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Are drivers of northern lights in the ionosphere?

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Abstract

It is reported that transverse electric fields penetrating the ionosphere either from distant space or from the upper atmosphere produce charge separations along the field lines by building up positive charges immediately above the ionosphere. Those parallel electric fields produced by the charge separation deserve auroral driver. This paper discusses why and how these internal drivers in the polar ionosphere are applied for the formation of spiral auroras in the dusk sector.

1. Introduction

Known as northern lights, spiral auroras with scale size from 1 km to several hundred km in the polar ionosphere are distinct features of substorms. These auroras are classified as discrete auroras generated by energetic electrons accelerated along the field lines. To explain these spiral patterns, two models are proposed according to rotational direction of the spirals, counterclockwise or clockwise viewed along the field lines. One is a current sheet model of auroras where current sheets originating in the magnetosphere twist along the field lines to show winding auroras at ionospheric altitudes [Hallinan, 1976; Partamies et al., 2001; Keiling et al., 2009]. Spirals are counterclockwise viewed along the field lines in the upward field aligned current region. The second is a charge sheet model where negative charge excess in the ionosphere causes spirals rotating clockwise, opposite to the current sheet model [Hallinan and Davis, 1970; Oguti, 1974]. The second model seems to violate the Gauss's law, because upward electric fields have negative potential regions at their footprint. To resolve this seeming paradox, the ionospheric injection scenario is applied [Saka, 2023].

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2. Quasi-neutral equilibrium solutions of the parallel electric fields (steady-state approximation)

Figure 1 shows vertical profiles of electrostatic potential generated above the ionosphere by the narrow negative charge sheet. The charge sheet is due to local accumulation/rarefaction of electric charges in the E-layer produced by external electric fields penetrating the polar ionosphere [Saka, 2021]. The vertical component of electric fields generated by the negative charge sheet displaced the mirror height of electrons to higher altitudes, causing a buildup of positive charges immediately above the ionosphere and negative charges in the magnetosphere [Saka, 2023]. Such charge separations along the field lines produced parallel electric fields. On the ground, those potential variations in the ionosphere may be observed as a change of atmospheric electric field in the global current circuit of the ionosphere-atmosphere-earth system [Tinsley et al., 1998].

Parallel electric fields influence temperature anisotropy of particles by changing their pitch-angle. Disparity in temperature anisotropy between species sustains steady-state parallel electric fields as quasi-neutral equilibrium solutions [Alfven and Falthammar, 1963; Persson, 1963, 1966]. For the case of upward electric fields, perpendicular temperature anisotropy of electrons ($T_{e\perp} > T_{e//}$) exceeds that of ions at any point of B. Upward electric fields thus produced by a narrow negative charge sheet constitute 1-D inverted-V above the ionosphere (Figure 2). Generation of upward electric fields above the negative charge sheet is analogous to a battery connected in series to a negative electrode in the ionosphere.

The parallel electric fields may persist until charge separation along field lines is discharged due to reduction of perpendicular temperature anisotropy of electrons by pitch-angle diffusion of electrons [Kennel and Petschek, 1966]. Discharge may occur locally and intermittently accompanying auroral precipitation. Such correlations are reported in the paper titled “Hiss emitting auroral activity” [Oguti, 1975a]. Flux tube filling perpendicular temperature anisotropy of electrons corresponds to area in polar ionosphere having higher occurrence probability of aurora. Those areas are a part of auroral oval. If expansion speeds of the discharge in the flux tube remain much the same after onset, the lifetime of the spiral auroras is linearly proportional to the scale size of the flux tube, shorter for smaller size and longer for larger size. According to Oguti (1975b), expansion speeds range in 6-8 km/s independent of their scale size from 1 km to 1000 km. Parallel electric fields vanish when perpendicular temperature anisotropy of electrons become equal to that of ions at any point of B.

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3. Clockwise spirals

We apply this ionospheric driver scenario to explain typical spiral auroras winding clockwise in the dusk sector. Those are known as "S-shaped structure" [Oguti, 1975b]. First, we assume precipitating electrons due to a discharge produced narrow sheet (1-D) of ion holes at the footprint of inverted-V potential. Because longitudinal extent of the ion hole is limited, electric fields converging in the center of the sheet develop along the sheet. Figure 3 depicts amplitude profiles of electrostatic potential (Φ), electric fields (E), and density difference between ions and electrons ($n_i - n_e$) in the ion hole. *X* denotes a distance from the center of the hole. Amplitudes of Φ, E, $n_i - n_e$, and distance *X* are in arbitrary scale. The ion hole ($-40 < X < 40$) is composed of electron rich regions ($n_e > n_i$) in $-27 < X < 27$ and ion walls ($n_i > n_e$) peaked at *X* = -37, 37. Total charges of ions and electrons are balanced. The profile of the density difference ($n_i - n_e$) is integrated with *X* to calculate electric fields and electrostatic potentials. It is assumed that this potential structure was retained for some time (~ 1 min), because ion holes are continuously produced by the discharge.

A winding motion of auroral sheet is caused by the space charge fields in the ion hole through ExB drift. The sequence of activities is believed to include: (1) exit motion of inverted-V potentials followed drift motion of auroral sheet, (2) one dimensional potential profile of ion hole in Figure 3 is conserved during the winding motion, and (3) ion rich region appears at the edge of the ion hole to maintain charge balance. The results are shown in Figure 4 in which auroral sheet rotated clockwise around the center viewed in a direction parallel to the background field lines. Auroral sheet developed expanding in length during rotation and left folding pattern at the center. Clockwise motions at the center reproduce "Curls" of charge sheet [Hallinan and Davis, 1970] or "Trailing rotation" [Figure 2b in Oguti, 1974]. A clockwise flapping motion of narrow auroral sheet may correspond to the "Flame-structure formation" in a rotation of the flame trains [Figure 5 in Oguti, 1975b], "Clockwise turning-over" in the process of poleward expansion of aurora [Figure 2 in Oguti, 1981], and "Splitting-fold over deformation" of a discrete arc in small-scale [Figure 3 in Oguti, 1981]. Figure 5 depicts twist motion of the auroral sheet in a background arc. The rotating arc in the background yields characteristic deformations referred to as "Splitting followed by rotational unfolding" of a discrete arc [Figure 1 in Oguti, 1978].

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4. Summary and discussion

Because of rotational symmetry deformation of small- and large-scale S-shaped spirals at a constant speed (6~8 km/s), it has been suggested that common physical processes may explain the deforming processes involved [Oguti, 1975b]. The internal processes of the polar ionosphere referred to as ionospheric injection partly correspond to common physical processes.

Required conditions for this ionospheric driver scenario generating substorm auroras are the ionosphere itself as well as transverse electric fields, originating either from distant space (field line dipolarization) or from the upper atmosphere (neutral winds). The ionospheric driver scenario proposed can accordingly be applied to any planets in the Solar system.

It is shown that auroral deformations starting with a splitting of the auroral arc that are referred to as S-shaped structures can be adequately explained by the ionospheric driver scenario. However, an ionospheric driver scenario may not be equally applicable to spiral auroras starting with a folding of the auroral arc (current sheet model). In that case, a magnetospheric driver scenario may be appropriate. Developed spiral forms are identical in both scenarios. To distinguish between the two scenarios in substorm auroras, deformation processes should be carefully examined to determine whether spiral auroras start with a folding of the auroral arc or a splitting of the auroral arc (Figure 6).

5. Data availability

No data sets were used in this article.

6. Competing interest

The author declares that there is no conflict of interest.

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Figure captions

Figure 1
Electrostatic potentials produced in vertical planes (X-Y, Z=0) and (X-Z, Y=0) by negative charge sheet in the ionosphere (Y-Z plane). Scales are arbitrary. Potential increases radially outward from the center of the sheet or with altitudes (X). The sheet is narrow in Z, 10% of Y. Green bars denote extent of negative charge sheet in Y (upper panel) and in Z (lower panel). Vertical component of the electric fields produces positive charge immediately above the ionosphere.

Figure 2
Inverted-V (battery) connected in series directly to the ionosphere (negative electrode). Ionospheric potential beneath the inverted-V is assumed to be negative, and 0 volt in the surroundings. Inverted-V potential is consisted of steady-state parallel electric fields. Auroral precipitations are due to discharge of the steady-state parallel electric fields, occurring locally and intermittently in the inverted-V. Precipitations create ion holes in the ionosphere (see Figure 3).

Figure 3
One dimensional ion hole in X represents auroral sheet. The ion hole model is applied to the auroral sheets independent of their scale size. Electric field profile marked by dotted arrow is used in Figure 4 to show a twist motion of the auroral sheet.

Figure 4
Clockwise rotation of auroral sheet. The auroral sheet initially in the east-west directions in black (T=0) deformed to red (T=Δt)), green (T=2Δt), blue (T=3Δ), and to purple (T=4Δt) in X-Y plane. X is east and Y is north. These motions were caused by the space charge fields in the ion hole through $E_\perp \times B$ drift.

Figure 5
Rotating motion of auroral sheet in background arc. Auroral sheet is marked in Black in the pre-existing background auroral arc (Light Cyan). Auroras are void in the white area

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removed by the rotating exit. Background arc was split while the exit rotated clockwise from (A) to (B). Unfolding deformation follows (C) through (E) and is finally released in (F), and (G). Sequence of the auroral sheet deformations from split of background arc, pleat unfolding, and its release referred to as “Splitting-unfolding deformation of auroral pleat” are illustrated in the right-bottom corner [adapted from Oguti, 1975b].

Figure 6

(A) Deformation of spiral auroras starting with splitting of auroral sheet. (B) Deformation of spiral auroras starting with folding. Initial auroral forms associated with splitting and folding are shown in red. In (A), auroral sheet twists clockwise viewed in a direction parallel to the field lines. In (B), auroral sheet rotates counterclockwise. Developed auroral sheets in blue are identical for (A) and (B).

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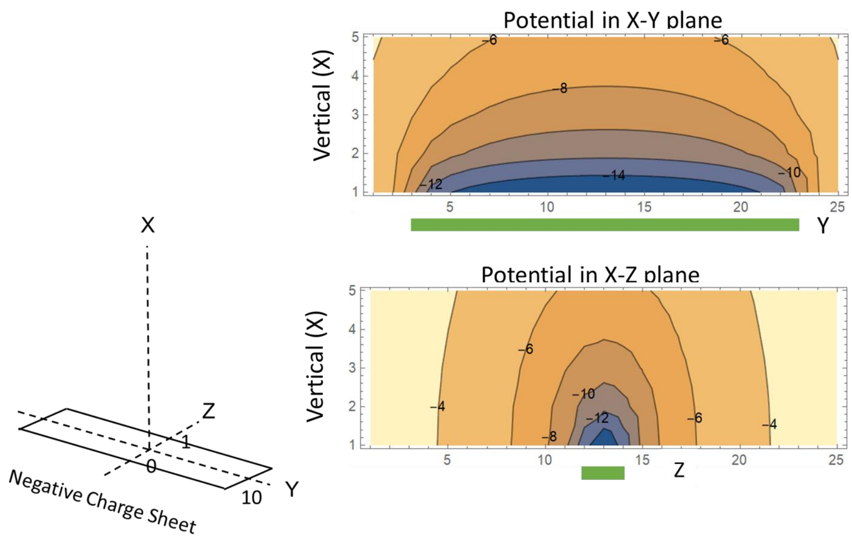

Figure 1

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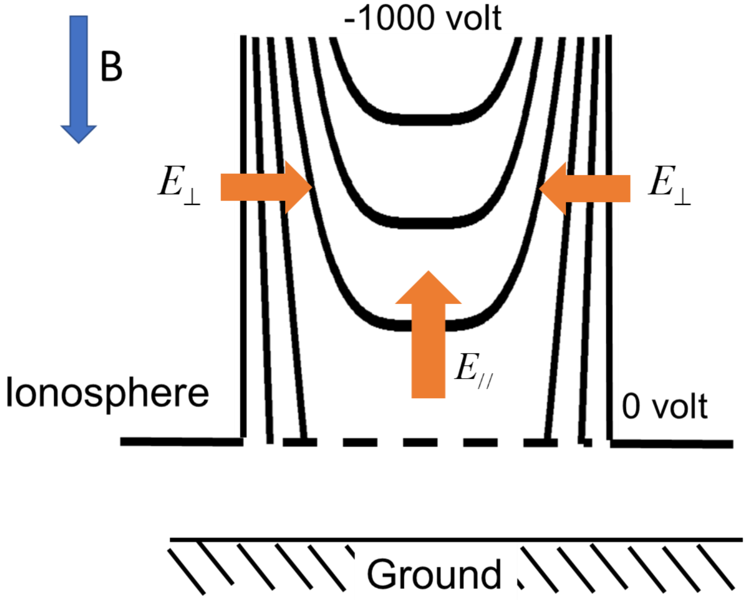

Figure 2

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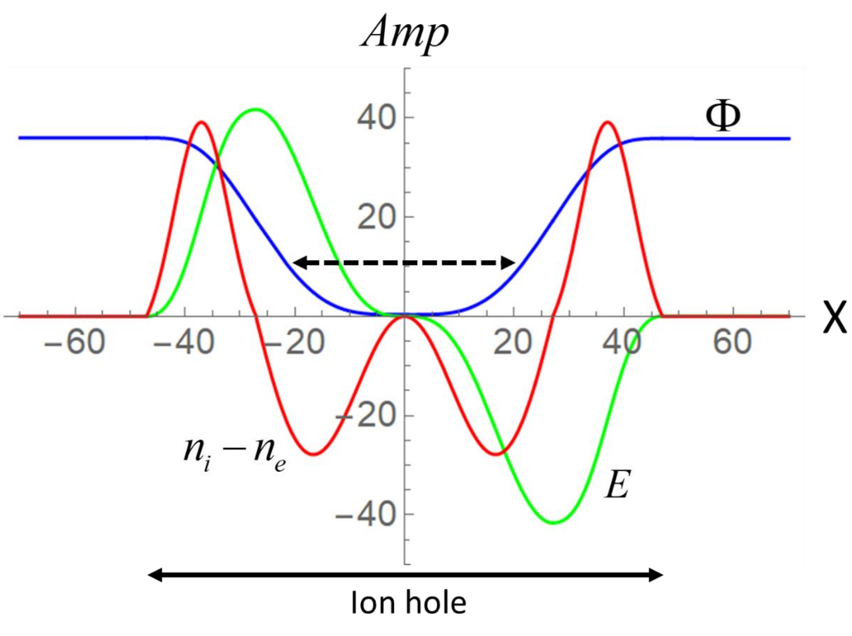

Figure 3

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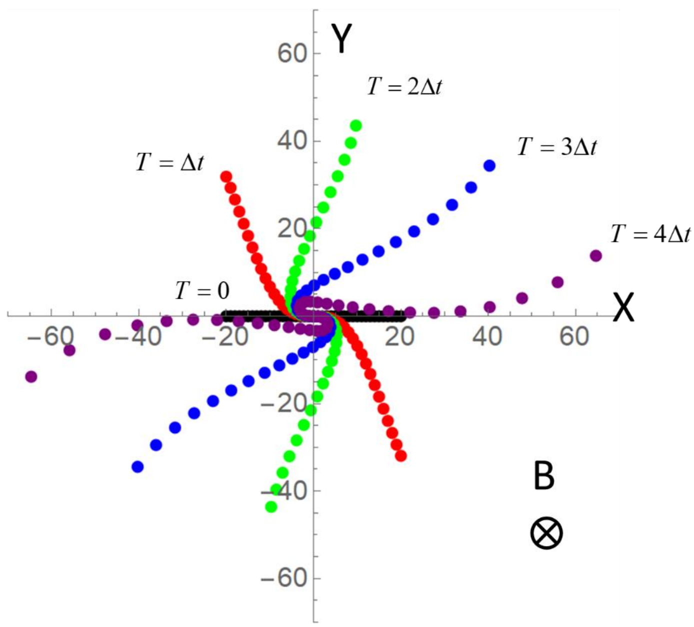

Figure 4

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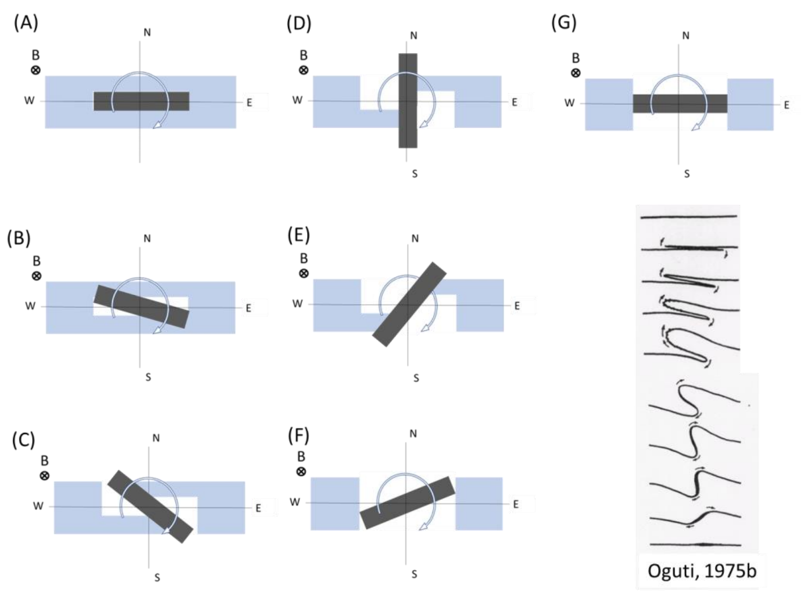

Figure 5

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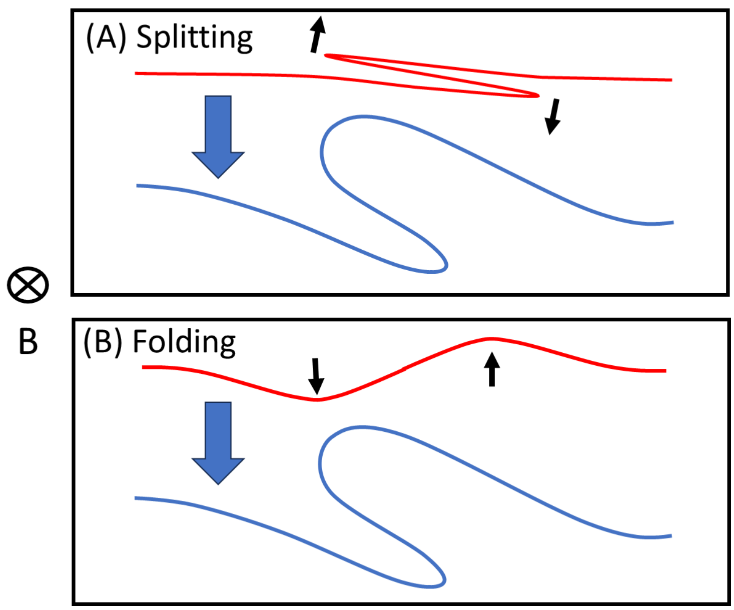

Figure 6