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Are drivers of northern lights in the ionosphere?

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Abstract

Known as northern lights, auroral spirals are distinct features of substorm auroras composed of large-scale spirals (100s km Surges) mixed with smaller scale ones (10s km Folds, and 1 km Rays). Spiral patterns are generally interpreted in terms of the field line mapping of the upward field-aligned currents produced in the magnetosphere during the field line dipolarization. The field line mapping results in opposing spiral rotations of small- and large-scale auroras. Because of a rotational symmetry deformation and similarity in deformation speeds (6~8 km/s) of small- and large-scale spirals, it has been suggested that common physical processes may underlie the deforming processes. Internal processes in the polar ionosphere (ionospheric driver) will be proposed as the general dynamic for spiral auroras. The ionospheric driver rotated in the ionosphere to produce spirals that characteristically differ from the field line mapping scenario.

1. Introduction

Decades of ground-satellite observations of auroras using imagers, magnetometers, and onboard particle and field detectors revealed that a primary driver of auroras associated with the substorms is in the magnetosphere. It has been recently suggested that an arrival of Bursty Bulk Flows [Angelopoulos et al., 1992], Dipolarization Front [Runov et al., 2011], and Plasma Bubbles (low entropy flux tubes) [Sergeev et al., 1996] from the tail may alter convection patterns in the midnight magnetosphere to initiate onset auroras, such as poleward boundary intensification, streamers, beading of the onset arc, and auroral bulge. Spiral forms in the auroral bulge ranging from small spatial scale (Rays, 1 km) to large (Westward Traveling Surges, 100s km) are distinct auroral forms associate with the dipolarization onset. In the magnetospheric driver scenario, auroral forms observed in the polar ionosphere are determined by the field line mapping [Borovsky, 1993; Stenbaek-Nielsen et al., 1999; Forsyth et al., 2020]. Due to a twist of the flux tubes by the upward

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field-aligned currents, auroral motion in spirals would show counterclockwise rotations viewed in a direction parallel to the background magnetic fields as proposed by the current sheet model [Hallinan, 1976; Nikolaev et al., 2015].

Meanwhile, negative charge excess, charge sheet deposited by auroral electron precipitations, or electron beams produced an opposite rotation of the spiral auroras [Oguti, 1974; 1978; Hallinan, 1970]. The charge sheet model was applied to small-sale spirals (Rays), while large-scale spirals are supposed attributable to the current sheet model [Hallinan, 1976]. Oguti (1975) however argued that the similar deformation processes among small and large-scale spirals suggest that general dynamics may produce small to large scale sizes. Oguti (2010) described spiral auroras in the auroral bulge as a whole "S-fractal manifold aurora".

To explain consistent rotations from small-scale to large-scale spirals, we propose the existence of internal processes in polar ionosphere which generate substorm auroras. This new scenario is referred to as ionospheric injection [Saka, 2019, 2021] and is summarized in Sect. 2. In Sect. 3, the ionospheric injection scenario will be adopted to explain spatial scale size, shapes, rotation, growth time, and potential drop associated with the spiral auroras. In Sect. 4, example of large-scale spirals triggered by the onset of field line dipolarization is presented. Summary and discussion of this scenario is given in Sect. 5.

2. Summary of ionospheric injection scenario

The ionospheric injection is first triggered by westward electric fields transmitted from the convection surge in the magnetosphere in association with dipolarization onset. In the E-layer, localized westward electric fields yield electron accumulation (negative charge region) in lower latitudes while ions are left behind (positive charge region) in the higher latitudes because of differing electron and ion mobility in the E-layer. Local breakdown of the charge neutrality in the ionosphere may immediately feedback to the magnetosphere by imposing imbalance in distributions of ions and electrons along the field lines. This imbalance can be understood by attracting ions (electrons) earthwards and repelling electrons (ions) tailward along the field lines by the appearance of negatively (positively) charged regions in the ionosphere. As a result, parallel electric fields directing upward (downward) are produced along the field lines from negatively (positively) charged regions in the ionosphere. The evaporations of ions (electrons) from negatively (positively) charged regions associated with parallel electric fields would interrupt the perfect neutralization of the ionosphere by the Pedersen currents but achieve quasi-neutral equilibrium of the ionosphere.

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Cold plasmas thus evaporated from the polar ionosphere are transported along the dynamical trajectories to the magnetosphere conserving the total energy (including electrostatic potentials) and first adiabatic invariant. However, ions/electrons traveling in accelerating potential gradients lose perpendicular and lower velocities in parallel component, leaving only the energetic part of ionospheric plasmas collimated along the field lines. While for ions/electrons traveling in the potential barrier, they do not change original pitch angle distributions and energies in the ionosphere. In the magnetic mirror geometry, pitch angle anisotropies of evaporated ions/electrons further develop initial potential gradients along the field lines. The potential drop would develop to retain sufficient energies for driving auroral precipitations in low altitude acceleration regions. Auroras are excited locally in the negatively charged regions, and black auroras are from positively charged regions in the ionosphere. Negatively charged and positively charged regions in the ionosphere correspond to electron rich and ion rich regions and are referred to as ion and electron holes, respectively.

3. Modeling the northern lights

An auroral sheet expanding in east-west directions appears at the low-latitude end of the flow channel created by the westward component of transient electric fields. The auroral sheet can be interpreted as 1-D ion hole along longitudes. Because longitudinal extent of the sheet is limited, perpendicular electric fields converging in the center of the sheet develop. Figure 1 depicts amplitude profiles of electrostatic potential (Φ), electric fields (E), and density difference between ions and electrons ($n_i - n_e$) in the sheet. *X* denotes a distance from the center of the sheet. Amplitudes of Φ, E, $n_i - n_e$, and distance *X* are in arbitrary scale. The sheet ($-40 < X < 40$) is composed of electron rich regions ($n_e > n_i$) in $-27 < X < 27$ and ion rich walls ($n_i > n_e$) peaked at *X* = -37, 37. Total charges of ions and electrons are balanced in the sheet. The electron rich regions did not uniformly expand but have two peaks at *X* = -18 and 18, because converging electric fields transported electrons towards the ion rich walls at *X* = -37, 37, though the velocity was two orders of magnitudes smaller than the ExB drift at 100km in altitudes [Kelley, 1989]. 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 arriving transient electric fields.

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A winding motion of auroral sheet is calculated in $-20 < X < 20$ through ExB drift using convergent electric fields and magnetic fields pointing downward (northern hemisphere). It is assumed that (1) one dimensional potential profile in Figure 1 is conserved during the winding motion, (2) the auroral acceleration region follows the motion of ion holes, (3) there are no auroras in ion rich regions. The results are shown in Figure 2 in which auroral sheet rotated clockwise around the center viewed in a direction parallel to the background field lines. Auroral sheet developed expanding its length during rotation and left folding pattern at the center. Growth time of the spiral aurora (Δt) can be given by, $\Delta t = r / v$. Here, *r* is scale size of the spiral aurora, and *v* is convection velocity defined by electric field drift. For the small-scale Rays (*r* = 1km), the growth time could be estimated to be 0.125 sec for drift velocity of the order of 8 km/s [e.g., Oguti, 1975], while for large-scale Surges (*r* = 1000km), the growth time increased to 125 sec (2.1 min) with the same electric field intensity (E = 400mV/m at V=8 km/s). Electric field intensities independent of the scale size of spiral aurora suggest that the converging electric fields in the auroral sheet are effectively shielded by the positive potential barriers peaked at X = -37, 37. For the converged electric fields with mean amplitudes of the order of 0.2V/m, the potential drop for the small-scale Rays (*r* = 1km) could be 100V, while for the large-scale Surges (*r* = 1000km) the potential drop could be 100kV in the polar ionosphere.

The winding forms of the auroral sheet was affected by the potential profiles in auroral sheet. For the case where electron rich regions have a single peak at the center (*X* = 0), winding motion that resembled jetting from the rotating nozzle was obtained (not shown).

4. Large-scale spirals

An example of large-scale spirals in all-sky image observed at 0331:00 UT 02 Jan 1986 in northern hemisphere (SHM; 55.9N, 267.9 in geographic coordinates) is presented in Figure 3 (adapted from Saka et al. (2012)). Multiple shear layers constituting the Westward Traveling Surge extended about 750 km in longitudes and 450 km in latitudes. It developed in the all-sky image following the onset of field line dipolarization at 0330:36 UT in magnetometer data at geosynchronous orbit. Shear layers were bounded at poleward boundary by poleward boundary aurora surge (PBAS) propagating eastward (solid arrow). Motions of shear layers are consistent with the spiral arms rotating clockwise in poleward latitudes as shown in Figure 2. Spiral arms in equatorward latitudes were not observed in this field-of-view. PBAS is an auroral manifestation of the flow shear in the midnight magnetosphere produced by the onset of field line dipolarization [Saka et al., 2012].

5. Discussion and Summary

The ionospheric injection scenario adequately explains the clockwise deformation of auroral arcs in auroral bulge regardless of scale sizes. Parallel electric fields pointing upward originated from the ion holes would draw upward field-aligned currents. Current sheet model may not be applicable to the ionospheric injection scenario, because drivers (ion holes) rotated in the polar ionosphere to produce spiral auroras not subject to field line mapping. The ionospheric injection scenario is consistent with the charge sheet model, though ion holes were not produced by the electron beams but rather by the evaporation of cold ions. The longitudinal scale size of ion holes may be determined by the longitudinal width of the equatorward flow channels created by the transient electric fields. In large-scale channels extending 100s km in east-west direction, smaller scale channels may be embedded to generate meso- and small-scale spirals.

6. Data availability

No data sets were used in this article.

7. Competing interest

The author declares that there is no conflict of interest.

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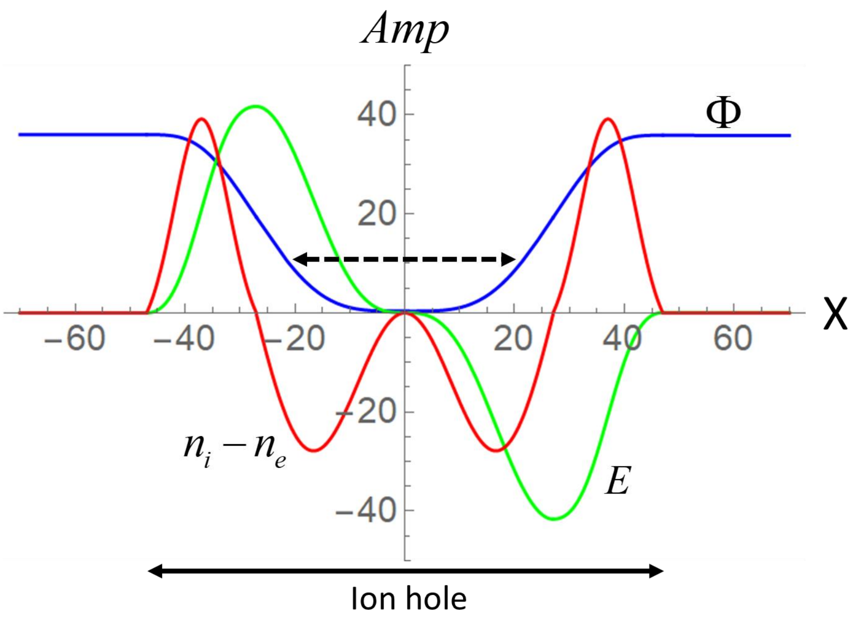

Figure 1

Distribution of electrostatic potentials (Φ, blue), electric fields (E, green), and density difference between ions and electrons ($n_i - n_e$, red) in one dimensional ion hole model. X is positive eastward. Winding motion of the negative potential region marked by dotted arrow is shown in Figure 2. See text for details.

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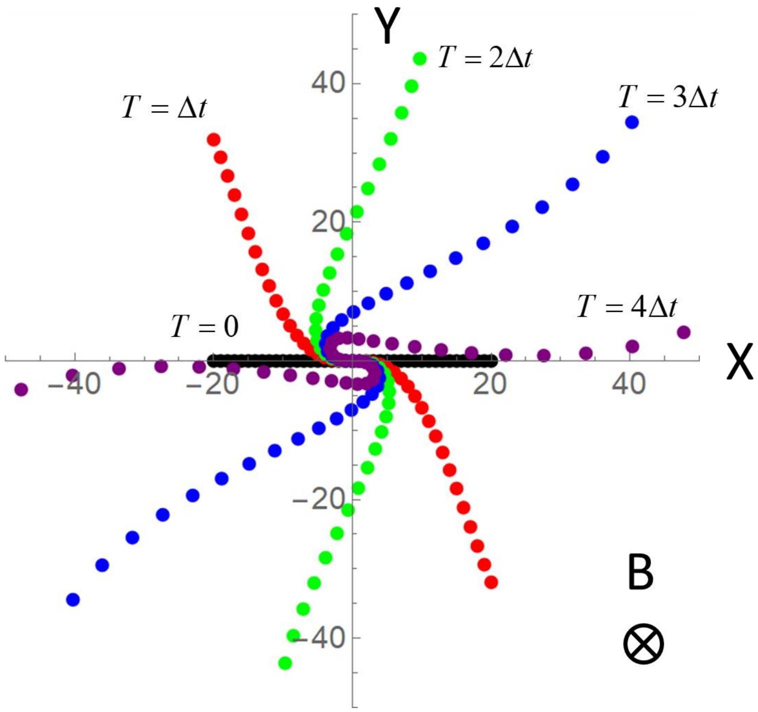

Figure 2

217 The auroral sheet initially in the east-west directions in black (T=0) deformed to red (T=Δt)),
218 green (T=2Δt), blue (T=3Δ), and to purple (T=4Δt) in X-Y plane. X is east and Y is north.
219 The ExB drift rotated each element of the auroral sheet represented by dots clockwise
220 viewed in a direction parallel to the background field lines. Direction of magnetic fields is
221 into the page.

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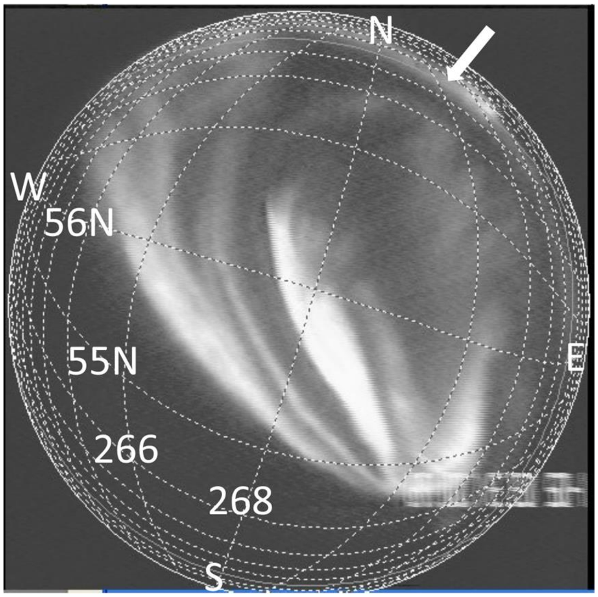

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Figure 3

All-sky image viewed from above the ionosphere for dipolarization event taken at 0331:00 UT in northern hemisphere, following the dipolarization spike at 0330:36 UT at geosynchronous orbit. Grids in the image are geographic longitudes and latitudes, nearly parallel to the geomagnetic coordinates. Grid separation 2 degrees in longitudes is 125 km along 56N and 112 km for one degree in latitudes. Poleward arrow denotes PBAS. See text for details.