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A THEORY OF CURRENT GENERATOR IN THE MAGNETOSPHERE-IONOSPHERE COUPLING

Takashi YAMAMOTO[1] and Masao OZAKI[2]

[1] *Department of Earth and Planetary Physics, University of Tokyo,*
3–1, Hongo 7-chome, Bunkyo-ku, Tokyo 113
[2] *Institute of Industrial Science, University of Tokyo,*
22–1, Roppongi 7-chome, Minato-ku, Tokyo 106

Abstract: A theoretical model for generation of a pair of region 1 and region 2 field-aligned currents (FACs) is presented. From the observed pattern of auroras, the existence of a hot plasma torus (HPT) in the magnetosphere can be assumed. An HPT is defined as a hot plasma contained in the magnetic shell which is connected to two ovals of diffuse auroras on the northern and southern polar ionospheres. It is porposed that region 1/region 2 FACs can be generated as a result of natural distortion of the HPT under the influence of the solar wind convection.

1. Introduction

Recently, based on the DMSP-F7 satellite observations IIJIMA *et al.* (1991) have examined the characteristics of large-scale field-aligned currents (FACs) during the growth phase of a substorm. Their findings are: (I) the total intensities (A/m) of the upward downward FACs are approximately balanced in a meridional plane, and (II) the region of the paired FACs is collocated with the region of enhanced precipitation of hot ($\gtrsim$keV) particles. The meridional balance of the region 1/region 2 FACs as well as their close association with the hot plasma population leads us to infer that the paired region 1 and region 2 FACs originate from the same source of a hot plasma in the magnetosphere.

Previous theoretical models for generating region 1/region 2 field-aligned currents have been proposed based on three paradigms of magnetospheric physics (For a brief review, see SISCOE and MAYNARD, 1991): (1) magnetic merging, (2) viscous interaction between solar wind and magnetospheric plasma, and (3) charge separation in the ring current plasma with pressure gradient directed toward local midnight. However, firstly, it seems difficult to understand, in terms of the magnetic reconnection, the generation of the paired region 1 and region 2 FACs with a merdional intensity balance. This is because the tail-current disruption (current wedge) merely causes a pair of region 1 upward and downward FACs typically centered around local midnight. Secondly, recent numerical simulations for coupling of the magnetopause-boundary layer to the polar ionosphere (WEI and LEE, 1992) have shown that the enhanced (viscosity-associated) FAC regions are limited to within about 100 km (as mapped to the ionosphere) from the magnetopause. It is then suggested that the viscous interaction between the solar wind and the magnetosphere contributes only to the generation of the high-latitude portions (close to the polar cap boundary) of the region 1 FACs in the morning and afternoon sectors.

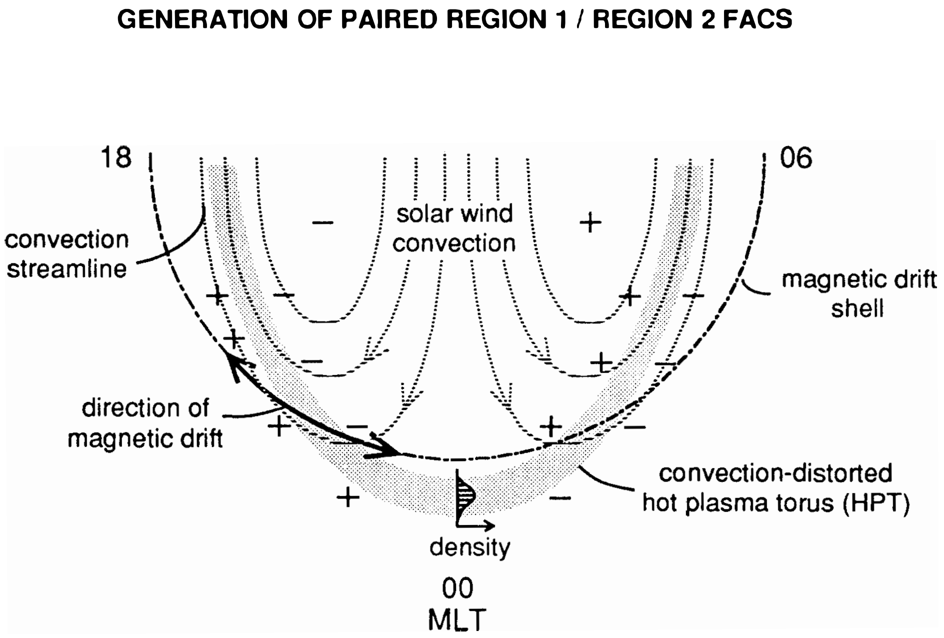
In the present paper we propose a new paradigm that the paired FACs result from "natural distortion" of the magnetospheric plasma distribution under the influence of solar wind convection (defined below). From the observed pattern of auroral luminosity, it can be reasonably assumed that the hot ($\gtrsim$keV) particles are concentrated to the closed magnetic shell which is connected with two ovals of diffuse auroras on the northern and southern polar ionospheres. In our analysis, a hot plasma contained in this magnetic shell having several degrees of latitudinal width is referred to as a hot plasma torus (HPT). On the other hand, as the solar wind flows across open field lines, the solar wind plasma loses momentum and energy through the $j \times B$ force. This implies that the polarization electric field is generated in the magnetosphere and the polarization charges are drained by a depolarizing current flow along the field lines to the ionospheric load. Due to the finite ionospheric conductivities, the space charges remain both in the magnetosphere and the ionosphere: the dawn and dusk sides of the polar caps are positively and negatively polarized, respectively. This means the appearance of twin vortex cell with antisunward flows in the center of the polar caps. In our paper, this two-cell convection directly driven by the solar wind is called the solar wind convection.

We presume that the polarization of the HPT distorted by the solar wind convection would be responsible for the generation of a pair of the region 1 and region 2 field-aligned currents. The numerically calculated production of the region 1/region 2 FACs is shown to be consistent with the observations (IIJIMA and POTEMRA, 1976, 1978).

2. Theory and Simulation

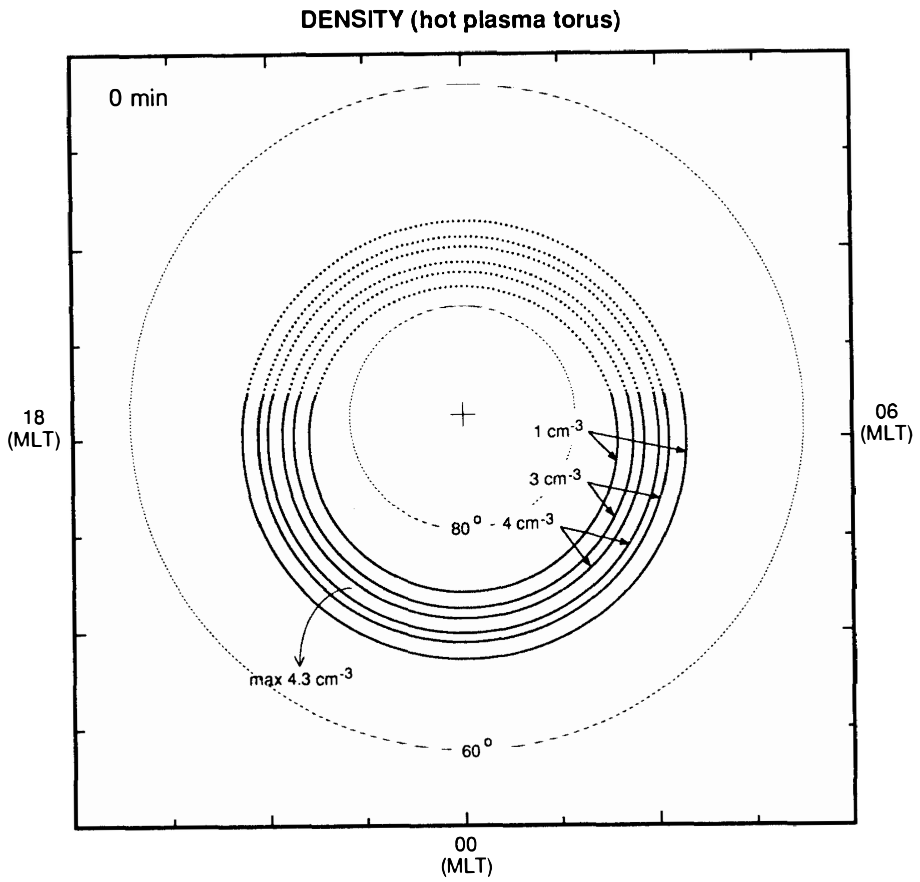
The solar wind convection pattern can be inferred from a simple theoretical model by LYONS (1985); the simple addition of a uniform interplanetary magnetic field and the earth's dipole magnetic field is used to evaluate electric field convection patterns over the polar caps that result from solar wind flow across open geomagnetic field lines. When the interplanetary magnetic field component B_z is negative, the resulting electric field gives rise to an antisunward convection in the center of the polar caps. The dipolar charge accumulation (positive on the dawnside and negative on the duskside) in the polar caps was shown to be a common feature for $B_z < 0$ and $|B_y/B_z| < 1$ (LYONS, 1985). As an extention of LYON's model, we assume that the dipolar charge accumulation in the polar cap produces a two-cell convection covering the entire auroral oval besides the polar cap.

Let us consider how the solar wind (two-cell) convection influences the configuration of a hot plasma torus (HPT). If it were not for the solar wind convection, the HPT would be shaped in such a way that any tangent of the HPT is parallel to the direction of the averaged total magnetic drift velocity; that virtual configuration of the HPT is called the magnetic drift torus. The relative location of the HPT (distorted by the solar wind convection) to the magnetic drift torus is schematically shown in Fig. 1, where their footpoints on the ionosphere are indicated as representing the torus configuration and, for simplicity, the magnetic drift torus is represented by a circle.



GENERATION OF PAIRED REGION 1 / REGION 2 FACS

Fig. 1. Schematic illustration for generation of paired region 1/region 2 field-aligned currents.



DENSITY (hot plasma torus)

Fig. 2a. Initial distribution of the HPT particles.

Thus, due to the distortion of the HPT, the pressure gradient has a component parallel to the magnetic drift. For this reason, the HPT can be polarized due to oppositely directed magnetic drifts of the HPT electrons and protons. The resulting polarization is such that the high-latitude and low-latitude portions of the HPT on the evening side are negative and positive, respectively, and the polarity is reversed on the morning side. Note that the space charge distribution shown in Fig. 1 is consistent with the commonly observed location for the region 1 and region 2 FACs.

Next, we estimate the FAC density generated by the proposed mechanism. From the one-fluid momentum equation, the temporal variation of the space charge density in the magnetosphere can be expressed as (*e.g.*, HASEGAWA and SATO, 1979).

$$\frac{\partial \rho_c}{\partial t} = -(\nabla \ln p)\cdot \boldsymbol{J}_m, \tag{1}$$

where $\boldsymbol{J}_m$ is the magnetic drift (gradient-B drift plus curvature drift) current density, p is the (isotropic) plasma pressure. In the above expression, the divergence of the inertia current density is neglected, because we consider large-scale ($\gtrsim 100\,\mathrm{km}$ at the ionospheric height) phenomena changing with the substorm time scale of longer than a few minutes. For quasi-neutrality, $\partial \rho_c/\partial t$ integrated over a magnetic flux tube must be equal to the outflux (or influx) of space charges from (or into) the flux tube. The field-aligned current (FAC) density $J_{\parallel i}$ at the ionospheric height is then given by

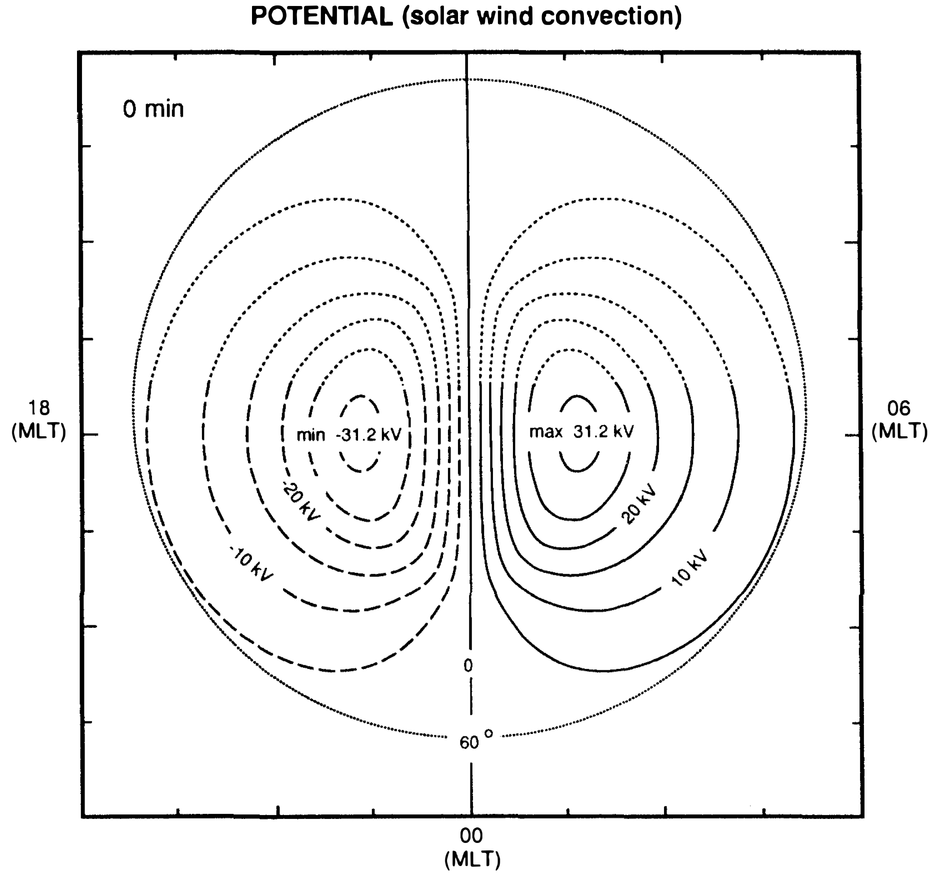


Fig. 2b. Solar wind convection pattern assumed in the simulation.

$$J_{\parallel i}A_i = -\int_0^{L_\parallel} \frac{\partial \rho_c}{\partial t} A(s)\mathrm{d}s = \int_0^{L_\parallel} (\nabla \ln p)\cdot J_m A(s)\mathrm{d}s\,, \tag{2}$$

where s is the field-aligned distance, $L_\parallel$ is the half of the total field line length, and $A(s)$ and A_i are the cross-sectional areas of the flux tube at a distance of s and the ionospheric height, respectively. For simple mathematical manipulation, we assume that the HPT temperature is constant and that the latitudinal profile $n(x)$ of the HPT density (at any local time) is given by $n(x)=(n_0/2)(1+\cos(\pi x/L_i))$ for $|x|<L_i$ where n_0 is the maximum density and L_i is the half width of the HPT at the ionospheric height. Taking account of the observed particle precipitation in the FAC region (IIJIMA *et al.*, 1991), we assume that the sum of proton and electron energies is ~8 keV and the density $n_0\sim 4\,\mathrm{cm}^{-3}$. For the field line at $L\sim 8\,\mathrm{R_e}$ and $L_i\sim 300\,\mathrm{km}$, $J_{\parallel i}(x)$ is finally calculated as

$$J_{\parallel i}(x)\sim 6.7\sin\theta\sin(\pi x/L_i) \quad (\mu\mathrm{A/m^2})\,, \tag{3}$$

where θ is an angle between the direction of the magnetic drift current and the tangent of the HPT. Note that $J_{\parallel i}$ estimated in eq. (3) attains an observable magnitude ($>0.1\ \mu\mathrm{A/m^2}$) for only 1° of the deflection angle θ and that the maximum value of $J_{\parallel i}$ exceeds $1.0\,\mu\mathrm{A/m^2}$ for $\theta \gtrsim 9°$.

In the following, using numerical simulations we explicitly demonstrate that the HPT distortion by the solar wind convection results in the generation of region 1/region 2 FACs. Under the assumptions that the magnetic field lines are equipotential and the

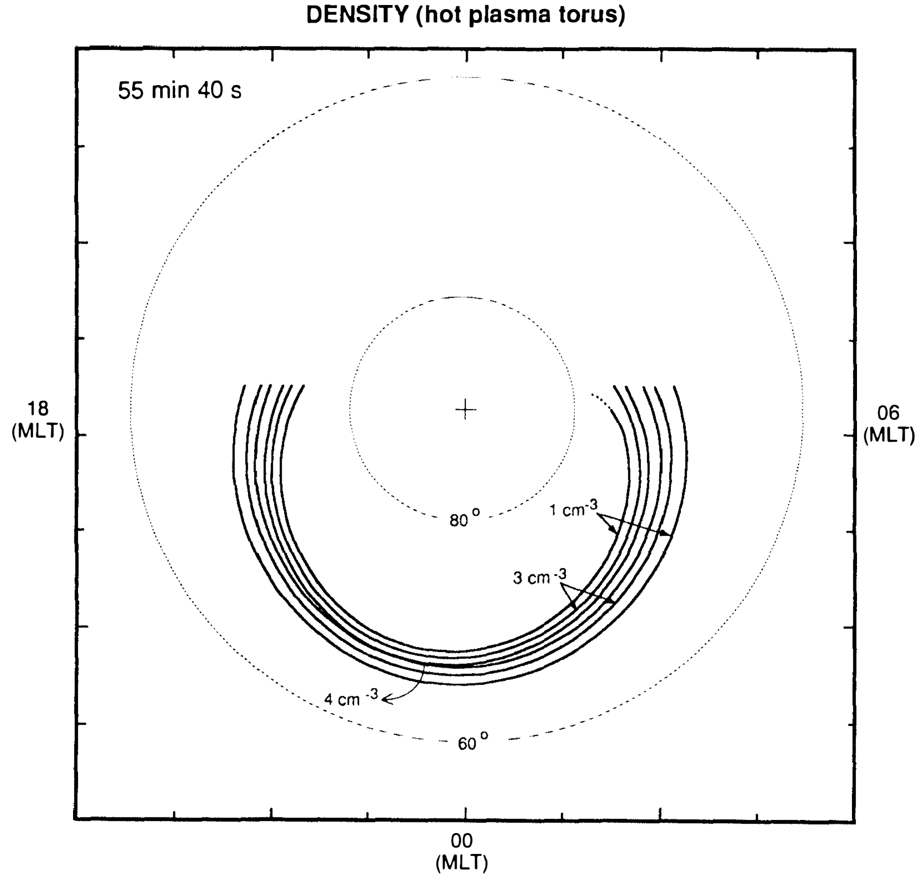


Fig. 3a. Number density of the deformed hot plasma torus at the time of ~56 min.

initial density of the HPT particles, along a field line, is independent of the altitude, we use the two-dimensional approximation that the electrostatic cross-field dynamics (concerning the electric drift) of a whole flux tube can be represented by the cross-field plasma dynamics at a representative altitude.

The initial distribution of the HPT particles is given as indicated by the isodensity contours in Fig. 2a. Practically, in our planar model, the density profile of the HPT particles is projected onto the ionosphere and the particle motions perpendicular to the magnetic field are calculated on the ionospheric plane. As a first approximation, neglecting the precipitation of protons, we follow only the dynamics of the HPT protons as representing the whole HPT dynamics. The perpendicular (to the magnetic field B) motions of the HPT particles can be calculated using the drift approximation because the temporal and spatial scales of the large-scale field-aligned current generation are much greater than the ion cyclotron period and radius. The guiding center positions of particles are advanced by using the predictor-corrector method (Lee and Okuda, 1978). To save the computational time, all the protons (electrons) in the (ionospheric) simulation plane are equally moved by the magnetic drift at the average velocity, *i.e.*, the two fluid approximation is used.

The solar wind convection pattern is specified as shown in Fig. 2b, where the

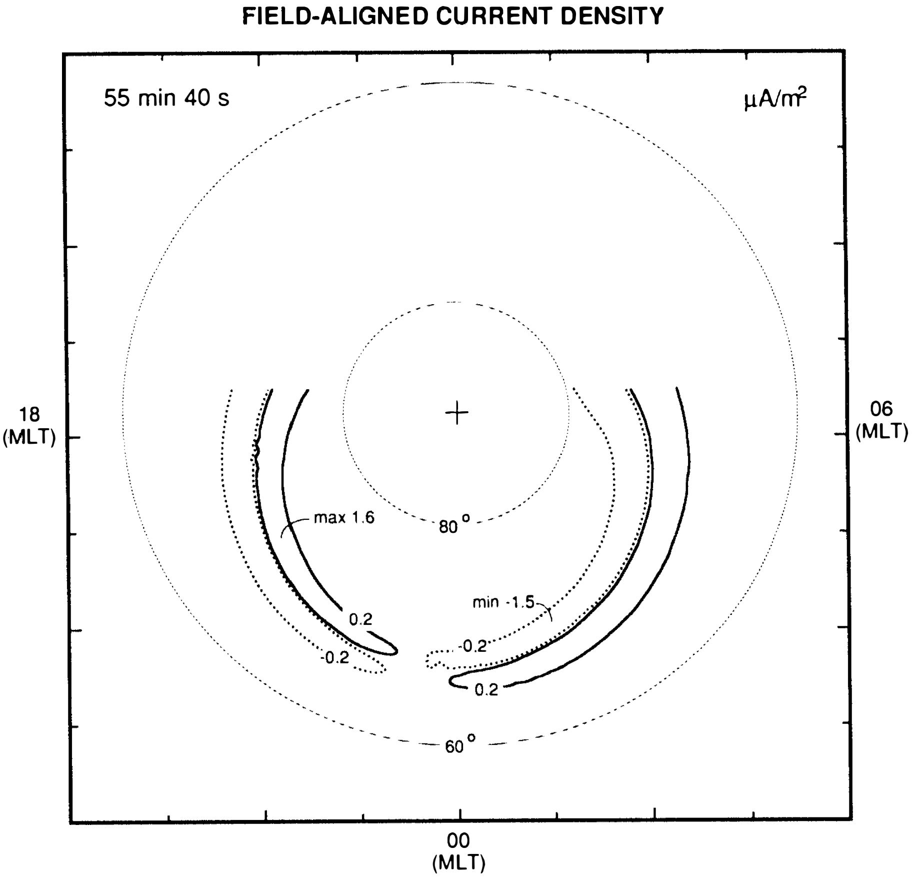


Fig. 3b. Field-aligned current density resulting from the HPT deformation. Solid equicontours are for upward FAC density $J_{\|i}$ (>0) at the ionospheric height while dotted contours are for downward FAC density $J_{\|i}$ (<0).

equipotential contours are indicated. The associated space charge density is determined so that the resulting potential drop across the open region is consistent with the result obtained by LYONS (1985). To obtain the potential from the space charge distribution, the Poisson equation is numerically solved under the boundary condition that the potential vanishes on the circle inscribed in the square frame in Fig. 2b. Note that the maximum potential difference given in Fig. 2b is also comparable to the polar cap potential drop inferred from the observations during substorms (*e.g.*, KAMIDE and BAUMJOHANN, 1985).

In our preliminary simulation, the solar wind convection in Fig. 2b is persistently impressed upon the hot plasma torus (HPT) in the magnetosphere. We do not include the electric fields which can arise from the polarization of the HPT. Numerical simulations are performed inside the circle inscribed in the square frame (see, *e.g.*, Fig. 2a), by using a particle-in-cell code (*e.g.*, OKUDA, 1985). This circular simulation domain is covered with 128×512 grid meshes in polar coordinate (r, θ). We restrict the present analysis for FAC generation to the nightside polar region because the problem of the dayside FAC generation seems more complicated. The HPT consists of 99712 super-particles with different density weights. Assuming that the background cold plasma is always neutral, we do not load super-particles for this particle population. The results to be presented are from runs using a time step of $\Delta t = 16.6\,\mathrm{s}$. The time step Δt is taken small enough to satisfy the Courant condition.

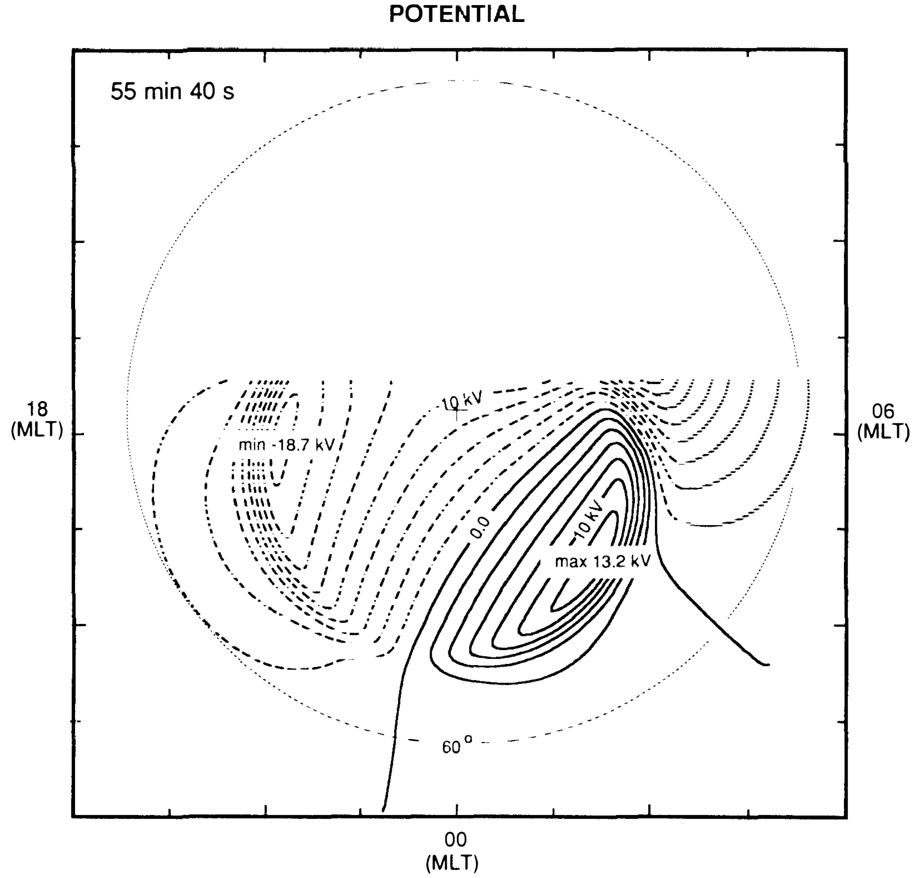


Fig. 3c. Electric potential distribution corresponding to the FAC distribution in Fig. 3b.

The simulation results are presented in Fig. 3. Figure 3a shows the number density of the hot plasma torus (HPT) which is obtained after impressing the solar wind convection for about 56 min. Figure 3b shows the field-aligned current density resulting from the HPT deformation in Fig. 3a. The maximum magnitude of the FAC density in excess of $\sim 0.6\,\mu\text{A/m}^2$ is already obtained about 14 min after we start impressing the solar wind convection. Figure 3c shows the corresponding electric potential at the time of ~56 min. This is calculated from the FAC distribution in Fig. 3b, based on the Pedersen current closure in the uniform ionosphere with the height-integrated Pedersen conductivity Σ_p of 5 mho.

3. Conclusions

It has been shown that paired region 1 and region 2 field-aligned currents can be generated as a result of the distortion of the hot plasma torus in the magnetosphere, which occurs under the influence of the solar wind convection. The numerically simulated pattern of region 1/region 2 field-aligned currents is found to agree with the observations.

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