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Are drivers of northern lights in the ionosphere?

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Abstract

We modeled an auroral arc as a negatively charged solitary potential area created by incident energetic electrons in the polar ionosphere. Those negative potential structures are often called ion holes wherein trapped electron populations are denser at the center than at the rim. When an ion hole becomes a sheet-like structure (auroral arc), shear flows are generated in the arc at a right angle to the arc alignment. Shear flows develop twist motion of the sheet into spiral auroras. To maintain spiral motions in the aurora, electron beams follow the auroral motion. This conjunction infers that ion hole in the collisional ionosphere is auroral driver itself.

1. Introduction

Known as northern lights, spiral auroras ranging in 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 incident energetic electrons that are accelerated along the field lines by parallel electric fields. Two spiral types are reported in the literature according to rotational direction when viewed along the field lines, counterclockwise (CCW) and clockwise (CW). However, opposite rotations in discrete aurora are not well understood [Haerendel, 2006]. The former type (CCW) is interpreted by wave polarizations where flux tubes containing upward field-aligned currents twist along the field lines to show winding auroras at ionospheric altitudes [Hallinan, 1976; Lysak and Song, 1996; Partamies et al., 2001; Keiling et al., 2009]. The second type (CW) is called the S-aurora where auroral vorticities are released by unfolding the degenerated pleat in clockwise directions that are counter to the first type [Oguti, 1974, 1975a, b]. We suggest that the unfolding processes are composed of twist, splitting, and rotation of the auroral arc. In this report, we regarded auroral arc as negatively charged solitary area in the polar ionosphere or an "ion hole." Those ion holes are not solitary waves caused by plasma kinetics in the collisionless plasmas [Temerin et al., 1983; McFadden et al., 2003] but rather solitary structures generated in collisional

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ionosphere by precipitating energetic electrons. Model of ion hole is presented in section 2. The parallel electric fields associated with ion hole are discussed in section 3. Twist motion of ion hole is simulated in section 4. Summary is included in section 5.

2. Ion hole model for auroral arc

In this section, we discuss how incident energetic electrons associated with particle precipitations generate a solitary area in the polar ionosphere with negative potentials, i.e., an ion hole. First, we assume that stop altitudes of the incident energetic electrons (2 - 10keV) range from 100km to 150km, where green (O; 557.7 nm) and blue (N_2^+; 427.8 nm) emission lines are activated to display auroras with lifetimes of 0.7s and 70 μs, respectively [Oguti, 2010]. The stop altitudes also correspond to a thin layer of collisional ions and collisionless electrons, often referred to as an ionosphere. At this stop altitude, incident energetic electrons produced negatively charged potentials composed of primary and secondary electrons. Some of those electrons peaked at the ionospheric altitudes and escaped outward along the field lines by a magnetic mirror force through the potential barrier. Meanwhile, collisional ions in the ionosphere are accumulated horizontally to confine these negative potential areas. The potential structure consistent with the ion hole is generated in the polar ionosphere, where trapped electron populations are greater at the center than at the rim. Electron populations initially peaked at the center may spread outward to the ion boundaries to minimize the entire electric field energy in the ion hole (Thomson's theorem, see below for one-dimensional case). Consequently, electric fields show peak amplitudes at the outer boundary of the negative potential structure with null amplitudes within the hole.

Electrons are subject to ExB drift at the outer boundary of the ion hole. The closed trajectory of electrons is shown in Figure 1(A) in black for axisymmetric two-dimensional case. Flow directions are marked by solid arrows. No residual of electron drift appears within the ion hole (complete ion hole). In Figure 1(B) we present the case where a complete ion hole forms a sheet-like structure expanded in longitudes. Sheet-like ion hole is divided into six circles along the principal axis with equal amplitudes. Electrons flowing along the outer boundary of the ion hole potential generate no residuals. Meanwhile, we present in Figure 1(C) the case where converging electric fields are produced in the ion hole by continuing precipitations. Converging electric fields along the principal axis (X) disrupt electron flows into six circles with varying amplitudes (incomplete ion hole). Residual flows are generated at the overlapped portion of the circle in the direction perpendicular to the principal axis as shown by solid arrows in red. Those shear flows twist the principal axis of the sheet. We considered two cases of the sheet-like ion hole, complete ion hole in Figures 1(B) and incomplete ion

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hole in Figure 1(C). Entire electric field energies of the arc defined by equation (1) are lower for the complete ion hole than incomplete ion hole. This difference may be related to the activity of the auroral arc. Electric field energy becomes low if the activity is past its peak. The sheet-like ion hole can be regarded as one-dimensional (1D) ion hole. In this case, residual flows can be given by the derivative of the electric field in X as will be discussed in section 4.

We discuss how electrons redistribute themselves in the ion hole to minimize electric field energies in accordance with the Thomson's theorem by using the 1D ion hole model. They initially peaked at the center, X=0 (Type 1 in Figure 2). Electrostatic field profiles in the bottom panel indicate converging electric fields with opposite peaks at both sides. In the following steps, electron populations distribute uniformly and they finally have two peaks at the edge of the arc (Type 2 and Type 3). Electric field energies U in the arc can be given by

$$U = \frac{\varepsilon_0}{2}\int E^2 dv \,. \qquad (1)$$

Here, ε_0 is dielectric constant in vacuum, and E is electric field intensity along X. Integration was carried out over X. The entire energy U of the arc decreased as electrons expand outward to approach ion boundaries (Type 2 and Type 3), because electric field amplitudes sharpen with opposite polarities peaking at the edge of the arc and null amplitudes expand in the middle of the arc. Electric energy U for Type 2 and Type 3 are 60% and 40% of that of Type 1, respectively. It is supposed that auroral arc is consistent with the Type 3 case. However, this pattern may be maintained while energetic electron precipitation continues.

3. Comments on parallel electric fields

It is understood that discreate aurora in the polar region are caused by energetic electrons accelerated by quasi-static parallel electric fields in a low altitude acceleration region [Carlson et al., 1998]. Unless quasi-static parallel electric fields vanish above the ionosphere or upward electric field region is not isolated from the ionosphere, negative space charge potential emerging in the ionosphere (ion hole) from the electron precipitation violates the Gauss's law. To isolate the low altitude acceleration region from the ionosphere (i.e., $E_{//}$=0 and $E_{\perp}$=0 above the ionosphere), the acceleration region should be a type of electrostatic double layer (DL) composed of positive ions earthward and negative electrons tailward in large-scale DL [Schriver and Ashour-Abdalla, 1993; Ergun et al., 2000; Saka, 2023] and in a band of small-scale DLs [Temerin et al., 1982; Bostrom et al., 1988]. From satellite

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observations, the lowest altitudes of the acceleration region are suggested to be 1100km, below which $E_{//}$ and $E_{\perp}$ associated with electrostatic shock vanish [Mozer, 1980]. This condition also enables continuity of ionospheric currents via field-aligned currents; i.e., upward field-aligned currents carried by upward parallel electric fields close via diversion of the Pedersen current originating in the negative potential region.

4. Twist motion of the 1D auroral arc

We discussed in section 2 how charged particles redistribute themselves along the arc to minimize entire free energy (Thomson's theorem) in a one-dimensional model of the auroral arc. The solution shows a converging electric field along the principal axis (arc alignment) with bimodal electron density profiles. Those parameters (charge distributions, electric fields, and electrostatic potential) consistent with the ion hole are again summarized in Figure 3. Electron populations are fully separated into positive X and negative X regions with null amplitude at X=0. Electric fields have a flat shelf with null amplitudes in the middle of the arc ($-5 < X < 5$).

Residual flows of electrons occur perpendicular to the arc alignment (Figure 4(A)). The amplitude of residual flow is proportional to the spatial gradient of the electric field intensity along the arc alignment ($\nabla_X |E|$), with a drift in the direction of $\tilde{E} \times \tilde{B}$. Here, $\tilde{E}$ and $\tilde{B}$ are unit vector of converging electric fields and background magnetic fields, respectively. There are two peaks in $-27 < X < 27$, positive and negative residuals in $X < 0$ and $X > 0$, respectively. There are no residuals out of these regions, because auroral electrons (primary + secondary) are confined in this limited region.

Assuming that the principal axis of the arc is subject to the electron drift defined by $\nabla_X |E| (\tilde{E} \times \tilde{B})$, motion of the 1D arc is simulated in Figure 4(B). We can divide the 1D ion hole into three regions in terms of its rotational direction. It is separated by the peaks of the residuals at X=-17 and 17. In the central part, -17<X<17, the principal axis twist clockwise, while for the right-hand side and left-hand side of the ion hole, the principal axis rotates counterclockwise. Motion of the principal axis is initiated by a peeling-off (T=0 to T=Δt) at X=-17 and at X=17, though a sharp twist (multiple arc) remains at the central part as marked by the rectangle in red. This is because of null amplitudes of the electric fields due to full separation of electron populations in the middle of the arc. These kinks at the central part

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may be released on the contrary by resolving full separation of the auroral electron populations by violating the Thomson's theorem. Or they may develop as clockwise spirals referred to as "curl" [Hallinan and Davis, 1970] and "trailing rotation" [Oguti, 1974].
The ion holes are approximated by two-dimensional negatively charged solitary areas created in the polar ionosphere. Meanwhile, a leakage of the vertical electric fields may occur above and below the ion hole. Vertical electric fields below the ion hole may be observed in the global current circuit of the ionosphere-atmosphere-earth system as negative potential regions in the ionosphere [Saka, 2021]. Vertical electric fields above the ion hole (downward electric fields) displace the mirror height of the trapped hot electrons to higher altitudes. This effect increases the upward parallel electric fields immediately above the ionosphere [Saka, 2023]. Consequently, we conclude motion of the ion hole may displace the electron beams to follow the ion hole drift. Due to a short lifetime of auroras less than 0.7s, electron beams following the ion hole refresh the twisting auroral arc. Spiral auroras are due to motion of incident energetic electrons synchronized with the drift of the arc. Or we conclude simply that ion hole is ionospheric driver of spiral auroras.

5. Summary

It is assumed that pre-activated magnetosphere accelerates primary electrons to generate negatively charged solitary potential area in the polar ionosphere. Those areas act as auroral driver and simultaneously twist, split, and rotate clockwise to form spiral auroras.

6. Acknowledgements

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7. Data availability

No data sets were used in this article.

8. Competing interest

The author declares that there is no conflict of interest.

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Figure Captions

Figure 1

(A) Axisymmetric two-dimensional ion hole viewed along the magnetic field direction. Blue circle indicates a limit of ion hole potential. Electric fields vanish beyond this limit. Closed circle in black denotes electron trajectories flowing in the direction of ExB drift (solid arrows) along the peak of electric field intensity at the outer boundary of electron populations. There appear no residual flows in the electron drift (complete ion hole).

(B) Complete ion hole shown in (A) is expanded in longitude to form sheet-like ion hole. The sheet-like ion hole is separated into six circles in X. There appeared no residual flows in the electron drifts.

(C) Same as (B) but electrostatic potential in the ion hole has minimum peaks at the center consisted of converging electric fields in X and in Y. Potential gradient in X breaks drift of electrons along the outer boundary of ion hole potential into six circles with varying intensities. These are depicted by thick and thin circles. Residual flows perpendicular to the principal axis appear at the overlapping portion of the circle as depicted by solid arrows in red (incomplete ion hole). They form shear flows at a right angle to the sheet.

Figure 2

One dimensional model of ion hole. “n” denotes number density of charged particles. Electrons (primary + secondary) marked by gray color peaked at the center of the arc (Type 1). Ionospheric ions (orange) at both ends confine electric fields E shown in the bottom. To minimize electric field energy U, electrons may spread in X to distribute uniformly (Type 2). Electron distribution further spread in Type 3 to decrease the field energy U.

Figure 3

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Distribution of electrostatic potentials (Φ, black dot), electric fields (*E*, black solid), and density difference between ions and electrons ($n_i - n_e$, red) in one dimensional ion hole model. X is in arbitral scale. Peaks of the negative charge (n_e) is separated in X, consistent with "Type 3" in Figure 2. Although they show a converging electric field pattern, the field intensity is null in the middle of the arc due to full separation of electron populations.

Figure 4

(A) Typical potential structure of 1D ion hole (Φ) same as in Figure 3. Residual drift of electrons ($\nabla_X |E|$) is overlayed.

(B) Twist motion of principal axis of the 1D ion hole. The principal axis initially in the east-west directions in blue (T=0) deformed to orange (T=5Δt) and to black (T=8Δt) in X-Y plane, where X is east and Y is north. Principal axis expands to both hemispheres. At the central part of the ion hole marked by a red rectangle, spiral auroras with a clockwise twist are generated. Twist motions are enlarged in the inset at the right.

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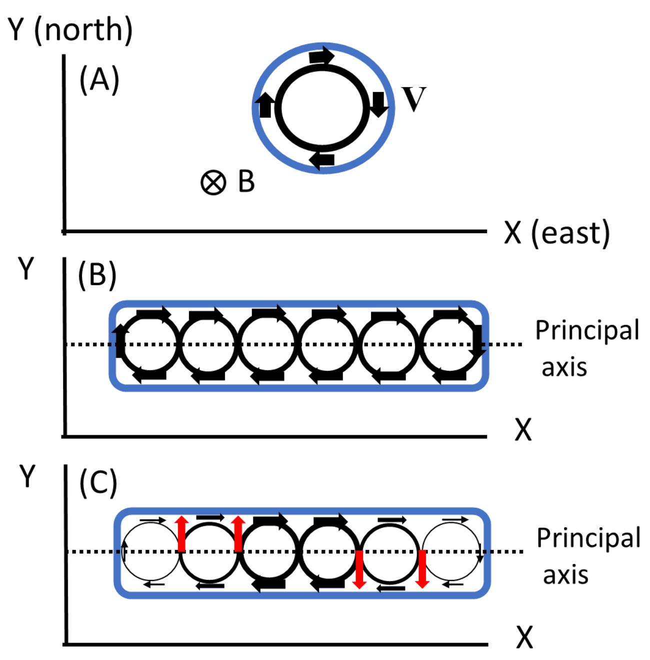

Figure 1

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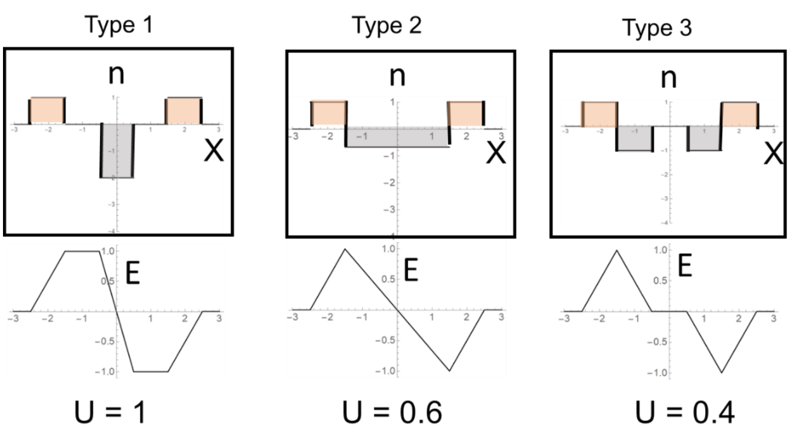

Figure 2

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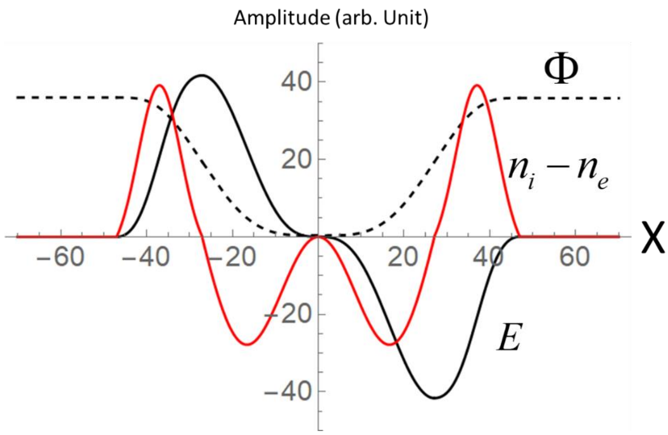

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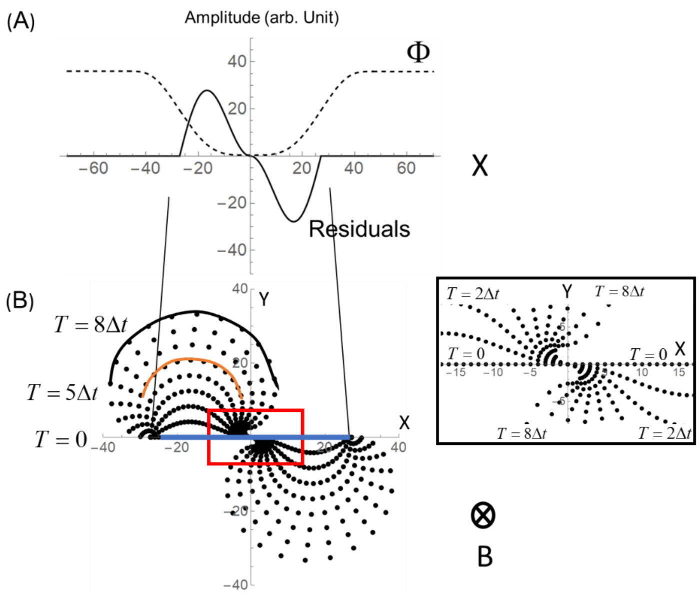

Figure 4