Author Reply to Referee 1

Each issue has been addressed in the Comment/Response format.

Comment1

Could you please provide references that field-line mapping results in opposing spiral rotations of small and large scale auroras.

Response

Hallinan, T.J., Auroral spirals 2 Theory, J. Geophys. Res., 81, 3959-3965, 1976.

Comment2

If I understand correctly the model, the driver is still related to a dipolarization in the magnetosphere.

Response

It is assumed that the driver is triggered by westward electric fields transmitted to the ionosphere from the field line dipolarization region.

Comment3

These sentences are unclear. -> "The ionospheric driver rotated in the ionosphere to produce spirals that characteristically differ from the field line mapping scenario".

Response

Upward field-aligned currents produce spiral motions of the aurora by magnetic shear which is generated by the field-aligned currents. This is the field line mapping scenario. Meanwhile, plasma flows in the ionosphere produce spiral motions, i.e., the ionospheric driver scenario

Comment3

These sentences are unclear. -> "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]".

Response

The phrase "charge sheet deposited by auroral electron precipitations" will be changed to "shear flow instabilities associated with charge sheet".

"Hallinan, 1970" should be "Hallinan and Davis, 1970".

Comment4

These sentences are unclear. -> "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."

Response

Local accumulations of the ions/electrons in the ionosphere affect parallel velocities of charged particles arriving in the ionosphere. A change of the parallel velocity displaces their mirror points. Electrons that displaced mirror points to higher altitudes increased their pitch angles at any point along the field lines, while ions that moved mirror point to lower altitudes enter the loss cone. Therefor ions do not change their pitch angle distributions. This may happen in negatively charged latitudes. For positively charged latitudes, ions increase pitch angles along the field lines and electrons do not change the pitch angle distributions. Imbalance of pitch angle distributions along the field lines for electrons and ions produces parallel electric fields. This scenario generates upward electric fields in the negatively charged regions, while in the positively charged regions downward electric fields appear, consistent with the charge separation scenario of ions and electrons along the field lines.

For example, upward displacement of mirror points from ionosphere to 234 km above increase the electron pitch angles at 10,000 km by 7.4 degrees.

Comment5

These sentences are unclear. -> "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."

Response

The field-aligned currents generated by the local parallel electric fields closed through the ionosphere via the Pedersen currents. To achieve this current loop, electrostatic potentials are built in the ionosphere. In homogeneous ionosphere, this relation can be written as,

$$\nabla^2\phi = -\frac{I_{//}}{\Sigma_P}$$; [Kamide and Matsushita, JGR, 84, 4083, 1979]

Substituting upward field-aligned currents, $I_{//} = -1.6\times10^{-6} A/m^2$ and $\Sigma_P = 1.0S$, we have $\nabla^2\phi = 1.6\times10^{-6} V/m^2$. For the horizontal scale of 100 km, $\phi = -10kV$. Meanwhile, the Poisson equation gives density difference $n_e - n_i = 8.9\times10^1 m^{-3}$ in the ionosphere. it is a fraction of the background populations ($10^{10} m^{-3}$). We assumed that this imbalance can be achieved by releasing some of ions out of the ionosphere by the upward electric fields.

Comment5

Introduction, could you please provide references on the classification of auroral spirals from 1 km to 100s of km size?

Response

Oguti, T., Metamorphoses of aurora, Memoirs of NIPR, series A, 12, 1975.

Hallinan, T.J., Auroral spirals 2 Theory, J. Geophys. Res., 81, 3959-3965, 1976.

Hallinan, T.J., and Davis, T.N., Small-scale auroral arc distortions, Planet. Space Sci., 18, 1735-1744, 1970.

Comment6

What are "the dynamical trajectories"? Which total energy do you mean?

Response

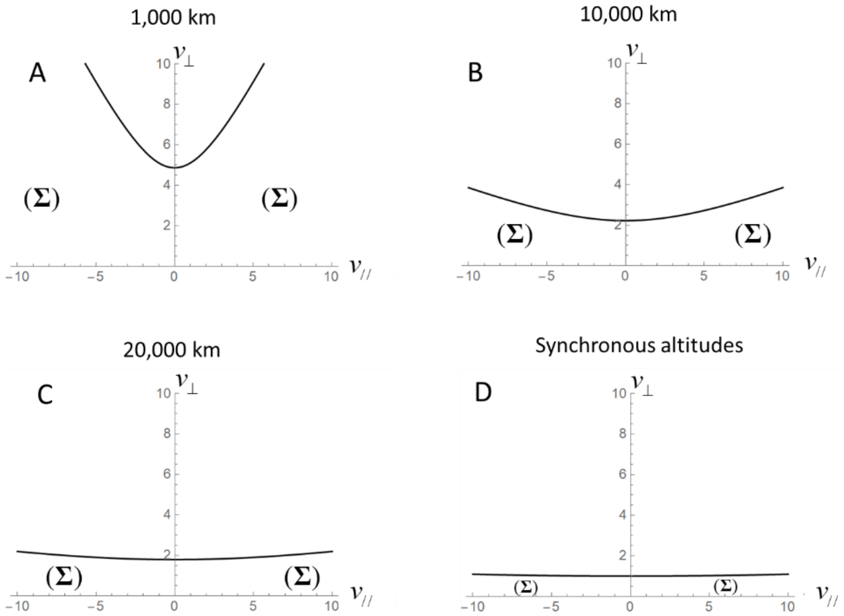
The dynamical trajectory denotes trajectories between two points of (v_para, v_perp, s) and (v'_para. V'_perp, s') in phase space. It is assumed that total energies of charged particles including electrostatic potential energies ($W = \frac{m_q}{2}(v_{//}^2 + v_{\perp}^2) + q|e|\Phi$) and magnetic moment of charged particles ($\mu = \frac{m_q}{2B} v_{\perp}^2$) are conserved along the dynamical trajectories.

Comment7

Why perpendicular velocities will be lost?

Response

To conserve magnetic moment of charged particles ($\mu = \frac{m_q}{2B} v_{\perp}^2$), perpendicular velocities decreased with increasing altitudes. Figures below show velocity distributions (v_para, v_perp) along dynamical trajectories of ionospheric plasmas at altitudes 1,000km, 10,000km, 20,000km, and at 50,000km. The parallel potentials behaved as potential barriers. It is clear that perpendicular velocities in the areas marked by Σ were decreased with increasing altitudes.



Adapted from [Saka, O., Ionospheric control of space weather, Ann. Geophys, 39, 455-460, 2021]

Comment8

Which formula is used to calculate electric fields and electrostatic potential?

Response

The electric fields and electrostatic potentials were calculated by integrating with X the Poisson equation ($\nabla^2\phi = -\dfrac{(n_i - n_e)}{\varepsilon_0}$) by assuming density difference of ion and electrons, ($n_i(x) - n_e(x)$).

Comment9

Which formula is used to calculate plot in Figure 2?

Response

Electric field profiles plotted in Figure 1 by green lines were assumed to be aligned along the auroral sheet. Plasma flows given by ExB drift is perpendicular to the auroral sheet. Because shear flows were not included, charge sheet instabilities may not occur in this model which contribute to the generation of small-scale spirals [Hallinan and Davis, 1970].

Comment10

please provide references for the numbers. -> “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”.

Response

We assumed the deformation speed of small-sale Rays to be 8 km/s from its growth time (0.4 sec) and its scale (3 km) [Oguti, 1975]. This velocity gives the electric fields of 400mV/m for $B=5x10^4$ nT. This value corresponds to the peaks of the electric fields (see green line in Figure 1). The mean amplitude of E is 200mV/m. The potential drop was calculated by multiplying E by r/2.

Reference: Oguti, T., Metamorphoses of aurora, Memoirs of NIPR, series A, 12, 1975.

Comment11

Figure 3, It is unclear how observations in Figure 3 are related to auroral spirals. More explanation is necessary.

it would be good to show the magnetic field observations from the geosynchronous orbit.

I do not see motion of shear layers in this Figure.

Response

Additional all-sky images (A to D: 0330:22-0332:30UT, January 2, 1986 at SHM) are presented in Figure A to show development of spiral auroras.

This event is associated with the second Pi2 marked in the top panel of Figure B. Consecutive field line dipolarization (G5_Inc in middle panel of Figure B) began at 0330:36 UT. Two more dipolarization cycles followed until 0331:45 UT.

Orange arrow in Figure A(A) demonstrates equatorward flow channels prior to the onset. Clockwise rotation of multiple shear layers developed after the dipolarization onset are shown in (B), (C) and (D). Images are viewed in a direction parallel to the field lines.

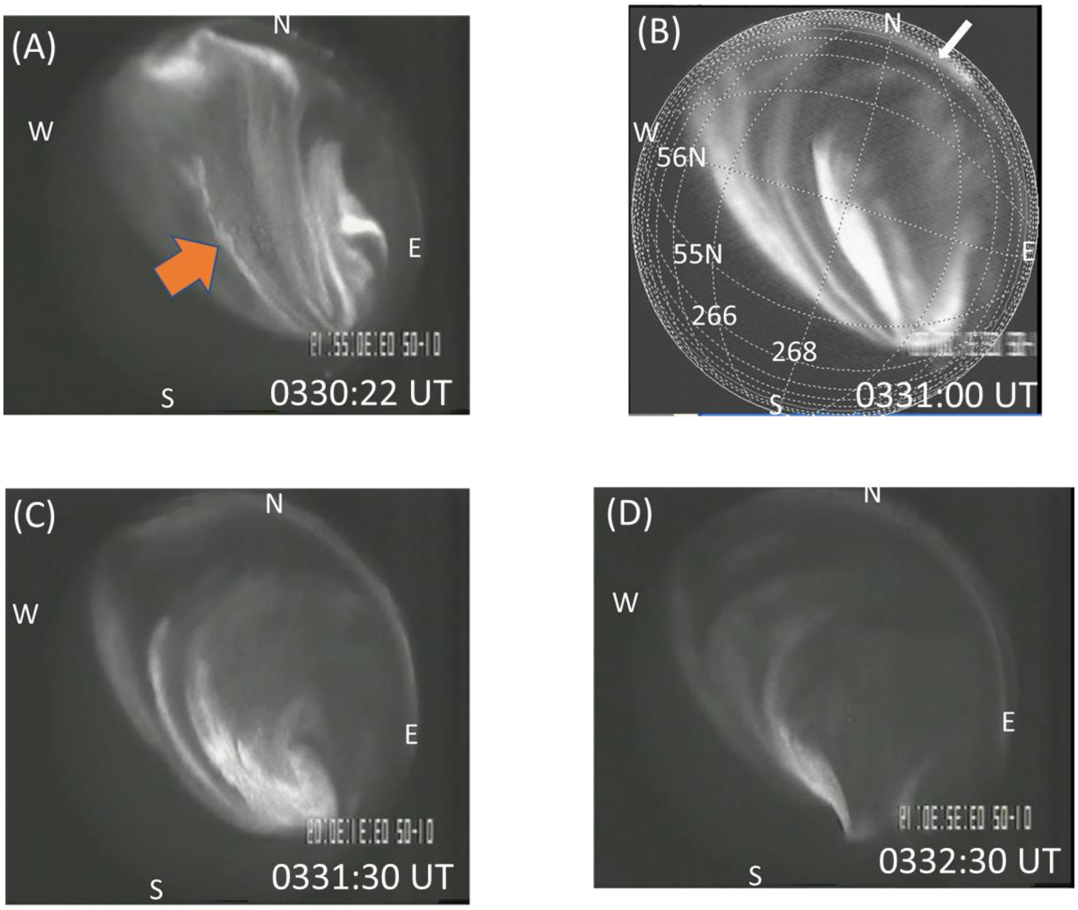


Figure A

Adapted from [Saka et al., Periodic aurora surge propagating eastward/westward at poleward boundary of aurora zone during the first 10 min intervals of Pi2 onset, J. Atmos. Solar Terr. Phys., 80, 285-295, 2012].

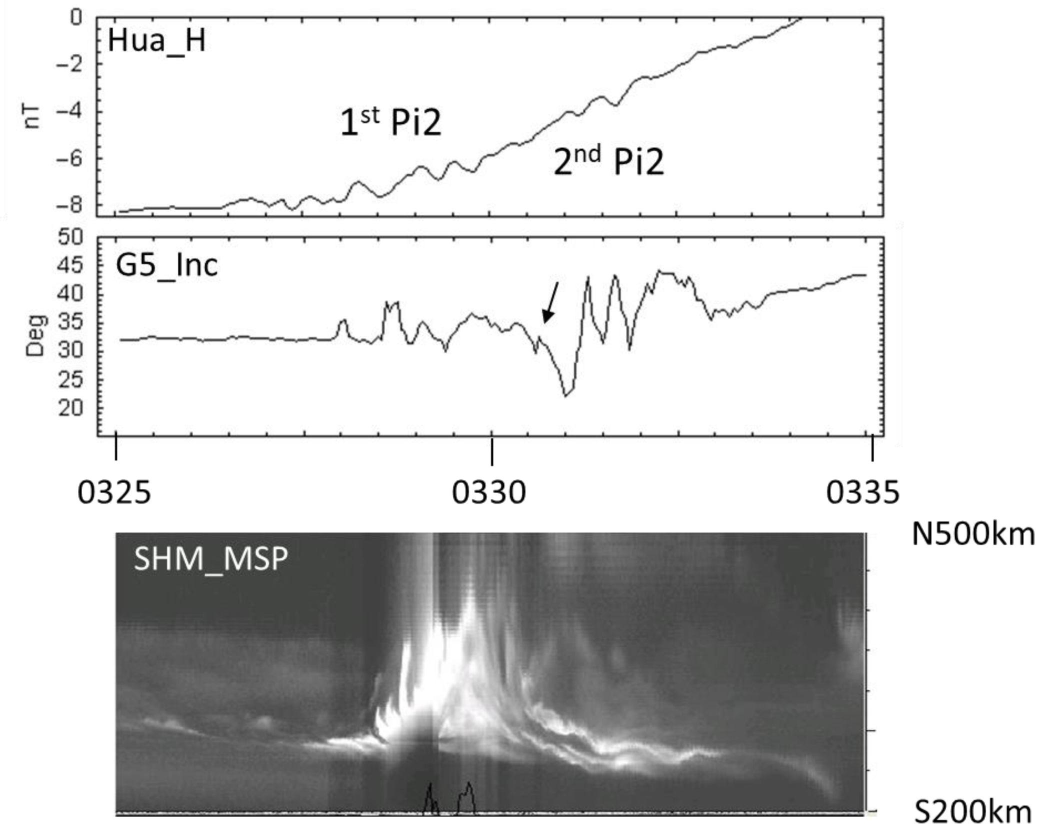


Figure B

Adapted from [Saka et al., Periodic aurora surge propagating eastward/westward at poleward boundary of aurora zone during the first 10 min intervals of Pi2 onset, J. Atmos. Solar Terr. Phys., 80, 285-295, 2012].

Keogram in the bottom panel of Figure B shows auroral breakups started at 0328:00 UT in association with the onsets of 1st Pi2 pulsations (Hua_H: top panel) and field line dipolarization at geosynchronous altitudes (G5_Inc: middle panel). During the 1st Pi2, auroral spirals like multiple shear layers in Figure 3 repeated in the field-of-view until 0329:00 UT. Please refer to Figure 19 in [Saka et al, 2021].

Comment12

this statement contradict to the statement in lines 73-75.

Response

In the ionospheric injection model proposed, spiral auroras are produced by the plasma drifts in the ionosphere. Mapping of these auroras may be traced back to the magnetosphere following the field line twist associated with the field-aligned currents.

Comment13

please provide a reference about the width of the flow channels.

Response

Flow channels, specifically equatorward plasma flows prior to the onset, are discussed in:
[Saka et al., Pre-onset auroral signatures and subsequent development of substorm auroras: a development of ionospheric loop currents at the onset latitudes, Ann Geophys., 32, 1011-1021, 2014]
[Saka et al., Ionospheric loop currents and associated ULF oscillations at geosynchronous altitudes during preonset intervals of substorm aurora, J. Geophys. Res., 120, doi:10.1002/2014JA020842, 2015]

Comment14

the plot in Figure 3 is has also source, it should be mentioned here.

Response

Auroral image in Figure 3 is available upon request to Osuke Saka (saka.o@nifty.com).