



Are drivers of northern lights in the ionosphere?

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Abstract

Within the first minute of Pi2 onset, macro-scale free vortices -characterized by two-cell, irrotational vortical flows- are excited in the midnight sector of the inner magnetosphere. This state persists for approximately 10 minutes. Rather than serving as a direct source of field-aligned current, these free vortex perturbations excite guided poloidal waves. As these waves transmit to the ionosphere, they create localized space charges. To maintain quasi-neutrality, ionosphere responds by generating parallel potential drops and outflows. These parallel potential drops subsequently produce a forced vortex that propagates down to the polar ionosphere. Within this forced vortex, electron fluids composed of primary and secondary electrons (which manifest as the aurora) undergo ExB drifts. Ultimately, the primary driver for the generation of these parallel potential drops resides within the polar ionosphere itself.

1. Introduction

Sakurai and Saito (1976) first demonstrated the validity of using low-latitude Pi2 pulsations to identify the onset of auroral substorms. Since then, low-latitude Pi2s have been widely used to accurately time substorm onsets [e.g., Saito et al., 1976]. Numerous observational studies have directly linked these low-latitude pulsations to bursts of high-speed convective plasma flows -specifically, bursty bulk flows (BBFs) - in inner plasma sheet [Kepko and Kivelson, 1999; Kepko et al., 2001; Hsu et al., 2012]. Consequently, geomagnetic Pi2 pulsations serve as a standard index in substorm research [Keiling and Takahashi, 2011, and references therein].

Concurrently, low-latitude Pi2 pulsations have been interpreted as waveguide-mode cavity oscillations, which are typically short-lived and do not establish a true, steady cavity mode [Allan et al., 1996; Li et al., 1998]. This waveguide mode is a low-latitude manifestation of a guided poloidal wave, triggered by a compressional stimulus applied at the outer boundary [Allan et al., 1985, 1986]. For these guided poloidal waves, the azimuthal wave



numbers are larger than those of the other components, resulting in a highly asymmetric mode where Poynting fluxes are guided along the magnetic field lines [Radoski, 1967, 1974]. When stimulated in the midnight magnetosphere, the guided poloidal wave carries inductive electric fields along the background field lines into the polar ionosphere. These transverse electric fields subsequently activate the ionosphere, directly initiating negative bays and meso-scale (100s km) discrete auroral forms.

In this study, we apply the guided poloidal wave model to substorm onset by assuming that the compressional stimulus is localized within the plasma convection boundaries of a BBF. The remainder of this paper is organized as follows. In Section 2, we investigate the physical conditions required to excite a compressional stimulus within convective plasma flows. Sections 3, 4, and 5, then discuss the mechanisms through which this compressional stimulus drives the initiation of macro-scale auroras.

2. Compressional stimulus

Magnetometer observations at geosynchronous altitude reveal Pi2-associated, macro-scale convective flows characterized by a two-cell vortical pattern in the midnight equatorial plane [Saka et al., 2007]. These two-cell flows exhibit counterclockwise (CCW) rotation in the dawn sector and clockwise (CW) rotation in the dusk sector. This rotation sense is opposite to that of the vortical flows driven by viscous interaction with the solar wind [Sato and Iijima, 1979].

During the initial pulse of a Pi2 pulsation (the first one-minute interval of the onset), magnetic field reconfigurations occur at nightside geosynchronous altitudes. These reconfigurations span all three magnetic field components and begin simultaneously with a tripartite signature: a decreased field magnitude, an increased inclination angle (dipolarization), and field line expansion toward the dayside sector (Figure 1). This reconfiguration front expands from the dawn to the dusk sectors, signifying global dipolarization within the inner magnetosphere. This phenomenon can be explained by the macroscopic transport of magnetic flux and plasma from the nightside to the dayside sector via shear flows. This interpretation is strongly supported by MHD simulations, where azimuthally localized BBFs initiate global-scale dipolarization in the inner magnetosphere [Melkin et al., 2019]. Furthermore, these shear flows have been observed to persist for approximately 10 minutes following the Pi2 onset [Saka et al., 2010].

Ground-based all-sky imaging of the onset aurora – defined as a meso-scale (100s km) discrete auroral form occurring simultaneously with the Pi2 onset - reveals that an auroral surge is excited at its poleward boundary [Saka et al., 2012]. This poleward boundary aurora surge (PBAS) is interpreted as the ionospheric manifestation of the magnetospheric shear



flows, specifically bifurcated BBFs. A velocity shear triggers low frequency MHD waves through Kelvin-Helmholtz (KH) instability [Parks, 1991]. In incompressible condition, the low frequency waves are evanescent mode (surface waves), decay in strength away from the surface of velocity shear.

The surface waves generate potential flows in the equatorial plane characterized as slip motions or free vortex flows [Saka et al., 2007]. Consequently, macro-scale, two-cell slip motions are excited earthward of the shear flows (Figure 2). The compressional stimulus occurs at the plasma slip motions labeled “2” and “4” in Figure 2. This localized displacement transmits the waveguide mode toward lower latitudes, while simultaneously sending westward and eastward inductive electric fields to higher latitudes, thereby initiating a transient response in the polar ionosphere [Keiling and Takahashi, 2011].

3. Auroral surge at poleward boundary of the onset aurora

Figure 3 represents the first example of meso-scale auroras captured during the initial pulse of a Pi2 pulsation, utilizing data recorded at Shamattawa (SHM), Canada, on January 2, 1986. The spiral form exhibits a clockwise turnover of the poleward arc as it detaches from the main body of the equatorward auroras. A second example, observed at Shamattawa on January 24, 1986, is shown in Figure 4. This event features a clockwise twist encompassing the entire auroral body. Together, these figures demonstrate that auroral deformations initiate in tandem with the onset of Pi2 pulsations recorded at the dip equator (Huancayo, geomagnetic latitude 1.0°N) and field line dipolarization at geosynchronous satellites Goes 5 and Goes 6 in the midnight sector. The all-sky images used in Figures 3 and 4 are adapted from Saka et al. (2012).

Figure 5 illustrates the poleward boundary aurora surge (PBAS) via an all-sky image for both the January 2 event (A) and the January 24 event (B), overlaid with the calculated footprint of a geosynchronous orbit. In the first event (January 2), the PBAS is positioned 5.5 degrees poleward of the equatorward boundary of the onset aurora, whereas in the second event (January 24), it lies 3 degrees poleward of the equatorward boundary of the onset aurora. Based on a statistical analysis of nine onset aurora events by Saka et al. (2012), the PBAS is distributed across invariant latitudes ranging from 68 to 74 degrees (Figure 6). This latitudinal span corresponds to 1 to 7 degrees poleward of the footprint of geosynchronous orbit calculated using the International Geomagnetic Reference Field (IGRF) model. The mean latitude of the PBAS (70 degrees invariant latitude) maps to $L=8.5$, which aligns with the penetration depth of low entropy BBFs in the inner magnetosphere [Dubyaagin et al., 2010]. The longitudinal scale of the PBAS is estimated to be 760 km at this mean latitude.



108 The onset auroras map to the inner magnetosphere, earthward of geosynchronous
109 altitudes, where local plasma dynamics are governed by macro-scale, two-cell free vortex
110 flows.

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113 **4. Auroral driver for onset auroras**

114 For approximately 10 minutes following the Pi2 onset, free vortex flows persist in the midnight
115 sector of the inner magnetosphere. The slip motions of plasmas in free vortex flows cannot
116 launch field-aligned currents to initiate auroral precipitations. Consequently, we propose a
117 new auroral driver model to explain the generation of the onset aurora in the inner
118 magnetosphere.

119 At the lower boundary of the ionosphere (at altitudes between 80 km and 140 km),
120 where collisional ions and collisionless electrons coexist [Rishbeth and Garriott, 1969], a local
121 breakdown of charge neutrality may be initiated by transverse electric fields transmitted via
122 guided poloidal wave. Although this neutrality breakdown may be temporarily neutralized by
123 Pedersen currents, complete cancellation is prevented because a fraction of the ionospheric
124 electrons and ions are released as outflows driven by parallel electric fields. These parallel
125 electric fields are initially produced by the displacement of the mirror height of trapped
126 electrons due to local space charges in the polar ionosphere. This displacement results in
127 charge separation along the field lines, characterized specifically by positive charges
128 immediately above the ionosphere and negative charges directed tailward. This novel
129 mechanism for generating parallel potential drops above the ionosphere is introduced here
130 as the “ionospheric injection model” [Saka, 2023].

131 Charge separation along geomagnetic field lines represents a steady-state solution for
132 parallel electric fields [Persson, 1963] and can be understood through an analogy with ion
133 sheaths in laboratory plasmas [Chen, 1974], though the resulting potential drop expands to
134 a macroscopic scale for auroral phenomena. Just as a laboratory ion sheath blocks electrons
135 but allows ions to escape to the device wall, the auroral acceleration region regulates
136 secondary electrons and ion outflows. The formation of an ion-rich layer -both in front of a
137 laboratory wall and above the ionosphere- is a necessary condition for creating smooth
138 potential drops. For that purpose, ions in laboratory plasmas escape at velocities exceeding
139 the ion acoustic speed (Bohm condition), whereas the auroral counterpart requires that the
140 mirror height of trapped electrons be displaced away from the ionosphere. A complementary
141 mechanism, analogous to an electron sheath, creates field-aligned charge separation with
142 earthward negative charges and tailward positive charges, which can be applied to the
143 formation of downward electric fields. As a result, a complementary pair of parallel potential



144 drops is produced. Ultimately, the free particle motions along the field lines directly driven by
 145 these potential drops – representing field-aligned currents - excite Alfvén waves in the inner
 146 magnetosphere.

147 For ion outflows, however, free particle motion cannot be applied below altitudes of
 148 1000 km due to low ion mobility. In these low-altitude regions, ion outflows are instead
 149 governed by steady-state ionospheric plasma transport dynamics [Kelley, 1989; Saka, 2019].

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152 **5. Flapping motion of the onset aurora**

153 Current density of the upward field-aligned current (FAC) carried by down-going electrons
 154 with incident Alfvén waves can be expressed as:

$$155 \quad J_{\parallel} = -\Sigma_A (\nabla \cdot \mathbf{E}_A), \quad (1)$$

156 where Σ_A denotes Alfvén conductance, defined as $1/(\mu_0 V_A)$. Conversely, the upward field-
 157 aligned current density resulting from the divergence of ionospheric currents is given by:

$$158 \quad J_{\parallel} = -\Sigma_P (\nabla \cdot \mathbf{E}_i), \quad (2)$$

159 where Σ_P is height integrated Pedersen conductivity. Remaining terms arising from
 160 nonuniform conductivity are neglected [Kan et al., 1982]. In equation (1), upward field-aligned
 161 currents carried by up-going ions are excluded because they do not initiate precipitation.

162 The matching conditions of FACs associated with the incident Alfvén wave and the
 163 divergence of the ionospheric current reduce to:

$$164 \quad \omega = (\Sigma_A / \Sigma_P) \Omega \quad (3)$$

165 Here $\Omega = -\nabla \cdot \mathbf{E}_A / B$ and $\omega = -\nabla \cdot \mathbf{E}_i / B$, where B represents the magnetic field intensity
 166 at the ionosphere.

167 Equation (3) indicates that the forced vortex Ω carried by Alfvén waves is mapped to the
 168 polar ionosphere as ω with reduced amplitudes. We utilize this relationship as an
 169 approximation, given that the center of the auroral substorm does not coincide perfectly with
 170 that of the Harang Discontinuity [Weygand et al., 2008].

171 Because the forced vortex Ω is embedded within the free vortex flows ($\Omega = 0$) of the
 172 inner magnetosphere, the combined structure forms a Rankine vortex. The inner portion of
 173 the flow is characterized by the forced vortex, whereas the outer region transitions into a free
 174 vortex, allowing for velocity decay at larger radial distances. When mapped to the polar
 175 ionosphere with reduced amplitudes, this Rankine vortex establishes an incomplete Cowling
 176 channel, driving upward and downward FACs at its equatorward and poleward edges,
 177 respectively [Baumjohann, 1983]. Alternatively, we investigate a scenario where the primary
 178 forced vortex is surrounded by an outer forced vortex of the opposite sign to suppress the
 179 core vortex amplitudes outside of the channel. As demonstrated below, the resulting vortical



180 flows mapped to the ionosphere establish the Harang Discontinuity.

181 Let us assume that the forced vortex Ω exhibits a positive amplitude at the center
 182 ($Y=0$) and a negative at the rim, corresponding to upward and downward FACs, respectively
 183 (Figure 7A). The electrostatic potential ϕ_i in the ionosphere associated with ω (the reduced
 184 amplitude of Ω) is calculated using $\nabla^2 \phi_i = B\omega$. The potential ϕ_i and the resulting ExB drift
 185 trajectories are shown in arbitrary scales in Figures 7B and 7C, respectively. A westward
 186 electrojet (flowing opposite to the ExB drift) appears in the poleward region of the channel
 187 ($10 > Y > 2$), while an eastward electrojet forms equatorward ($-10 < Y < -2$). When merged with
 188 polar cap convection patterns, the forced vortex ω can be identified as the Harang
 189 Discontinuity (HD) [Koskinen and Pulkkinen, 1995; Weygand et al., 2008]. The formation of
 190 the HD has also been reported as a high-latitude geomagnetic event occurring in association
 191 with Pi2 pulsations [Rostoker and Samson, 1981; Samson and Rostoker, 1983].

192 The upward electric fields drive the precipitation of energetic electrons into the polar
 193 ionosphere. The stopping altitudes of these energetic electrons (2 - 10keV) range from
 194 100km to 150km, where green (O ; 557.7 nm) and blue (N_2^+ ; 427.8 nm) emission lines are
 195 activated [Rees, 1989; Tohmatsu, 1990]. The stopping altitude corresponds to the
 196 ionospheric E-layer. Within this E-layer, we assume that an onset aurora composed of
 197 primary and secondary collisionless electrons ($T_e \sim 100$ eV) aligns along the X-axis where
 198 $\Omega > 0$. Within the electrostatic potential configuration shown in Figure 7B, the onset aurora
 199 in the E-layer turns clockwise and rotates around ($X=0, Y=0$), while its poleward edge splits
 200 along the ExB drift trajectories shown in Figure 7C. Under the ionospheric injection scenario,
 201 although the vorticity Ω above the ionosphere is modified by the motion of the onset auroras,
 202 this modification may provide feedback to the aurora to sustain its steady motion. The
 203 repeated movement of these arc fragments along the trajectories, combined with the
 204 clockwise rotation of the entire arc body, produces the characteristic flapping motion of the
 205 onset aurora.

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208 **6. Discussion**

209 A new auroral acceleration model has been presented, focusing specifically on the onset
 210 aurora that occurs during the first one-minute interval of Pi2 onset. In this model, acceleration
 211 regions are established immediately above the ionosphere, analogous to ion/electron sheath
 212 formation in laboratory plasmas, generating a complementary pair of parallel potential drops
 213 and associated field-aligned currents. Onset auroras driven by this novel acceleration
 214 mechanism manifest as meso-scale discrete auroras within the auroral bulge. The forced



215 vortex region in the auroral core can be identified as the Harang Discontinuity. Ultimately, the
 216 ExB drift of primary and secondary electrons within this forced vortex structure provides a
 217 robust physical explanation for the characteristic flapping motion of the onset aurora.

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220 **7. Acknowledgements**

221 The author thanks to anonymous referees for their critical comments and helpful suggestions.

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224 **8. Data availability**

225 Data used are from Global Aurora Dynamics Campaign [Oguti et al., 1988]. Figures 3 through
 226 6 are adapted from Saka et al., 2012. This data is available upon request to Osuke Saka
 227 (osuke.saka001@gmail.com).

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230 **9. Competing interest**

231 The author declares that there is no conflict of interest.

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Figure captions

Figure 1

321 Local time distribution of the initial change of the field lines at Pi2 onset, measured along the



geosynchronous orbit. **(A)** Change of field magnitude (B), where black indicates a decrease and white indicates an increase. **(B)** Change of inclination angle (θ), where black indicates a decrease and white indicates an increase. **(C)** Change in field line rotation (Φ), where black indicates clockwise rotation and white indicates counterclockwise rotation as viewed from above the equatorial plane. Adapted from Saka et al. (2000).

Figure 2

Schematic illustration of a macro-scale, two-cell pattern (CCW in dawn sector and CW in dusk sector) excited in the equatorial plane by the passage of bidirectional flow at the outer boundary. The bidirectional flow, with a wavelength of $4.7R_e$ and moving at a velocity (U) of 300 km/s, generates a 100 sec Pi2 pulse. Consecutive plasma displacements marked 1 through 5 demonstrate slip motions in vortical flows. Adapted from Saka et al. (2012).

Figure 3

(A) A 10-minute time series starting from 03:25:00 UT on January 2, 1986, showing a keogram along the geomagnetic meridian passing Shamattawa (SHM; 66.3N, 336.0 in geomagnetic coordinates). **(B)** The H component of the magnetic field at Huancayo (HUA), located at the dip equator (1.0N, 355.5 in geomagnetic coordinates). **(C)** The inclination angle of field lines at the geosynchronous satellite GOES 5 (satellite footprint: 64.0N, 349.8 in geomagnetic coordinates). The initial pulse of the Pi 2 pulsations and the associated magnetic dipolarization onset at 03:28:30 UT are indicated by vertical red bar. All-sky images at the bottom are viewed from above the ionosphere (looking downward along the field lines). The poleward expansion of the onset aurora, characterized by a clockwise turnover of the splitting arc, is demonstrated in consecutive images at 03:28:30 and 03:29:00 UT. On the right, an all-sky image overlayed with a geographic grid is presented, with latitude lines (55N, 56N) and longitude lines (268, 270) highlighted. The geomagnetic meridian passing through the optical station (SHM) is marked by a solid line. The auroral animation for 1 min intervals starting at 03:28:00 UT is available in the file 0102(1986).mp4 at <https://sites.google.com/view/auroral-image/>.

Figure 4

Same as Figure 3, but for the auroral event beginning at 04:40:00 UT on January 24, 1986. The inclination angle of field lines is observed by GOES 6 (satellite footprint: 63.6N, 321.3 in



geomagnetic coordinates). The spiral form of the onset aurora exhibits a clockwise rotation. The auroral arc initiates at 04:43:00 UT, and its clockwise rotation is demonstrated in the subsequent images at 04:44:00, 04:44:30 and 04:45:00 UT. The dark portion at the bottom of the images is a masking effect applied to eliminate moonlight interference. The auroral animation for 2-minute intervals starting at 04:43:00 UT is available in the file 0124(1986).mp4 at <https://sites.google.com/view/auroral-image/>.

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Figure 5

Selected all-sky images recorded at SHM for the events presented in Figures 3 and 4. The overlaid grids indicate geographic longitudes and latitudes, with latitude lines (55N, 56N and 57N) and longitude lines (268 and 270) explicitly labeled. The calculated footprint of a geosynchronous orbit based on the IGRF model is also overlayed. In the all-sky imagery, the poleward boundary aurora surge (PBAS) is visible at the poleward boundary of the image, propagating eastward at a velocity of approximately 12-24 km/s.

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Figure 6

Latitudinal distribution of nine observed PBAS events plotted against invariant latitude. The horizontal axis indicates the longitudinal spread of the PBAS in degrees within geographic coordinates, spanning from 7 degrees west to 13 degrees east of the zenith meridian of the optical stations. These nine cases are observed via all-sky images at SHM and Great Whale River (65.7N, 351.2 in geomagnetic coordinates) on Jan 02, 24, 27 and 30 1986.

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Figure 7

(A) A two-dimensional distribution model of the forced vortex Ω carried by incident Alfvén waves. Positive and negative amplitudes correspond to upward and downward field-aligned currents, respectively. (B) Electrostatic potential profiles (ϕ_i) in the polar ionosphere calculated using $\nabla^2 \phi_i = B\omega$, where $\omega = (\Sigma_A/\Sigma_P)\Omega$. The profile exhibits a negative peak at the center and decays to zero at the outer edge. (C) ExB drift trajectories (representing trajectories for collisionless electrons) within the electrostatic potential configuration. The scales in panels (A), (B), and (C) are arbitrary.



First one-min-interval of Pi2 onset

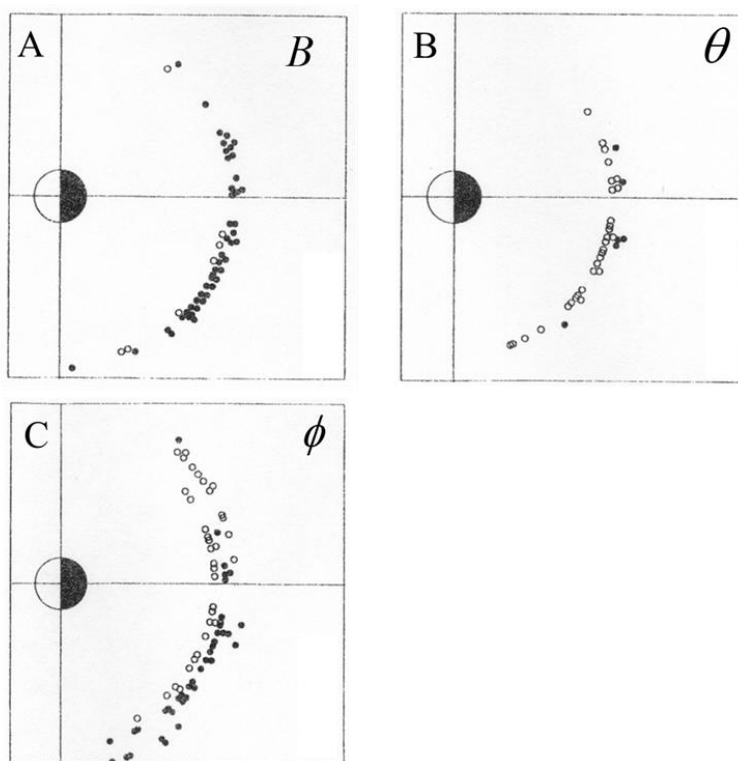
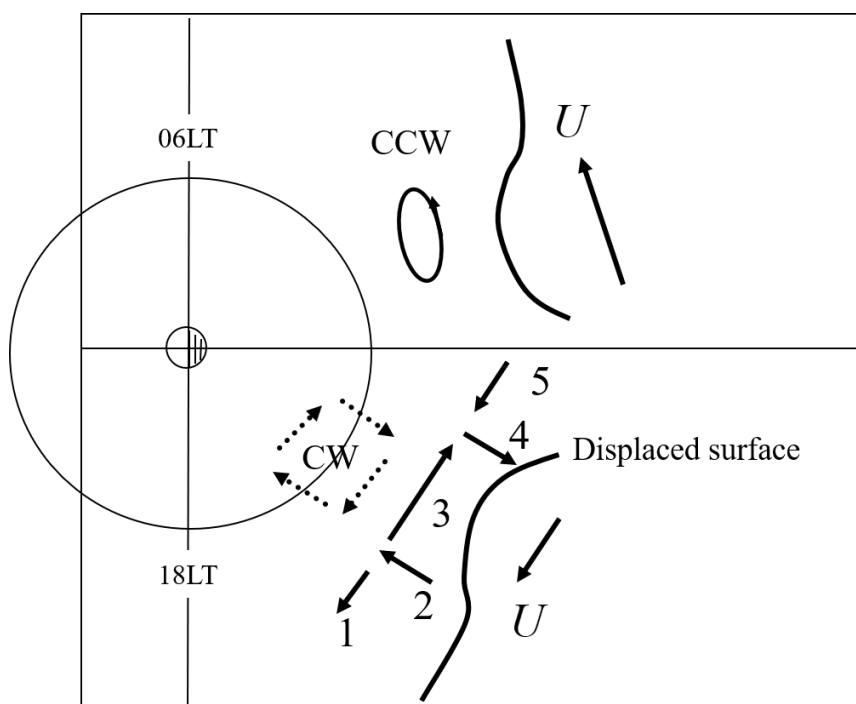


Figure 1



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Figure 2

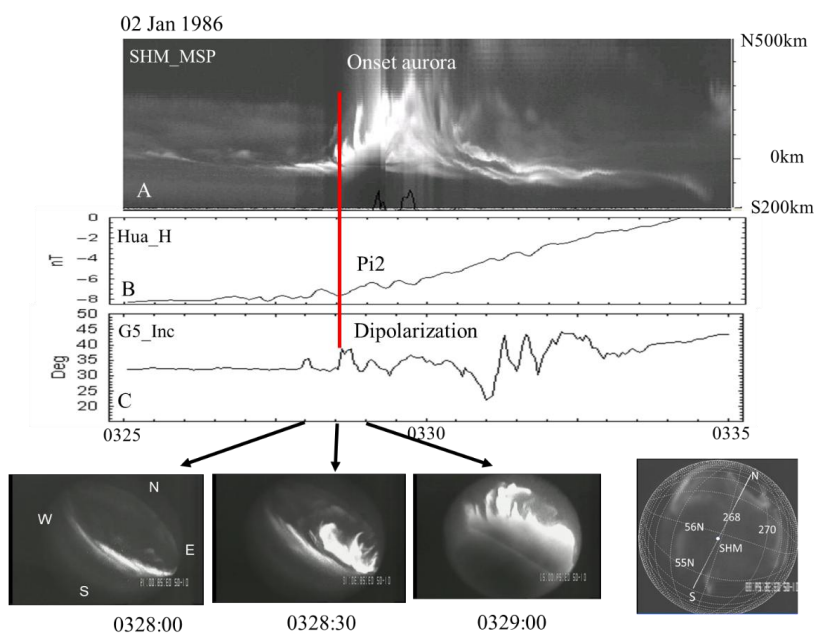


Figure 3

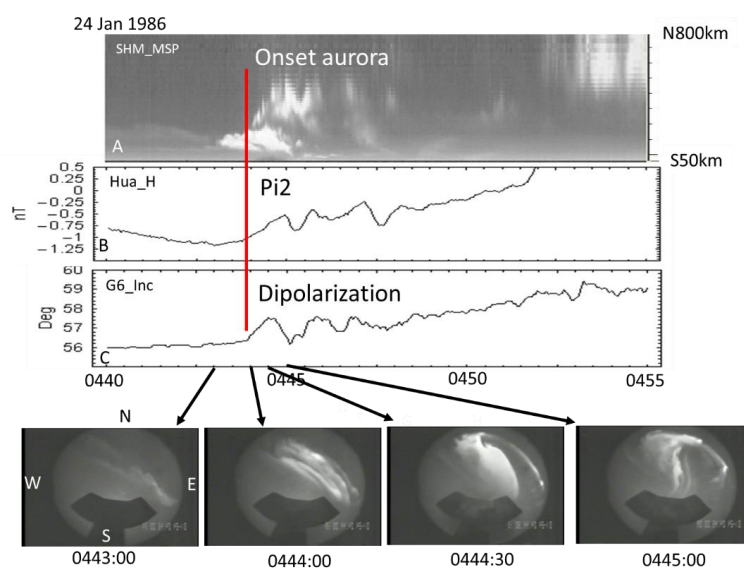


Figure 4

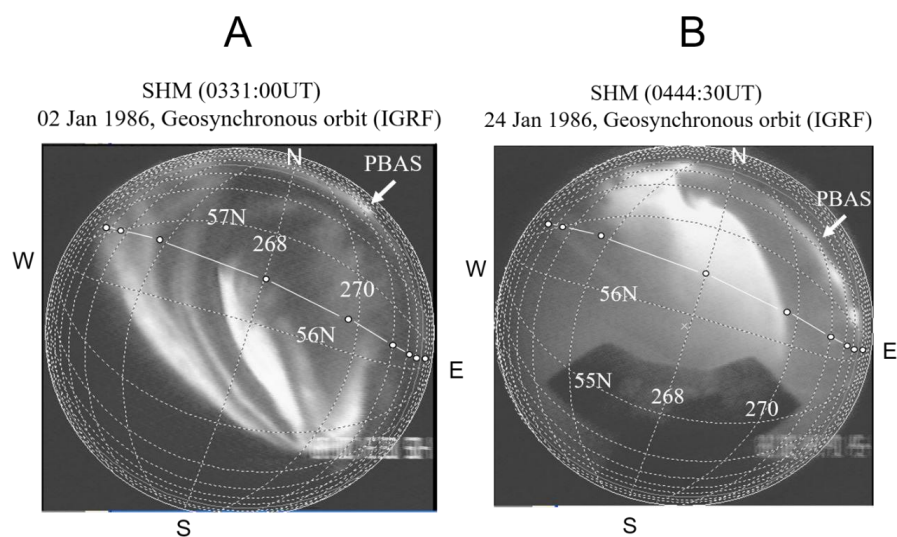


Figure 5

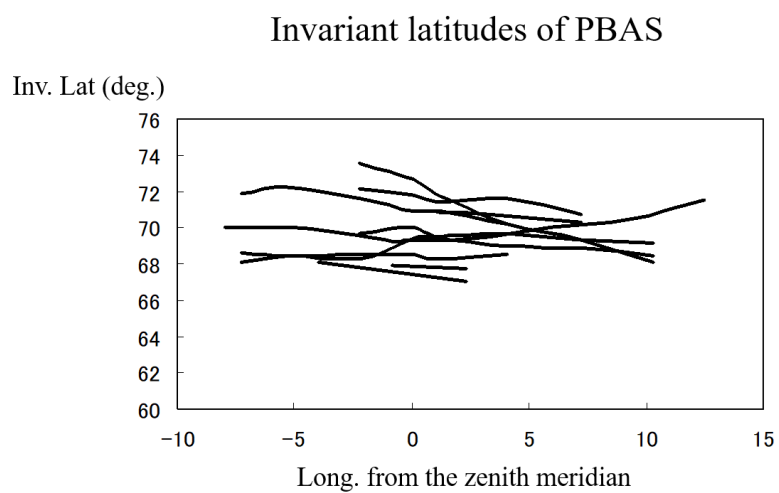


Figure 6

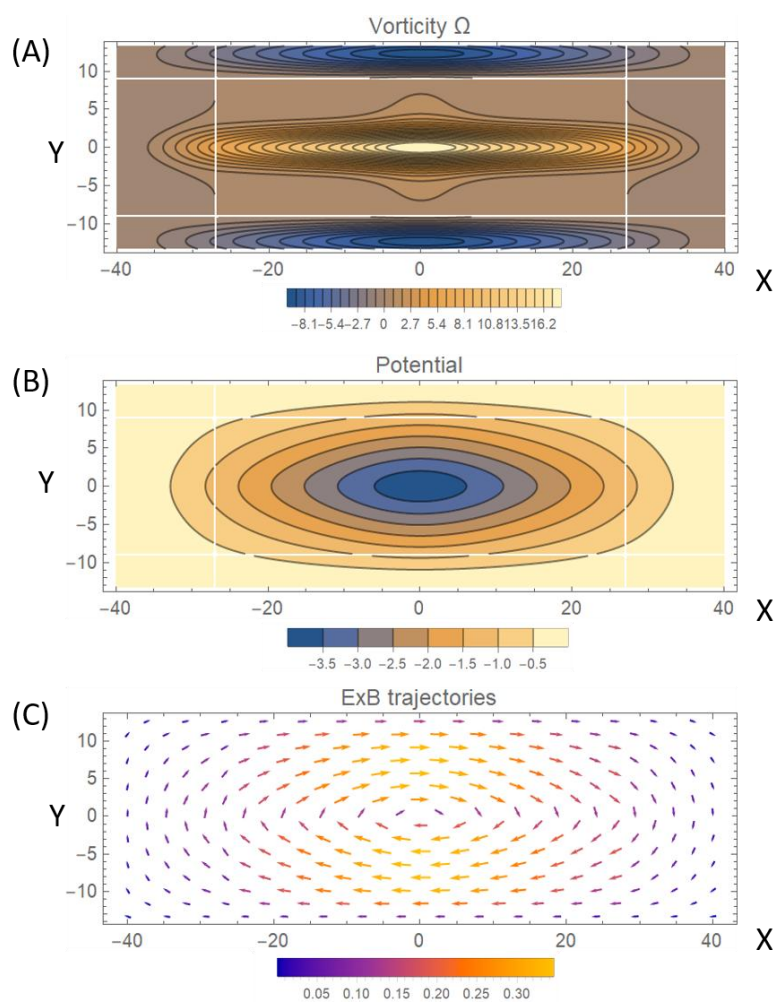


Figure 7