetic field to form two crests with maximum ionization density near ±15 magnetic latitudes. The E× B drift uplift both electrons and ions with the same velocity.

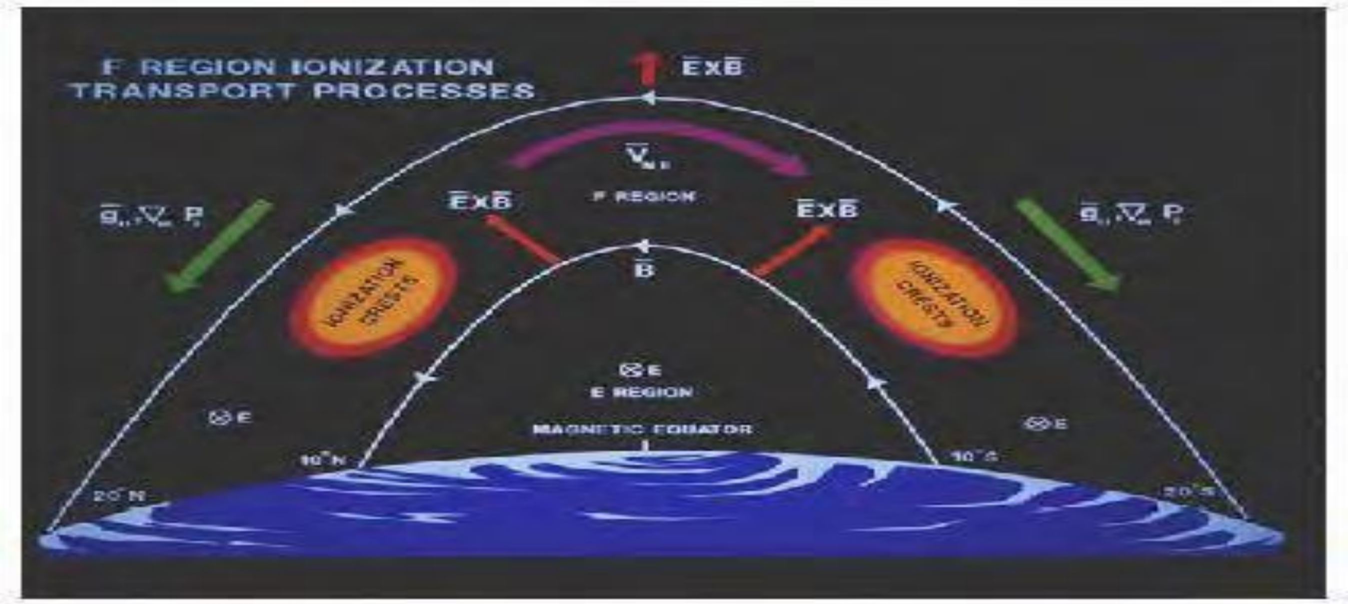

Figure 2.2: Schematic of the formation of the latitude variation of ionization density in the equatorial F region, known as the equatorial ionization anomaly or the Appleton anomaly.

The diagram illustrates that during daytime the eastward dynamo electric field from the E region maps along the magnetic field to F region heights above the magnetic equator. The plasma moves upward due to the E × B drift and then diffuses along the magnetic field to form two crests with maximum ionization density near ±15 magnetic latitude and minimum ionization at the magnetic equator (Bakale,2008).

EIA Control Process

The EIA is controlled by the unique equatorial electrodynamics associated with electrojet (EEJ) and the Fountain effect. The Fountain effect is an electrodynamics lifting of the plasma which drifts upwards until the pressure and gravity force are huge enough to push the plasma back through the magnetic field lines to higher latitudes (Balan *et al.*, 2022). This effect is the consequence of the fact that magnetic field lines run almost horizontally at the geomagnetic equator. The EIA is characterized by crests and troughs which are formed not only from accumulation of diffusing plasma, but also from the removal of plasma from around the equator by upward **E**×**B** drift (Kalita *et al*., 2017).

Venkatesh *et al.* (2017), pointed out that the driving force behind the fountain effect is the E × B drifts over the equator being controlled by the strength of the EEJ. Thus, the EEJ and EIA are the most typical equatorial and low-latitude ionospheric phenomena, and the characteristics of EEJ play a vital role on the electron density distribution over equatorial and low latitudes.

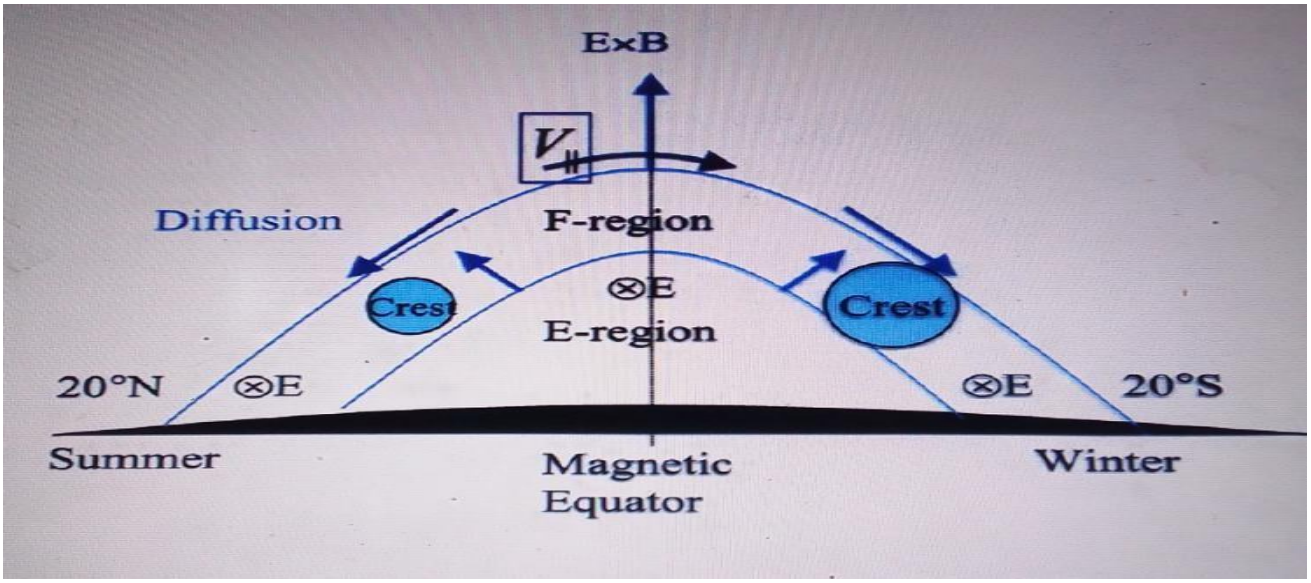

Figure 3.0: Fountain effects and asymmetry of the equatorial anomaly. An interhemispheric wind blowing from the summer to the winter hemisphere produces an asymmetry between two peak densities of the equatorial anomaly. E denotes an eastward electric field, and B is the northward

EIA Variability

Variations of the EIA have been extensively studied over various sectors. The previous studies have revealed that the EIA main parameters such as the magnitude, occurrence time, locations of the crest as well as crest to trough ratio exhibit significant variations with local time, season, solar and geomagnetic activities. This extreme variability is driven to a large extent by change in composition, thermospheric wind and wave, and tidal forces of lower atmospheric origin, changes in the equatorial electrojet (EEJ) together with the associated variations in ExB drift velocity, as well as changes in noon solar zenith angle in relation with the geometry of magnetic field lines (Astafyeya *et al.*, 2015), some of these variations are discussed herein.

Temporal Variation of EIA

Related studies have shown that the EIA four-wave structure begins to form from 08:00 to 10:00 LT, becoming most significant from 12:00 to 16:00 LT, and decaying from 00:00 to 02:00 LT (Fang et al., 2016). Therefore, it can be assumed that the EIA after midnight is the residue of the EIA after the eastward electric field disappearance, and its intensity depends on the ionospheric activity before midnight.

Hemispherical Variation of EIA

The density in the northern (winter) hemisphere is slightly greater than that in the southern hemisphere due to winter anomaly (or larger O/N2 ratio in winter compared to summer).

Based on Ogwala *et al.* (2022)'s simulation, this interhemispheric asymmetry is due to enhanced neutral equatorial wind during high solar activity periods, same as suggested by (li *et al.*, 2018).

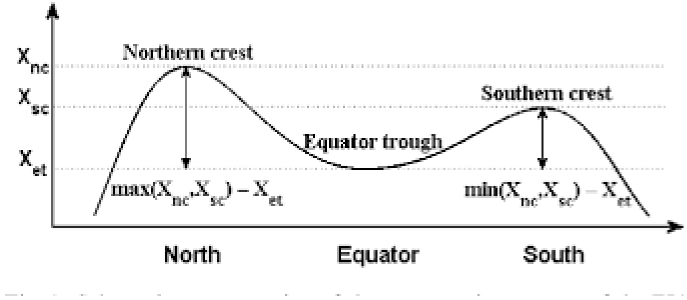

Fig 3.2: Hemispherical Representation of EIA

EIA During Geomagnetic Storm

The mechanisms of the EIA in storm conditions are similar to those under geomagnetically quiet conditions. However, the competing effects from the chemistry process, E×B drifts, and neutral winds during storms are quite dynamic (Zhang, 2017). During the early stages of major geomagnetic storms especially super storms, the plasma fountain becomes a super fountain (*Balan et al.*, 2018) and the EIA becomes strong with over 1000% increase in density at the crests that shift up to ±30° latitudes (*Balan et al.*, 2022). Such strong EIA was suggested to occur due to strong eastward PPEF (Kalita *et al.*, 2017) though modeling studies later showed that PPEF alone is unlikely to produce the strong EIA (*Balan et al.*, 2018).

EIA Implication /Application

a) EIA have societal consequences since they are associated with disruptions in communications and satellite navigation, and they illuminate frontiers in ion-neutral coupling physics.

b) Seasonal statistics will be valuable for understanding the EIA response to atmospheric tides, and will guide future attempts to describe these phenomena with numerical models, as GOLD presents a new ability to image the variability of ionospheric plasma and, ultimately, to understand its causes, which is one of the low and mid latitudes (equatorial) irregularities.

c) The EIA induced effect on the ionosphere is capable of generating favorable conditions for the occurrence of some other dynamical processes in the ionosphere. Hence understanding the EIA induced ionospheric modifications is a subject of intense scientific interest (Ashwathy et al., 2018)

d) The ionospheric response to the storm main phase was widely studied; however, the ionospheric storm effects during the storm initial and recovery phases, which were not fully addressed, need further investigation.

e) Jayachandran *et al.*, (1997) study also shows that the location of the crest is important in addition to the strength of the anomaly. This is helpful for the improved estimation of total electron content (TEC) and range delays required for satellite-based communication and navigation applications.

f) The poleward gradient of the equatorial ionization anomaly (EIA) introduces more intense propagation effects on trans-ionospheric satellite links in comparison to the equatorward gradient.

SUMMARY OF CLARIFICATION ON SOME MISCONCEPTIONS ON EIA

The following facts were validated through the recent studies by renowned space physics scientists (Balan *et al.,* 2022; Manu et al., 2023)

The EIA is formed not from the accumulation of plasma at the crests but mainly from the removal of plasma from around the equator by the upward **E**x**B** drift with small accumulation when the crests are within approximately ±20º magnetic latitudes; and the amount of accumulation reduces with latitude and becomes zero by approximately ±25º.

This large structure known as the equatorial ionization anomaly (IEA) covers about half the global area in 24 hours, and position of the crests and crest-to-trough ratio vary with various geophysical conditions

It is clarified that the EPF is not upward **E**x**B** plasma drift at the equator followed by downward plasma diffusion along the field lines, but it is field perpendicular **E**x**B** plasma drift and field-aligned plasma diffusion acting together all along the field lines at all altitudes and plasm flowing in the direction of the resultant.

The neutral wind makes EPF and EIA asymmetric with stronger fountain in the hemisphere of poleward wind and stronger crest usually occurring in the hemisphere of equatorward wind especially at equinoxes when winter anomaly is absent.

During early stages of daytime main phase of major geomagnetic storms, the plasma fountain becomes a super fountain and EIA becomes strong not due to eastward prompt penetration electric field (PPEF) alone but due to the combined effect of eastward PPEF and storm-time equatorward winds (SEW).

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