Response of the Equatorial Ionosphere to the Geomagnetic $DP2$ current system

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Abstract: The response of equatorial ionosphere to the magnetospheric origin $DP2$ current system fluctuations is examined using ground-based multi-instrument observations. The interaction between the solar wind and magnetosphere generates a convection electric field that can penetrate to the ionosphere and cause the $DP2$ current system. The quasi-periodic $DP2$ current system, which fluctuates coherently with fluctuations of the IMF $B_z$, penetrates nearly instantaneously to the dayside equatorial region at all longitudes and modulates the electrodynamics that governs the equatorial density distributions. In this paper, using magnetometers at high and equatorial latitudes, we demonstrate that the quasi-periodic $DP2$ current system penetrates to the equator and causes the dayside equatorial electrojet (EEJ) and the independently measured ionospheric drift velocity to fluctuate coherently with the high-latitude $DP2$ current as well as with the IMF $B_z$ component. At the same time, radar observations show that the ionospheric density layers move up and down, causing the density to fluctuate up and down coherently with the EEJ and IMF $B_z$.

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Introduction

It is well known that geomagnetic disturbances in the high-latitude region consist of two morphologically distinct current systems (DP1 and DP2 currents) that are associated directly with magnetospheric convection. The DP1 (disturbance polar of the first type) current (the substorm westward electrojet) disturbance, which is associated with the substorm expansion phase [Claver and Kamide, 1985], is characterized by a strong intensification of the westward auroral electrojet and cause the formation of magnetic bays in the auroral region [Nishida, 1968]. While the DP1 current system is localized in the near local midnight region, the polar region DP2 (disturbance polar of the second type) current disturbances is global and characterized by quasi-periodic magnetic fluctuations with a timescale of 30 minutes to several hours [e.g., Nishida, 1968; Kikuchi et al., 1996; 2000; 2008]. Unlike the DP1 current system, the DP2 current system can occur during both quiet and disturbed times and its impact can be detected at all latitudes with different magnitudes [Claver and Kamide, 1985]. All of these phenomenological characteristics have been determined primarily from ground magnetometer observations over many decades.

Understanding the formation of the quasi-periodic ionospheric current systems is very important to our comprehension of the solar wind magnetosphere-ionosphere coupling process and its impact on the equatorial density distribution. In the presence of interplanetary magnetic field, the interaction between solar wind and magnetosphere produces a dawn-to-dusk convection electric field ($E_y = -(V_z \times B_z)$). This electric field can then penetrate
into the magnetosphere when the $IMF \ B_z$ turns south, and drives $DP2$ current system [Nishida, 1968]. The equivalent $DP2$ current fluctuation, which consists of twin current vortices at high latitudes and zonal current component at low latitudes, then extends all over the Earth from the pole to the equator and [e.g., Nishida, 1968]. Since the solar wind speed is relatively steady compared to $IMF \ B_z$, the time fluctuation of the convection electric field may be directly proportional to the variation of $IMF \ B_z$ instead of solar wind speed. Thus, the time fluctuation of the $DP2$ current systems both at high-latitude and equatorial region is primarily controlled by the $IMF \ B_z$ fluctuation. Nishida, [1968], using the combined data from Explorer 18 (IMP 1) spacecraft and ground-based magnetometers, demonstrated that the $DP2$ currents both at high and equatorial latitudes coherently fluctuate with $IMF \ B_z$. Therefore, the presence of the $DP2$ current fluctuation at the equator is the direct result of the quasi-periodic interplanetary electric field that penetrates into the magnetosphere and down to the equatorial ionosphere through the TM0 (zero order transverse magnetic) mode waves in the Earth-ionosphere waveguide Kikuchi et al. [2008].

When the $IMF \ B_z$ turns south the interaction between the geomagnetic field and $IMF$ produces two reconnection locations, at the dayside (sunward side) and nightside (tail side) [Nishida, 1968]. Although it is the source of many important processes, such as energization of charged particles and expansion of substorm (or formation of $DP1$ current system), the field-aligned currents that originate from nightside reconnection may not be the cause for the $DP2$ current system; because the transit time of the event from
the tail side reconnection region (away from the ground by 10s to few hundred \( R_E \)) to the ground is much greater than the \( DP2 \) fluctuation time. This implies that field-aligned currents that originate from dayside reconnection drives the \( DP2 \) current system. However, the time varying interplanetary electric field can penetrate into the magnetosphere if the electric conductivity along the field lines on the magnetopause is low. Parker [1967] suggested the magnetopause surface conductivity decreases in the region where the angle between solar wind velocity and the geomagnetic field decrease. Since the conductivity along the field lines on front side of the magnetopause is believed to be high, the time varying electric field cannot penetrate to the magnetosphere from the front side of the magnetopause but instead it penetrates from around the morning-evening sector of the magnetopause where field-aligned electric conductivity is low and the finite potential difference is applied across the magnetopause [Nishida, 1968].

Although there have been many studies of the \( DP2 \) current system and its impact on magnetic fluctuations in the equatorial region [e.g., Nishida, 1967; Clauer and Kamide, 1985; Kikuchi et al., 1996; 2000; 2008; Trivedi et al., 2002], there are still several important questions that remain unresolved. One of these major questions is; what kind of impact can the \( DP2 \) current system impose on the equatorial ionospheric density distribution? This study for the first time shows the response of the ionospheric density distribution to the fluctuation of the \( DP2 \) current system at the equator, that can modulate the equatorial electrodynamics to fluctuate with the same periodicity as the \( DP2 \) current system or as \( IMF B_Z \).

**Data Analysis**

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For this study, we used data from ground-based magnetometers that are located at auroral and equatorial latitudes to estimate the DP2 currents and the EEJ that occurred on 16 February 2016 and 2 May 2010. The detailed description of the technique that we use to identify the DP2 current systems and EEJ from the magnetometer observations can be found in [e.g., Kikuchi et al., 1996] and [Anderson et al., 2004; Yizengaw et al., 2014, and the reference therein], respectively. The magnetometers we use for this study are operated under the umbrella of African Meridian B-field Education and Research (AMBER) [Yizengaw and Moldwin, 2009], INTERMAGNET [Love and Chulliat, 2003], and the Low Latitude Ionospheric Sensor Network (LISN) [Valladares and Chau, 2012] projects. The geographic and geomagnetic coordinates of the magnetometers used are listed in Table 1.

Similarly, to estimate the response of the ionosphere to the DP2 current system dynamics, we use vertical total electron content (VTEC) measurements from GPS receivers operated under the LISN networks and ionosonde observations from the Global Ionospheric Radio Observatory (GIRO) network [Reinisch and Galkin, 2011]. Figure 1 shows the location of all magnetometers, GPS receivers, and ionosonde stations that are used in this study. The solid and dashed curves depict the location of the magnetic equator and the region of EEJ (i.e., ±3.5° magnetic latitudes), respectively. The colored solid curves at the bottom left corner of Figure 1 shows the ground tracks of the GPS satellites, of which the PRN and the starting time of each pass are also shown at the beginning of each pass.

Observations:
Figure 2 (top panel) shows the characteristics of solar wind parameters; IMF Bz (black curve) and the dawn-to-dusk interplanetary electric field (IEF) (red curve) observed on 16 February 2016. Both of them show strong quasi-periodic fluctuations with a dominant periodicity of around 45 minutes. Although the solar wind parameters show periodic fluctuations, there was no significant magnetic storm activity. Dst index was quiet with Dst > -60 nT but Kp index indicates the presence of a moderate storm with Kp = 5, which is surprising as the DP2 current fluctuation can also occur during geomagnetically quiet periods [Claver and Kamide, 1985].

The second panel from the top in Figure 2 depicts the X-components (approximately north-south direction) magnetic field variations obtained from four magnetometers located at high and auroral latitudes. Different colors represent different stations where the stations’ codes and geomagnetic latitudes are shown at the right side. In order to maintain the magnetic field fluctuation within the same range limit, we multiplied the magnetic field fluctuation with the correspondingly colored numbers shown inside each panel.

The third panel of Figure 2 from the top, indicates the X-component magnetic field fluctuations observed in the equatorial region, within ±8° geomagnetic latitude, using stations located at different longitudes. The different colors represent different longitudes (noted on the right side of the panel), expanding from west American to west African regions. All of them exhibit coherent fluctuation with IMF Bz, in which the fluctuations are stronger around local noon when solar UV irradiation is stronger and thus ionospheric conductance enhanced. Finally, the EEJ, which is directly proportional to the equatorial vertical drift [e.g., Anderson et
that governs the equatorial ionospheric density distribution, that was calculated at two
different longitudes show identical fluctuation (see the bottom panel of Figure 2) with the same
periodicity of IMF $B_z$ fluctuations. The magnitude and direction of EEJ is calculated using
pairs of ground magnetometers located approximately at the dip equator and off the
geomagnetic equator ($\sim 6–9^\circ$ geomagnetic) latitudes [Anderson et al., 2004; Yizengaw et al.,
2014]. The vertical solid lines, shown from second to bottom panels, depict the local noon for
the corresponding stations. The vertical dashed lines shown in all panels indicate the time
coincidence of the IMF $B_z$ minimum point (or the IEF peaks), the magnetic variation peaks at
different latitudes and longitudes, and the EEJ peaks.

Figure 3 presents the response of the ionosphere for the quasi-periodic fluctuations of the
solar wind parameters and the EEJ measurements. The top panel shows the EEJ at the western
and eastern side of South America, which is the same as in Figure 2 bottom panel. The vertical
solid lines indicate the local noon for the correspondingly colored EEJs. The second panel from
the top show the VTEC obtained by the GPS receiver located at Jicamarca on 16 February 2016.
The corresponding filtered VTEC (by subtracting the sixth order polynomial fit from the actual
VTEC) shows clear VTEC fluctuations that exhibit good correlation with EEJ fluctuation.
Different colors represent the VTEC segment obtained by tracking different GPS satellites in
which the pseudo-random noise (PRN) numbers of each satellite are given at the right side. The
ground tracks of each satellite are shown, as line curves, in Figure 1, which are correspondingly
colored as the VTEC curves shown in the second and third panels of Figure 3. The contour in the
bottom two panels in Figure 3 depicts the aggregate number of return echoes recorded by the digisonde at Boa Vista on 15 and 16 February 2016 (as a function of height and time). Ionograms were recorded once every 15 minutes, and the return echoes are summed over all sounding frequencies. The color represents the level of total echo amplitudes at any given height and time, and the white curve indicates the EEJ estimated from the nearby pair of magnetometers located at the 76.9°W meridian. The height of maximum total echo amplitude often coincides with hmF2, especially in terms of their time rate of change. Thus, we used the height of maximum total echo amplitude fluctuations to track the up-and-down movement of the ionospheric F-layer, which is a good indicator how the ionospheric density fluctuates up and down in the presence of DP2 current systems.

The top panel in Figure 4 shows another example, specifically the periodic IMF $B_z$ (black curve) fluctuations and the respective IEF (red curve) observed on 2 May 2010. The middle panel presents the magnetic variation observed at three equatorial stations located at different longitudes which are noted on the right side, and the fluctuations are stronger around local noon. The solid vertical lines depict local noon of the corresponding stations. Unlike the 16 February 2016 event, the Jicamarca radar was running on JULIA (Jicamarca Unattended Long-term investigations of the Ionosphere and Atmosphere) mode and provided ionospheric vertical irregularity drifts during the 2 May 2010 event. The irregularity vertical drift (red curve) is overplotted with the EEJ (black curve) estimated using the pair of ground magnetometers in the Jicamarca meridian and is shown in the bottom panel of Figure 4. The irregularity drift shows
excellent correlation with the $EEJ$ and with the $IMF Bz$ quasi-periodic fluctuations shown in the top panel, implying a source and effect relationship between the $IMF$ fluctuations and the vertical drift fluctuations at the equator.

Discussion and Conclusion

The interaction between the solar wind and the magnetosphere drives the region 1 ($R1$) and region 2 ($R2$) field aligned current ($FAC$) systems and the associated magnetospheric plasma convection. The $R1$ & $R2$ $FAC$s in general setup electric field that may generate current system at high latitude that has quasi-periodic fluctuation with very good one-to-one correlation with the $IMF Bz$ variations. Since the magnetic effect of Pederson currents on the ground level is roughly equal in magnitude but opposite in sign to the magnetic effect of FAC, the magnetic disturbance observed at high-latitudes ground level is due to Hall currents [e.g., McPherron, 1995]. Thus, the $DP2$ fluctuations at high-latitudes are due to the combined effect of Hall conductivity and the solar wind driven convection electric field [e.g., Clauer and Kamide, 1985; Kikuchi et al., 1996; 2000]. The $DP2$ fluctuation then extends to the equatorial ionosphere almost instantaneously (see Figures 2 & 4) through the TM0 mode waves in the Earth-ionosphere waveguide [e.g., Kikuchi et al., 2008].

The second panel in Figure 2 shows the magnetic field at northern high and auroral latitudes (THL, HOA, and NAQ) that mostly do not show clear correlation with $IMF Bz$ fluctuations during the given time interval (09:00 UT – 20:00 UT). The polar region (THL) magnetic variation was experiencing a deep magnetic bay during this time interval, which is expected as
the station was in the nightside during February. The strong magnetic bays were also observed at auroral latitudes (IQA) during 9-14 UT, which was in local morning toward local noon indicated by the blue vertical solid line. After 14:00 UT (i.e., when the station was moving to dayside) the DP2 current dominates at IQA and shows coherent fluctuations with IMF Bz during 14:00-17:00 UT. The magnetic field variations at NAQ, of which its local noon is located at ~15:00 UT as indicated by green solid vertical line, do not show any significant magnetic bay; instead it shows good correlation with IMF Bz during 14:00-19:00 UT. The mid-latitude station (KEP) located on the dayside southern region mostly shows one-to-one correlation with the IMF Bz fluctuations. The comparison of magnetic fluctuations at different latitudes, such as at THL, IQA, NAQ, KEP, shows the DP2 fluctuations indeed decrease in magnitude as latitude decreases until it gets enhanced considerably (see the third panel from the top of Figure 2) due to the presence of Cowling effect at the dip equator.

The question is - what makes the DP2 current system fluctuates both at high and low-latitudes coherently? It has been demonstrated that this could be due to the imbalance of R1 and R2 FAC current systems. By separating the R1 and R2 FACs from radar electric field measurements, using the combination of ground-based magnetometers and EISCAT radar data, Kikuchi et al. [2000] showed a significant decrease (increase) of EEJ at the geomagnetic equator when IMF Bz turns north (south) and when there is a steep decrease (increase) of R1 FACs and increase (decrease) of R2 FACs. The R2 FACs generally setup a transient electric field that is opposite in direction with that of R1 FACs and produce a shielding effect [e.g., Kikuchi et al., 2008].
Similarly, when $IMF\ B_z$ turns south (north) both the $DP2$ current system and the $EEJ$ at the equator gets enhanced (decayed) or becomes eastward (westward), and irregularity drift at the equator turns upward (downward) as shown in Figure 2 & 3. The excellent time coincidence between the $IMF\ B_z$ minimum points and $EEJ$ peaks, as pointed out by the vertical dashed lines that pass through them, indicates that the $EEJ$ enhanced (decayed) when $IMF\ B_z$ turns south (north) which is consistent with the results reported in Kikuchi et al. [2000].

Thus, comparing Figures 2 and 3 the vertical dashed lines provide an excellent view that the periodic imbalance of $R1$ & $R2$ FACs systems causes the $EEJ$ and thus the vertical drift velocity fluctuation at the equator. The fluctuating vertical drift, which controls the vertical motion of the ionosphere, in turn causes the F-layer vertical height to fluctuate up (down) coherently with $IMF\ B_z$ as shown in Figure 3. The positions of $EEJ$ peaks (white curves) are directly correlated with ionosonde estimated ionospheric backscatter echo peaks as shown in the fourth panel from the top of Figure 3. The fluctuating height of backscatter echo amplitude peaks, which often coincides with $hmF2$, is used to track the up-and-down movement of the ionospheric F-layer.

While the strong F-region echoes show clearly visible up and down fluctuations of the F-layer’s virtual height during $DP2$ fluctuations event on 16 February, the echoes detected by the same ionosonde during the time without $DP2$ fluctuations event on 15 February do not show any up and down fluctuation. This clearly demonstrates how the $DP2$ current fluctuation controls not only the electrodynamics but also the ionospheric F-layer height. Similarly, the filtered $VTEC$ from four different satellites (third panel in Figure 2) show almost coherent fluctuation with the
EEJ and thus with IMF Bz. The time delay between the filtered VTEC as well as the ionospheric echo and EEJ peaks, in which the VTEC and ionospheric echo peaks appears about 20-30 minutes after EEJ peak time, is due to the duration of the vertical drift perturbation and that the ionospheric density peaks occur at the time when the layer stops moving upward or when the drift velocity reverse its direction. This clearly demonstrates that the magnetospheric origin quasi-periodic electric field can penetrate to the magnetosphere and drive DP2 current fluctuations that extend to the lower latitude ionosphere and causes the EEJ and thus vertical drift at the equator to fluctuate and create significant effect on the equatorial density distribution by making the F-layer moves up and down. The bottom panel of Figure 4 shows another example of the DP2 current modulation of the drift velocity as it is demonstrated by the independently measured ionospheric irregularity drift (red curve) that fluctuates coherently with the EEJ as well as with DP2 current and IMF Bz. Similar correlation between the magnetospheric origin electric field and the ground-based radar measured electric field during magnetic storm periods have been performed, mainly in the absence of DP2 current fluctuation [e.g., Kelley et al., 2003; Huang et al., 2007; Sobral et al., 1997]. However, for the first time, we report the solar wind-magnetosphere-ionosphere interactions driven DP2 current systems not only modulate ionospheric equatorial electrodynamics but also cause the ionospheric density distributions to fluctuate up and down.

It is worth mentioning about the small-scale fluctuation embedded in the large quasi-periodic EEJ variation, e.g., shown in between 16:45 – 17:50 UT in Figure 4. Yizengaw et al. [2013]
reported that the ULF wave in the Pc5 range is the possible cause for the formation of those small-scale EEJ fluctuations that are predominantly visible in Figure 4 compared to that of Figure 2 where these fluctuations are visible only at the eastward peaks of EEJ.

In general, when the FACs are in continuous dynamic, they form significantly fluctuating DP2 current systems that can easily penetrate to the equatorial region and modulate the equatorial electrodynamics that are responsible for the complicated nature of dayside ionospheric density height variations at the equator. Therefore, understanding of the DP2 current systems, such as its source, condition of its penetration to the equatorial region, and the impact it can produce onto the ionospheric density distribution is very important to understand the physics of equatorial electrodynamics that govern the equatorial density distribution. Because its impact on the equatorial ionosphere is significant, it can greatly affect the communication and navigation systems.

Acknowledgment

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References


### Table 1: List of instruments used for this study

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**List of Magnetometers**

**GPS receivers**

- Jicamarca: -11.95, -76.88, -0.87, 16.35, LISN

**Ionosonde Station**

- Boa Vista: 2.8, -60.7, 12.55, 13.47, GIRO
Figure Caption:

Figure 1: The geographic locations of the ground-based instruments that are used in this analysis.

Figure 2. (top to bottom) IMF $B_z$ (black curve) and IEF (red curve), the X-component of four high latitudes magnetometers, X-component magnetic field variation from six equatorial magnetometers, and EEJ estimated at different meridians.

Figure 3. EEJ estimated at two different longitudes (top panel), VTEC segments from four different PRN and the corresponding filtered VTEC (second and third panels from the top). The bottom two panels show the range-time-intensity-style plot of ionospheric echoes received from ionosonde located at Boa Vista, and the over-plotted white curves depict the EEJ during the corresponding days given at the top of each panel.

Figure 4. As for Figure 2 but for a different day that is given at the top of the panels.
Equatorial Electrojet fluctuation on 16 February 2016

Ionospheric VTEC response on 16 February 2016

Ionoosonde echo amplitude at Boo Visto on 16 February 2016

Ionoosonde echo amplitude at Boo Visto on 15 February 2016

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