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On the historical origins of the CEJ, DP2 and Ddyn current systems and their roles in the predictions of ionospheric responses to geomagnetic storms at equatorial latitudes

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Abstract

In this short letter, we recall the differences between the Counter electrojet (CEJ), which is a phenomenon observed on the magnetically quiet days and the disturbance dynamo (Ddyn), which can be observed during and after a geomagnetic storm. The CEJ is well-known to occur near the geomagnetic dip equator. It can be identified by a reversal in the horizontal component (H) of the geomagnetic field daily regular variations. In contrasts to equatorial electrojet (EEJ) that flows eastward in the daytime the CEJ in considered to flow westward. The magnetic signatures of the reversed solar quiet (S_q) current at the low latitude during magnetic storms are due to the Ddyn. This disturbance (Ddyn) is produced by current systems that are driven by thermospheric storm winds originating from the Joule heating of enhanced high latitude currents. The DP2 is the magnetic effect of current systems at high latitudes. These currents are associated with the coupling of magnetosphere and ionosphere through geomagnetic field lines. They are associated to the magnetospheric convection. During intense magnetic storms these high latitude currents are enhanced and their magnetic effects can extend toward the low latitudes This work shows that the study of magnetic

perturbations makes it possible to understand the disturbances of the ionospheric electric currents. The use of an efficient treatment of the magnetic signals makes it possible to separate the magnetic effects of the different perturbations PPEF and DDEF. This was performed in the paper Nava et al. (2016).

Key words: Counter electrojet, Disturbance Dynamo, prompt penetration of the magnetospheric convection electric field, geomagnetic field variations.

1 Introduction

Studies on the terrestrial magnetic field began more than one and a half centuries ago. In 1889, Schuster established the first map of the diurnal equivalent electric currents deduced from records of ground magnetic data. Later, this diurnal variation averaged over the five quietest days in a month was called solar quiet, S_q (Chapman, 1919). After 1919, a lot of efforts regarding the knowledge, science and research on magnetic data had been essentially concentrated on their morphologies and the theory of the ionospheric dynamo was developed to explain the regular variation of the Earth’s magnetic field (Chapman and Bartels, 1940). At the magnetic equator, shortly after the installation of a magnetic observatory at Huancayo, Peru in 1922, it was found that the quiet time daily regular variation of the horizontal (H) geomagnetic field intensity was twice and half greater than that observed at the mid latitudes (Chapman, 1951). This abnormal amplification of the S_q of H near the dip-equator was interpreted as an intense eastward current and named equatorial electrojet (EEJ) by Chapman (1951). Later, in 1962, Gouin discovered on certain magnetic quiet days in the daytime that daily regular variation of H is reversed, indicating the reversal of the eastward EEJ toward the opposite direction, that is, in the westward direction. Gouin and Mayaud (1967) referred to this westward reversal of the EEJ as counter electrojet (CEJ).

During magnetic disturbed periods, there two are main physical processes influencing the ionospheric electric currents on a planetary scale: 1) the prompt penetration of the magnetospheric convection electric field (PPEF) and 2) and the ionospheric disturbance dynamo electric field (DDEF). The PPEF was first revealed by Nishida et al. (1966) by its magnetic signature called later DP2 by Nishida (1968). The first model on this PPEF was produced by Vasyliunas (1970). On the second physical process (DDEF), Blanc and Richmond (1980) developed the theory of the Ionospheric disturbance dynamo in order to explain the effect of auroral Joule heating on global ionospheric currents and electric fields. Later, Fambitakoye et al. (1990) established the equivalent current of the disturbance dynamo during geomagnetic storm of March 23, 1979. They observed that on that day (March 23, 1979), signatures of S_q currents at different locations around the world exhibited reversed S_q or “anti S_q” patterns. In 2005, Le Huy and Amory Mazaudier extracted the magnetic signature of the counter S_q during a geomagnetic storm from magnetic data and named it “Ddyn”. In summary, we will like to report that:

I Similar to the normal eastward EEJ, the reversed EEJ (CEJ) can be easily identified from magnetic observations, only during geomagnetic quiet periods between the dawn and dusk.

II The reversals of S_q and EEJ during the main phase of geomagnetic storms are caused by magnetospheric ring current and enhanced high latitude ionospheric currents.

III Tertiary reversals due to the Ddyn (wind dynamo effect) are strongly associated with currents that are driven by the winds related to the Joule heating of enhanced high latitude currents (Blanc and Richmond, 1980; Le Huy and Amory-Mazaudier, 2005). Zaka et al., (2010) simulated the disturbance dynamo magnetic perturbations using the

NCAR TIE-GCM. The patterns of the disturbance dynamo signature and its source “anti - Sq” current system are well reproduced by the model. However, the model significantly underestimates the amplitude of disturbance dynamo effects when compared with observations.

In the next sections 2 and 3, we will explain in details, the difference between the reversals in the geomagnetic field variations, which are due to CEJ and Ddyn currents. This is important in order to sensitize scientists and prevent them from misinterpreting geomagnetic terms and parameters regarding their future works. In section 4, we will discuss the relationship between DP2 and Ddyn including their roles in the efforts made by Nava et al. (2016) at identifying and separating them during geomagnetic storm at equatorial latitude. The implication of identifying and separating DP2 and Ddyn is aimed at contributing to how the future models could be improved to predict accurately ionospheric responses to stormy events at equatorial regions.

2 The Counter Electrojet (CEJ)

It was P. Gouin, the Director of the observatory in Addis Ababa, Ethiopia who first discovered that during some magnetic quite days, the diurnal variations of the H component of the geomagnetic field exhibits reversals at certain periods, especially in the morning and in the afternoon. This reversal was interpreted as a westward current flow in the opposite direction of the EEJ on quite day. The first publication to substantiate his finding was published in Nature in 1962. Figure 1 is an extract from Gouin (1962) works that illustrates reversal in the direction of the H component daily variation on January 3, 1962. Following this discovery, Gouin and Mayaud (1967) further analyzed 8 years of H component geomagnetic data at Addis-Ababa and called the observed phenomenon ‘counter-electrojet’, a characteristic that occurred during magnetic quiet period. Our figure 2 here shows Gouin and Mayaud (1967) figure 1 of S_q in the equinox, the S_R in a day and the mean of S_R from three consecutive days for four different years (1958, 1961, 1964, 1965). The S and q letters in the S_q correspond to the geomagnetic field variations related to solar radiation and during geomagnetic quiet period, respectively. Also, S_R is the regular magnetic variation associated to the regular ionospheric dynamo. As can be observed from our figure 2, CEJ was seen in the morning and as well in the afternoon hours. This novel work of Gouin and Mayaud (1967) published in French is available in English in the review edited by the committee of history of IAGA (Amory-Mazaudier, 2006).

Following these novel experimental studies (Gouin, 1962, Gouin and Mayaud, 1967) on CEJ, a theoretical study made by Hanuise et al. (1983) that was based on the dynamo model of Richmond (1973) was used to simulate CEJ events. A CEJ event was successfully reproduced by Hanuise et al. (1983) model and revealed the combination of (2, 2) and (2, 4) solar tides, which are strongly related to S_q and EEJ.

3 The Disturbance Dynamo (Ddyn)

Blanc and Richmond (1980) produced a simulation on the ionospheric disturbance Dynamo which predicted a reversed electrojet at the Equator. This significantly improved our understanding regarding the effect of auroral zone Joule heating on the ionospheric electric currents. The Joule heating generates thermospheric storm winds and creates a Hadley cell between the pole and the equator. These thermospheric storm winds modified the circulation of ionospheric electric currents and produced an equatorial current flowing westward opposite to the regular current flowing eastward. Figure 3 is from Blanc and Richmond (1980) works that showed and explained the reversed electrojet (REJ) during stormy periods. After the publication of Blanc and Richmond (1980), Mayaud (1982) wrote a comment explaining that the mechanism proposed by Blanc and Richmond (1980) could now explain the attenuation or even the “disappearance” of the EEJ during geomagnetic storms. Mayaud (1982) did not misrepresent the REJ signature for a CEJ during stormy period.

Le Huy and Amory-Mazaudier (2005) isolated the magnetic signature of this westward equatorial electric current for several storms and they called it Ddyn. The paper is titled “Magnetic signature of the Ionospheric disturbance dynamo at equatorial latitudes: «Ddyn». They never misrepresent these disturbances for CEJ and the questions of why they used letter D and how they arrived at Ddyn are resolved.

According to Le Huy and Amory-Mazaudier (2005), they referenced the works of Cole (1966) and Kamide and Fukushima (1972) and reported that letter D was used to quantify the formulation of geomagnetic field disturbances associated with electric currents of geomagnetic storms circulating the ionosphere-magnetosphere system. The equation is:

$$D = DCF + DR + DT + DP + [Ddyn] \qquad (1)$$

Where;

DCF – magnetic disturbance due to the Chapman Ferraro currents

DR – magnetic disturbance due to the Ring current

DT – magnetic disturbance due to the the Tail currents

DP – magnetic disturbance due to the DP1 and DP2 at that time

[Ddyn]– magnetic disturbance due to Ionospheric disturbed dynamo, not discovered in 1966

(In this equation we consider the perturbation as a whole (external and induced part DG as Cole, 1966) Fukushima and Kamide added the induced current DG in their equation)

When Cole (1966) and Kamide and Fukushima (1972) formulated equation 1 that describes the magnetic disturbance associated with the electrical currents flowing between the ionosphere and magnetosphere during geomagnetic storms. At that time, the theory of ionospheric disturbance dynamo did not exist and the magnetic disturbance Ddyn -had not yet been demonstrated. At that time, the well-known geomagnetic disturbances that perturbed the ionospheric currents are polar disturbances (DP) revealed by Nishida et al. (1966) . The letter D is Disturbance and the letter P is Polar. To differentiate the solar wind-magnetosphere-ionosphere interaction at the polar latitudes from equatorial latitudes, Le Huy and Amory-Mazaudier (2005) replaced the suffix P with dyn, so, DP becomes Ddyn.

4. Separation between the (DP2) and (Ddyn) magnetic signatures of PPEF and DDEF performed by Nava et al. (2016)

Apart from CEJ that is well-known to occur during magnetically quiet days, the detailed knowledge of the relationship between the Ddyn and DP2 and their individual role during geomagnetic storms are not well-known. These challenges are major threats to accurate prediction of the ionospheric responses to storms at equatorial latitudes. In order to improve our understanding as regard predicting ionospheric responses at equatorial latitude during stormy periods, the knowledge of the Earth's magnetic field on how to identify and separate the co-existence of DP2 and Ddyn is crucial. The H variation of the Earth's magnetic field is given by

$$\Delta H = S_R + D \qquad (2)$$

S_R - the regular magnetic variation associated with the regular ionospheric dynamo

D - equation (1) and has two parts: a magnetospheric (mag) and an ionospheric (iono) part, which are represented by

$$\mathrm{Dmag}\ (\mathrm{DR} + \mathrm{DCF} + \mathrm{DT}) \qquad (3)$$

$$\mathrm{Diono}\ (\mathrm{DP2} + \mathrm{Ddyn}) \qquad (4)$$

The magnetic disturbance Dmag can be roughly estimated by the storm magnetic index SYM-H

Substituting equations 3 and 4 into equation 2, it becomes

$$\text{Diono} = \Delta H - S_R - \text{SYM-H} \tag{5}$$

$$\text{DP2} + \text{Ddyn} = \Delta H - S_R - \text{SYM-H} \tag{6}$$

At the beginning of the perturbation the magnetic effect Ddyn is not present in the equatorial zone. Indeed, several hours are necessary for the magnetic disturbance of the ionospheric dynamo, Ddyn, to be installed at low latitudes. During the period while Ddyn is attempting to reach equatorial region, DP2 that is significant at all of the latitudes is

$$\text{DP2} = \Delta H - S_R - \text{SYM-H} \tag{7}$$

Also, DP2 is zero on worldwide scale when a magnetically quiet day immediately follows a stormy period characterized by no auroral activity. Hence, equation 6 becomes

$$\text{Ddyn} = \Delta H - S_R - \text{SYM-H} \tag{8}$$

In general, the above formulae indicate that DP2 and Ddyn are strongly related, but they could be separated relying on the following basic characteristics:

(i) Period (T) of events: $T < 3$ hours for DP2 and $T \sim 24$ hours for Ddyn
(ii) Ionospheric responses to DP2 => worldwide perturbation in UT time
(iii) Ionospheric responses to Ddyn => worldwide perturbation in LT time
(iv) DP2 is related to the Bz component of the IMF
(v) Ddyn is related to the Joule heating from the auroral zone

Le Huy and Amory Mazaudier (2005), Mene et al. (2011), Fathy et al. (2014) and Nava et al. (2016) characterized the DP2 and Ddyn. However, their inclusion into recent models at improving predictions accuracy of geomagnetic storm responses at equatorial latitudes is not yet implemented.

Nava et al. (2016) used all of the above discussed equations during St. Patrick's stormy day in March, 2015, and they used wavelet analysis to separate DP2 and Ddyn. They observed the diurnal oscillation of Ddyn at different local time in the three different longitude sectors (Asian, African and American sectors) during geomagnetic storm, which confirmed the presence of Ddyn. Ddyn appeared as a negative excursion of the diurnal component of the Earth's magnetic field compared to the regular quiet one. In addition at all the longitudes investigated Nava et al. (2016) characterized short-term oscillations (~ 2 hours) strongly linked with the Bz component of the IMF, and this is the signature of the DP2. Therefore, this is a clearer evidence that the magnetic effects of the prompt penetration of the magnetospheric convection electric field PPEF (DP2) was completely separated from the magnetic effects of the Disturbance Dynamo Electric Field DDEF (Ddyn).

In summary, understanding the role of physical processes as PPEF and DDEF in the electrodynamics coupling between high and low latitudes during geomagnetic storm play a significant role at improving future models regarding this coupling, and the magnetic data are very useful, if they are well interpreted. This means that if all of the processes described here are included in future ionospheric models, such models could have better potential at predicting ionospheric responses during stormy periods at equatorial latitudes. Apart from taking cognizance of the motions of ionization, electric fields and ionospheric electric currents circulating the E-layer dynamo, the thermal expansion of the atmosphere at higher altitudes in the F region associated with changes in the temperature and the motions of the atmosphere inducing changes in the composition of O/ N_2 (Fuller Rowell et al., 1994; Nava et al., 2016) are also very important.

5. Conclusion

We have reported the characterization of magnetic signatures of the counter electrojet (CEJ), polar disturbance (DP2) and disturbance dynamo (Ddyn) with respect to their historical origin. We have highlighted the importance of classifying these magnetic variations according to their sources. Also, we clarified that an electric current flowing in the opposite direction to the normal direction and attributed to the atmospheric source differs from interaction between the solar wind and the magnetosphere. We have been able to reveal the capability of DP2 and Ddyn at improving future models regarding prediction of ionospheric responses at equatorial region during geomagnetic storm. It is important to keep the definitions of phenomena in accordance with the efforts of those who discovered them in order to preserve our scientific heritage.

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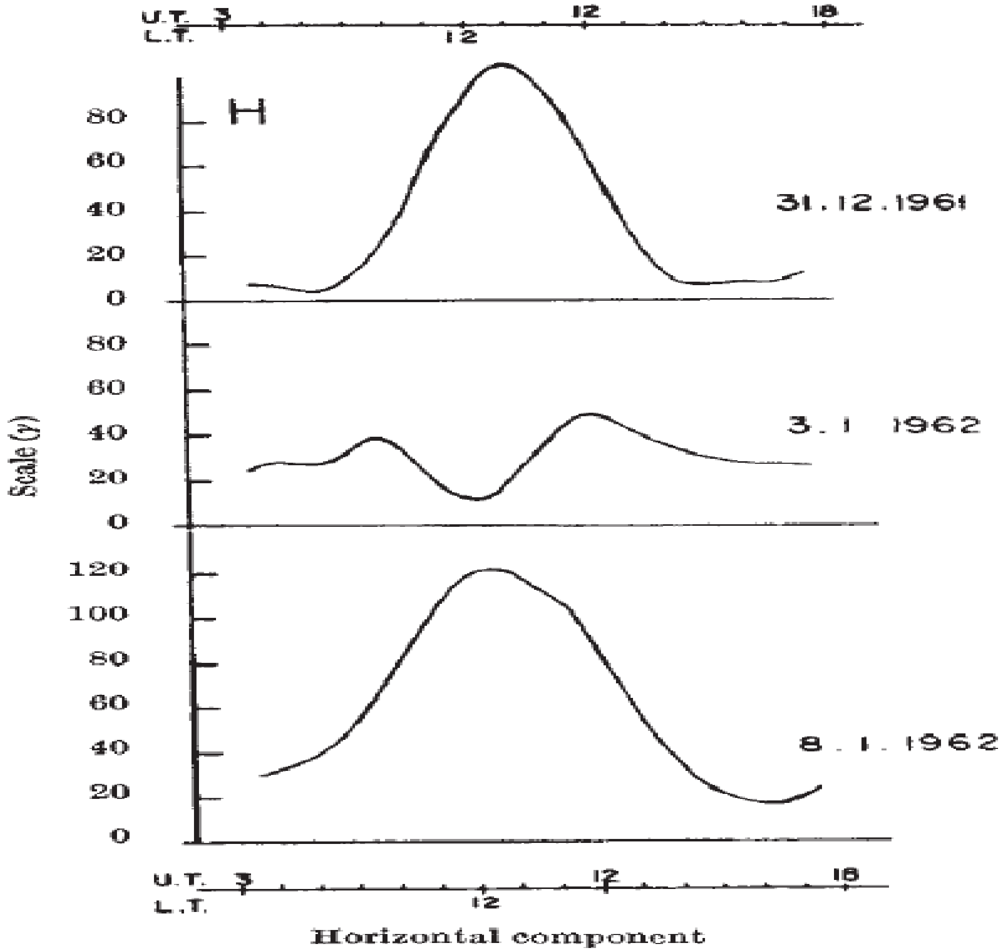

Fig. 1. Extreme phases of the phenomenon showing the reversal in the direction of the *H*-component daily variation on January 3, 1962

Fig. 1: Extreme phase of the phenomenon showing the reversal in the direction of the H-component daily variation on January 3, 1962 (After Gouin, 1962)

Figure 2 from Gouin and Mayaud (1967)

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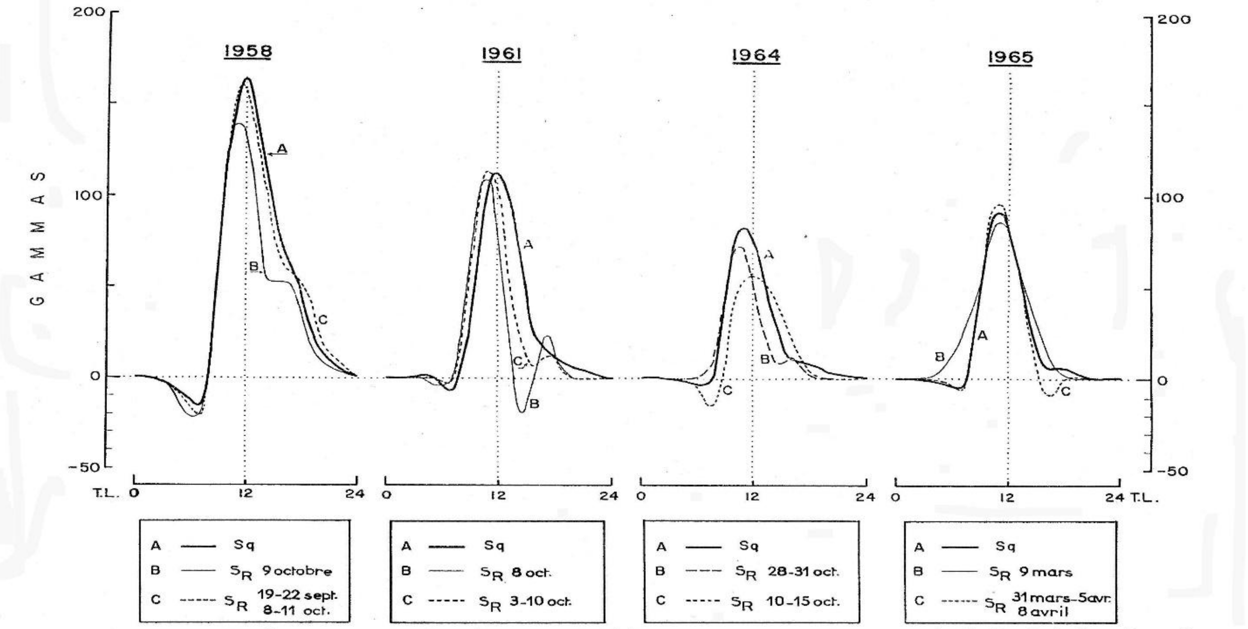

FIG. 1. — Courbes Sq d'équinoxe et courbes SR pour un jour individuel ou pour une série de jours individuels de la même saison de la composante H à Addis-Abeba, corrigées de la variation non-cyclique.

Sq and and S_R curves of the H component at Adis Abeba, during equinoxes , for an individual day or for a series of individual days of the same season corrected for the non-cyclic variation

Figure 3 from Blanc and Richmond (1980)

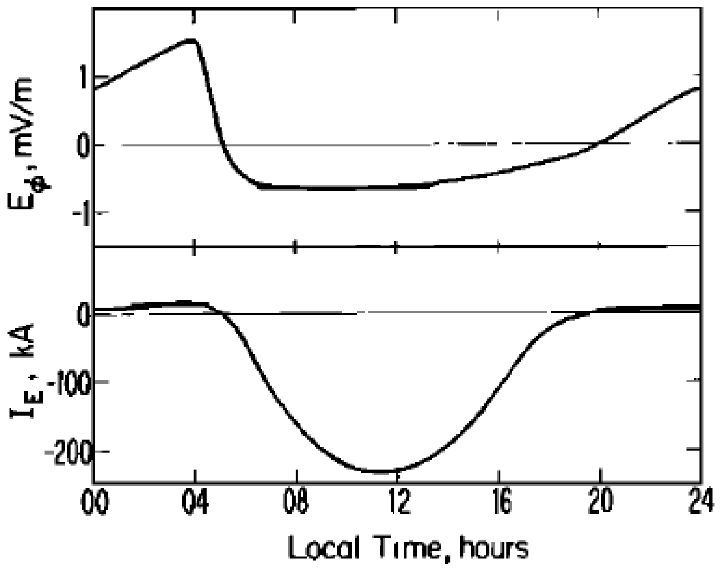

Fig. 9. Local time distributions of the equatorial electrojet parameters E_ϕ, eastward electrostatic field, and I_E, total eastward current flow between +10° and -10° magnetic latitude. Both are basically reversed from their observed normal quiet-day variation.