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Features of the Night-Time F-Region Currents Over Equatorial Africa (August, 2001)

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ABSTRACT

In this paper, we present the features of the equatorial F-region current systems over equatorial Africa during nighttime on 05[th]August, 2001 observed at midnight. The observations have inferred from in situ CHAMP satellite measurements of the vector magnetic field. The magnitudes of the current along all the three magnetic field components (X, Y, Z) of the Earth's magnetic field varied considerably. The B_x-component recorded a diamagnetic effect of about 8nT, B_y-component recorded a current density of 5mA/m, and B_z-component reached a value of 3mA/m. The F-region dynamo, gravity dynamo and plasma-pressure gradients are the possible mechanisms for the occurrence of these currents. The signatures confined to the equatorial region bounded by the Appleton anomaly.

Keywords: Ionosphere, Equatorial ionosphere, ionospheric current systems, magnetic field

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INTRODUCTION

The ionosphere is the part of the Earth's upper atmosphere where the ions and electrons are present in quantities sufficient to affect the propagation of radio waves (Campbell, 2003). It results when the solar radiation (Extreme Ultraviolet and X-rays) from the Sun ionizes the otherwise neutral upper atmosphere (S Maus & Lühr, 2006; Park et al., 2010). The presence of the charged particles in the upper atmosphere makes it an electrical conductor and thus supports the ionospheric currents. The ionosphere has three main layers: The D-region (50- 90km-absent at night), the E-region (90km -160km), and the F-region (160-1000km) (Maus & Lühr, 2006).The E-region, due to recombination processes, loses its electrodynamics influence on the ionosphere at night; however, that influence is much more significant during the day due to the E-region dynamo. The F-region is highly ionized and this ionization persists into the nighttime, thus enabling it play a dominant role in the nighttime ionospheric F-region dynamo (Rishbeth, 1971).

Electrodynamics processes in the equatorial ionosphere are due to the special geometry of the geomagnetic field. Quite different structures occur at E and F-region altitudes. The F-region current systems are mainly due to meridional currents and gravity driven currents. The ionospheric currents are responsible for a large part of variations of the geomagnetic field, although most of the geomagnetic field itself is results from the dynamo action in the Earth's core. The currents flow according to the Ohm's law, but the electric conductivity is anisotropic because of the effect of the geomagnetic field. While electric fields play the dominant role as drivers of electric currents in the ionospheric E-Region, the important current drivers in the F-region are pressure gradients and the

Earth's gravity field acting on the plasma. The existence of meridional currents was confirmed by means of rocket measurements (Musmann & Seiler, 1978) of the peak deflections of the eastward magnetic field component $\mathbf{B_y}$ at an altitude of about 125km and latitude of about 3.5^0 south of the dip equator. Later on, reported vertically upward flowing currents at an altitude of about 400km above the dip equator (Maeda, Iyemori, Araki, & Kamei, 1982) using Magsat spacecraft data. Their typical values are now known to be a bipolar variation in the magnetic field i.e. eastward magnetic field component, $\mathbf{B_y}$. The F-region electric currents are generally weak and difficult to detect as a number of background perturbations masks them. Although the F-region is extensively studied, only a few of these studies have focused on the night side, more so, on the equatorial ionosphere over Africa. In this paper, we present features of the nighttime F-region currents in the African sector of the equatorial ionosphere, as inferred from in situ CHAMP measurements. The results are for a single day of August (05/08/2001) which gave clear features in all the three magnetic components of the magnetic field. The data analyzed using Fortran and field models (Crustal field model, Cubic Spline fit and International Geomagnetic Reference Field (IGRF10) model) (Stefan Maus et al., 2005).

IONOSPHERIC CURRENT DRIVERS

The ionospheric current driving forces are gravity, pressure and F-region dynamo. These together give rise to the total F-region current consisting of the gravity-driven currents, pressure gradient currents and F -region dynamo currents. In order to compute these components we proceed as follows: (i) For F-region dynamo contribution, we need to compute the particle velocity starting from the equation $F = q\mathbf{E}$ **.** From this, we obtain the charged particle velocity as,

$$V_j = \Sigma_j \frac{F_i \times B}{q_j \times B^2} \quad (1)$$

where V_j is the particle velocity. The gravitational forces exerted on the ions and electrons are $m_i\mathbf{g}$ and $m_e\mathbf{g}$ respectively and from this we have the ion velocity as,

$$V_i = \frac{m_i g \times B}{qB^2} \quad (2)$$

Where the electron velocity is negligible due its small mass. For the pressure gradient force, $F = \nabla(nKT)$ and this yields the ion and electrons velocities, which are independent of mass as,

$$V_i = \frac{\nabla(N_i kT) \times B}{qB^2} \quad , \quad V_e = \frac{\nabla(N_e kT) \times B}{qB^2} \quad (3)$$

Finally, the drag force between plasma and neutral air is also taken into account, where the frictional force term is, $m_i v_i(u - v_{in})$. Here, v_{in} is the collision frequency and $\mathbf{u}$ the neutral wind. From the relation, $E = -v \times B$, we get the ion velocity as

$$v_i = m_i v_{in} \frac{E + u \times B}{qB^2}$$

Putting all these effects together, we obtain the resulting current density **j,** is (Kelley, 1989), given by,

$$\boldsymbol{j} = \sigma E + \{n m_i \boldsymbol{g} \times \boldsymbol{B} - k\nabla[(T_i + T_e)n] \times \boldsymbol{B}\}\frac{1}{B^2} \quad (4)$$

where $\boldsymbol{\sigma}$ is the conductivity tensor, $\boldsymbol{E}$ is the electric field, $\boldsymbol{g}$ is the gravitational acceleration, n is the electron density, $\boldsymbol{m_i}$ is the ion mass, **k** is the Boltzmann constant, $\boldsymbol{B}$ is the ambient magnetic field and $\boldsymbol{T_e}$ and $\boldsymbol{T_e}$ are the electron and ion temperatures respectively. At the F-region, the first term on the right-hand side of Eq (4) represents the currents due to F-region dynamo (Pedersen currents), the second the gravity-driven currents and the third term pressure driven currents. The currents driven by the F-region dynamo can be derived directly from CHAMP magnetic field measurements as follows: Using peak-to-peak variation of the magnetic $\boldsymbol{B_y}$ component, when the CHAMP satellite is passing over the dip equatorial region, the integrated, vertical current strength, $\boldsymbol{j_z}$, may be estimated. Using the infinite current sheet approximation (Lühr, Maus, Rother, & Cooke, 2002),

$$\Delta B_y = \frac{\mu_0}{2} j_z \quad (5)$$

where $\boldsymbol{j_z}$ is the current density, μ_0 is the susceptibility of free space and $\Delta\boldsymbol{B_y}$ the magnetic signal resulting from a current that flows vertically upwards or downwards i.e. in *z*-direction.

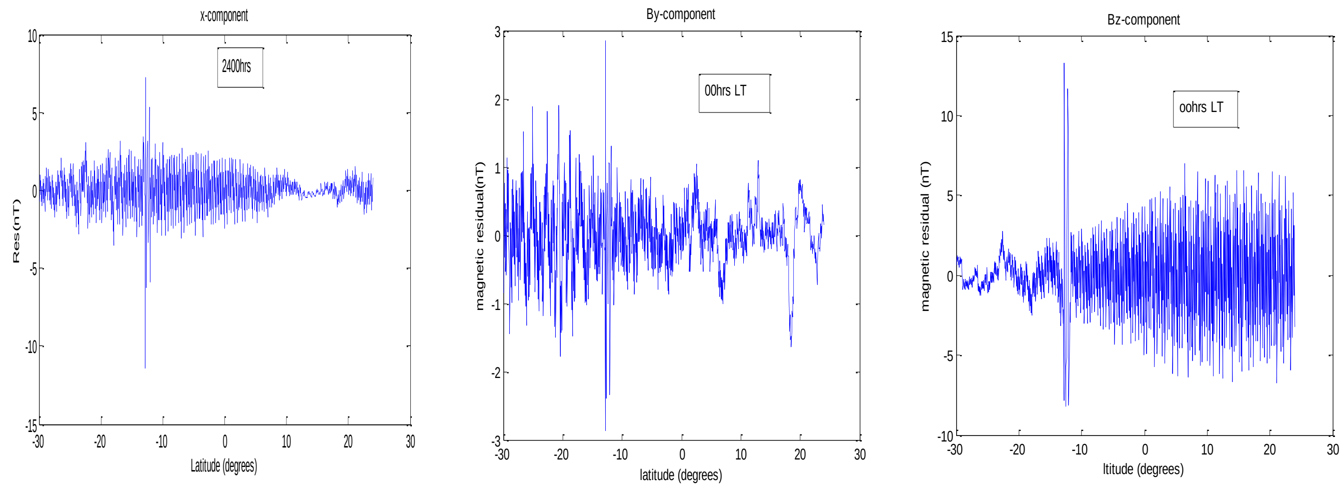
METHODOLOGY

Challenging Minisatellite Payload (CHAMP) (Wickert et al., 2001) was launched on 15th July, 2000 with an initial altitude of 450km into an almost circular, near-polar orbit with an inclination of 87.3^0. The primary objectives were to carry out in situ measurements related to the gravity field, the atmosphere, and the magnetic field (Lühr). Magnetic field measurements recorded by the CHAMP fluxgate magnetometer used in this study for the magnetic field vector was only a single day of the month of August, 2001. This day (05/08/2001) had distinctive magnetic signatures in all the three magnetic field components. The latitudinal range considered in our case was between-30^0S to 30^0N of geomagnetic coordinates.

We transformed the measured vector field measurements into the local Cartesian North-East-Down (NEC) system and angles needed for the transformation provided by a set of star cameras, which determined the spacecraft altitude with a resolution of arc seconds. The data in the North-East- Down (NEC) coordinate system were selected from the CDF files and converted into ASCII format columns in terms of year, month, day, latitude, and longitude, altitude, *X*, *Y* and *Z* components. Only nighttime data (20h 00 to 05h 00 UT) were selected and we only considered measurements during quiet periods with $Dst \leq 20$. Magnetic field signatures recorded by CHAMP comprise the sum of contributions from various sources such as magnetic field signatures due to primary contributions of the Earth's core and Earth's crust, ionosphere, magnetosphere, the magnetosphere-ionosphere coupling currents, as well as the fields due to the coupling between hemispheres. We eliminated the other contributions to the magnetic field measurements using Fortran-based software and field models (IGRF10), Crustal field model, cubic spline fit). This model (IGRF10) was used (spherical degree of 13) to subtract the Earth's main field contributions and the crustal field model of degree up to 90 to determine lithospheric effects. Then, to remove ring currents effects, we performed a cubic spline fit to the *X, Y,* and *Z* residuals as a function of latitude, and subtracted it from the residuals obtained from the previous data processing steps. The resultant external field effects are now only due to F-region currents.

RESULTS AND DISCUSSION

Significant number of magnetic signatures observed at latitudes bounded by the equatorial anomaly (figures, a, b and c). The following figures show typical examples of the magnetic signatures of equatorial spread F. The systematic analysis of currents in all the components is as follows.



a b c

Fig1. These figures a, b and c, **s**howing the magnetic residual son latitude of -13^0

We attribute the B_x-component of the magnetic field to the plasma pressure gradient currents. From the last term of Eq (4), we can calculate the magnitude of these currents. These currents are flowing around regions of enhanced plasma pressure in a sense that the magnetic field is considerably reduced in these regions of dense plasma. We observe these currents in Equatorial Ionization Anomaly (latitude of -13^0). During local times past sunset until midnight, steep density gradients form both on the F region bottom side and along the plasma trough above the dip equator (Lühr, Maus, & Rother, 2004). For pressure gradient currents, we apply only a first order approximation. Based on the assumption of a stationary momentum equation, every change in plasma pressure is counter-balanced by an adjustment of the magnetic pressure (Lühr & Maus, 2006) as follows;

$$\left(\frac{B-b}{2\mu_0}\right)^2 + \Delta[N_e(T_i+T_e)]k = const$$

where μ_0 is the susceptibility of free space and b is the magnetic field required to balance the change in plasma pressure, B is ambient field strength of 30,000 nT and the constant $k = 1.38\times10^{-23}$. Neglecting the quadratic term, b^2 because b is 10000 times smaller than *B*, we have;

$$b = \Delta N_e(T_e+T_i)k\frac{\mu_0}{B}$$

This is the diamagnetic effect and it reduces the magnetic field strength. Obtaining the values of these parameters from IRI-2007, (Bilitza & Reinisch, 2008) we get, $b = 8nT$. In the case of the B_y-component, the currents are derived directly from CHAMP magnetic field measurements. We therefore use Eq (5) to calculate these currents. The B_y-component records a magnetic residual of $\pm$3nT. This yields a current density of 5mA/m. The vertical component, B_z, (vertical downwards), reflects the of gravity-driven currents. From our plots, we observe an average magnetic field strength of about $\pm$10nT on this component. There is aclear evidence that the bipolar deflections, which we can attribute to the effect of gravity driven currents persist up to 24 hours LT. From the second term of Eq (4) and utilizing the electron density from IRI-2007, we get a current density of 3mA/m. The calculated value from these IRI parameters seems lower than the observed values. The following are the mechanisms that we can attribute to the currents observed in the low latitude equatorial region.

i) Pre-reversal (post sunset) Enhancement

The post-sunset enhancement or pre-reversal enhancement of the zonal field occurs during all epochs and seasons studied except for the solar minimum solstices (Heelis, Kendall, Moffett, Windle, & Rishbeth, 1974). It results in a large eastward electric field, which can lift the F-layer plasma to very high altitudes where recombination is low and collisions are rare. The lifting of the plasma creates a sharp east-west gradient and an enhanced zonal electric field is established leading to divergence free motion of the plasma (i.e. $\nabla . J = 0$).

ii) Equatorial Spread-F

The R-T instability can cause irregularities to grow in the equatorial ionosphere. It thus leads to a steep upward-directed gradient, which develops on the bottom side of the nighttime

F-region. These irregularities develop into plasma-depleted bubbles. Intense polarization of the electric field within the bubbles resulting in the rise of the bubbles to the topside at a velocity much greater than the ambient F-region plasma drift had been reported (Anderson & Haerendel, 1979). The bubbles lifted to altitude map down along the magnetic field line to Equatorial Anomaly regions.

iii) The Midnight Temperature Maximum

This is the occurrence of a local maximum in neutral temperature around midnight hours over low equatorial latitudes. The effect of this phenomenon on the low equatorial region has been extensively studied as reported by (Sridharan, 1998). This phenomenon would have more effects on the plasma-driven currents that are temperature dependent.

CONCLUSION

The observed F-region currents at CHAMP altitude varies in magnitude in all the three geomagnetic components on this day of August. However, the current occur on the same latitude -13^0 (southern hemisphere and a region bounded by the Equatorial Ionospheric Anomaly). The IRI values are not accurately predicting the magnitude of the F-region currents. More ground-based data will provide a better comparison to our observed predictions.

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