Publications

2-10-2022

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Alimaganbetov, M., & Streltsov, A. (2022). Feedback Interactions Between the Ionosphere and Magnetosphere at Middle Latitude. *Journal of Geophysical Research: Space Physics*, (). <https://doi.org/10.1029/2021JA029990>

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Feedback Interactions Between the Ionosphere and Magnetosphere at Middle Latitude.

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Key Points:

- We investigate ULF waves observed at Palmer station in Antarctica during substorms.
- Our simulations demonstrate that these waves can be produced by the ionospheric feedback instability.
- We show that the main role in the development of the instability belongs to the plasmopause.

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This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the [Version of Record](#). Please cite this article as doi: [10.1029/2021JA029990](https://doi.org/10.1029/2021JA029990).

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Abstract

Observations show that magnetic pulsations with frequencies around 1 mHz are frequently detected simultaneously at different latitudes on the ground, in the inner magnetosphere, and in the solar wind. The coupling between oscillations in the dynamic pressure or magnetic field carried by the solar wind and the ULF waves detected on the ground at high latitudes has been suggested in several studies. We present results from a numerical study of ultra-low-frequency waves detected by the ground magnetometers at middle latitudes during substorm. We investigate the hypothesis that these waves are generated by the ionospheric feedback instability driven by the large-scale electric field in the ionosphere. This field is associated with the surface waves propagating along the ambient magnetic field on strong perpendicular gradient in the plasma density occurring in the equatorial magnetosphere. The gradient in the plasma density is associated with the plasmopause. The plasmopause moves to the middle latitude when the plasmasphere erodes during substorm. The energy from the external driver can be coupled to the large-scale surface Alfvén waves traveling along the field lines into the ionosphere and generate small-scale intense ULF waves and field-aligned currents at middle latitude. The simulations of the two-fluid MHD model confirms this scenario, and the numerical results show a good quantitative agreement with the observations.

1 Introduction

Ultra-low frequency (ULF) electromagnetic waves carry significant fluxes of the electromagnetic power, mass and momentum in the highly coupled solar wind-magnetosphere-ionosphere system. Their role in the global energy exchange increases many times during magnetically active times like the geomagnetic storms and substorms. This is one of the main reasons why these waves and the associated field-aligned currents are extensively studied at high latitudes in connection with the discrete auroral arcs and other non-luminous phenomena.

One of the most frequently considered mechanisms responsible for the generation of the large-amplitude ULF waves is the global magnetospheric field-line resonator (FLR) formed by the magnetic field line bounded by the conjugate locations in the ionosphere. Shear Alfvén waves can form a standing pattern between these locations. If there is an external or internal driver that provides power with a frequency matching one of the eigenfrequencies of the system, then the resonator can produce large-amplitude ULF waves.

This idea had been proposed in classical papers by Cummings et al. (1969); Southwood (1974) and extensively studied after that, e.g., Chen and Hasegawa (1974); Streltsov and Lotko (1995).

The existence of the global magnetospheric resonator is strongly supported by the frequent observations obtained with ground magnetometers and radars, particularly, by these of electromagnetic oscillations with discrete frequencies of 0.8, 1.3, 1.9, and 3.5 mHz in the night-side auroral zone (Samson, Harrold, et al., 1992; Fenrich et al., 1995). The same frequencies also have been detected in the field-aligned particle fluxes and luminosity of the discrete auroral arcs (Xu et al., 1993). The fact that at high altitudes these frequencies match the eigenfrequencies of the magnetic field lines stretched to the magnetotail (Lui & Cheng, 2001) provides a rationale to interpret them as a manifestation of the global field line resonator (Samson, Wallis, et al., 1992; Walker et al., 1992).

FLR can be driven by several physical mechanisms. It can be a reconnection in the magnetotail (Angelopoulos et al., 2002), or the Kelvin-Helmholtz instabilities on the magnetopause or on the flanks of the magnetosphere in the so-called low-latitude boundary layers (Galinsky & Sonnerup, 1994; Marin et al., 2014). It can be energetic electron injections (Pilipenko et al., 2002) or feedback-active ionosphere-magnetosphere interactions driven by the electric field in the ionosphere (Atkinson, 1970; Sato, 1978; Trakhtengertz & Feldstein, 1984; Lysak, 1991).

At the same time, studies of the power spectral density of the ULF waves detected during substorms on the ground at different latitudes demonstrate that the main power of these waves is in the frequency range less than 1 mHz (Takahashi et al., 2001; Mishin et al., 2002; Mann et al., 2004; Rae et al., 2012). Observations conducted on the ground and in space reveals that the waves with such ultra-low frequencies are observed on very low L -shells (e.g., near $L = 1.6$), where these frequencies are way less than the fundamental eigenfrequency of the corresponding field line (Francia & Villante, 1997). Also, these frequencies have been simultaneously detected in the oscillations of the solar wind plasma density, measured by the Wind and Advanced Composite Explorer (ACE) spacecrafts far upstream from the Earth, and in the oscillations of the magnetic field measured by the Geostationary Operational Environmental Satellite (GOES) 8 spacecraft in the day-side magnetosphere on the geosynchronous orbit (Kepko et al., 2002; Viall et al., 2009).

These observations suggest that the waves are produced by the phenomena occurring outside the Earth's magnetosphere. For example, Horvath and Lovell (2021) show the correlation between surface waves on the plasmopause and Kelvin-Helmholtz waves in the solar wind in the magnetopause region, whereas Kepko and Spence (2003) suggest that the oscillations in the dynamic plasma pressure or the magnetic field carried by the solar wind can serve as a direct driver of the Earth's magnetosphere and produce electromagnetic waves with the frequency ≈ 1 mHz detected on the ground. Recent studies by Alimaganbetov and Streltsov (2018, 2020) support this hypothesis. These authors analyzed oscillations of the magnetic field detected by the ACE satellite in the solar wind and ground magnetometers at high ($L = 5.76$), middle ($L = 2.46$), and low ($L = 1.87$) latitudes during 84 intense substorms and found a good correlation between oscillations with frequencies less than 1 mHz observed in all these locations. They concluded that the oscillations of the magnetic field carried by the solar wind are the main driver of electromagnetic waves with frequency less than 1 mHz observed at different latitudes on the ground during substorms. However, they did not provide a quantitative explanation of why this happens. Such an explanation is the goal of this paper.

We propose that the main role in the generation of ULF waves at middle latitudes during substorm belongs to the plasmopause. Recent studies by Streltsov and Mishin (2018, 2020) reveal that the plasmopause provides conditions for converting the kinetic energy of energetic particles moving toward the Earth from the magnetotail during substorms into a large-scale electric field in the subauroral zone. This field penetrates into the ionosphere and drives there the ionospheric feedback instability (IFI) generating density irregularities, field-aligned currents, and intense ULF waves. The plasmopause is characterized by a strong gradient in the plasma density across the ambient magnetic field. Studies of the field-line resonances by Streltsov and Lotko (1995) and Streltsov et al. (1998) demonstrate that the external driver (e.g., compressible MHD modes propagating across the ambient magnetic field) can generate large-scale Alfvénic surface waves on such gradients, as suggested by Hasegawa (1976). These surface waves deliver the electromagnetic power into the ionosphere and activate the ionospheric feedback instability there. Therefore, if this hypothesis is correct, then during the substorms observations from ground magnetometers will show the magnetic oscillations with frequencies ≈ 1 mHz produced by the external driver as well as the oscillations with frequencies corresponding to the magnetospheric resonator driven by the IFI.

During magnetically quiet times the plasmopause normally locates at magnetic shells $L = 4-6$. During substorms the plasmasphere can be severely eroded and the plasmopause moves to $L = 2-3$ (Goldstein et al., 2003, 2019). This fact may explain observations of ULF waves in the solar wind and at middle latitudes on the ground reported by Alimaganbetov and Streltsov (2020). Our goal is to investigate this hypothesis by modeling one of the substorm events reported by Alimaganbetov and Streltsov (2020) with a two-fluid MHD code developed by Streltsov and Foster (2004) for studying electromagnetic coupling between the ionosphere and the magnetosphere in the subauroral zone. In particular, we want to investigate the role of the plasmopause in the generation of the intense ULF waves with frequencies observed during these events at middle latitudes and to provide a detailed quantitative description of the spatial structure and temporal behavior of these waves.

2 Observations

We choose the day of 09/28/2016 for the simulations for several reasons. Firstly, from our previous analysis we found that during the substorm event around 1600 UTC on 09/28/2016 PSD spectra of the magnetic fields observed by three ground stations at high, mid and low latitudes, and the ACE satellite had similar dominant frequencies around 0.50-0.65 mHz, showing a good correlation. Figure 1, reproduced from the study by Alimaganbetov and Streltsov (2020), shows magnetic fluctuations recorded by the ACE satellite in the Earth's L1 Lagrangian point and the ground magnetometers at the Poker Flat, Alaska ($L = 5.76$) and Palmer, Antarctica ($L = 2.46$) stations during a substorm occurred on 09/28/2016 around 1600 UTC. Figures 1A, 1B, and 1C show the B_Y component of the magnetic field in the GSM coordinate system detected by ACE, the B_H component in the HDZ coordinate system recorded at Poker Flat, and the B_X component in the GSE coordinate system at the Palmer station, respectively. The original signals are shown with the red lines and the black lines shows the low-frequency (< 0.7 mHz) trend in these signals. The time for the ACE data is adjusted by 0.75 hours to take into account the solar wind speed during this event. Figures 1D, 1E, and 1F show the de-trended magnetic field (obtained as a difference between “red” and “black” curves in Figures 1A, 1B, and 1C). Figures 1G, 1H, and 1I show the power spectral density (PSD) of these fields calculated within a time window of 4.5 hours centered near the maximum of the observed fields.

Secondly, there were a few major substorms during that day. According to the data provided by the World Data Center, those substorms occurred around 1000, 1300, 1500-1900 and 2000 UTC. Particularly after 1500 UTC, the AE index suddenly increased from the usual 500 nT to around 1000 nT and stayed at this value until around 1900 UTC, sometimes even reaching 1500 nT. The Dst index suddenly increased from the average 30 nT to around 50 nT at 1600 UTC.

Finally, the RBSP satellites allowed us to also reveal a severe depletion of the plasmasphere to mid $L=2-3$ during this day at times close to the times of observed substorms. Figure 2 shows with a black curve the plasma density measured by the NASA Van Allen Probe (also known as Radiation Belt Substorm Probe (RBSP)) B satellite on 09/28/2016. RBSP satellites fly in the equatorial plane and the blue line in Figure 2 shows L -shells of the satellite trajectory during this time interval. The horizontal solid red line marks $L = 2.46$ which corresponds to the L shell of the Palmer station. Four vertical dashed red lines marks moments of time when the satellite crosses the Palmer's L -shell.

Figure 3 shows the electron density vs L -shells measured by the satellite near $L = 2.46$ at these four moments of time. Figures 3A and 3B show a relatively strong gradient in the electron density in the region around $L = 2.7-2.8$, where the density changes from $\approx 400 \text{ cm}^{-3}$ at $L = 2.8$ to $\approx 1400 \text{ cm}^{-3}$ at $L = 2.6$. This location corresponds to the location of the plasmopause which is moved to middle latitudes during the substorm compared to its location during quiet times, as reported by Goldstein et al. (2019). Figure 3C shows less sharp gradient around $L = 2.7$, which suggests that the plasmopause is being gradually shifted back to higher latitudes: from $L = 2.8$ in Figure 3B to around $L = 2.85$ and $L = 3$ in Figure 3C. Figure 3D shows that the plasmasphere is strongly eroded and the plasmopause is located near $L = 2.40$.

Several possible scenarios can explain these observations. One of them is that Figures 3A and 3B illustrate behavior of the plasmasphere during one substorm and Figure 3D shows plasma density profiles produced by another substorm occurred later this day. These scenarios are not the main focus of our study. The most important information for our study is that during substorms strong gradients in the plasma density occur at the low L -shell corresponding to the latitudes of the Palmer station in Antarctica. This information will be used in the simulations of the magnetosphere-ionosphere interactions described in the next section.

3 Simulations

3.1 Model

Plasma in the Earth's inner magnetosphere is magnetized and is relatively cold (plasma $\beta \ll 1$). ULF shear Alfvén waves in such plasma can be described with a reduced two-fluid MHD model developed by Chmyrev et al. (1988) and actively used after that, e.g., by Streltsov et al. (1998); Streltsov and Foster (2004); Streltsov and Mishin (2020). The word “reduced” means that the model contains only shear/Alfvén MHD mode. Fast (magnetosonic) and slow (ion acoustic) modes are not included in the model. The model consists of the parallel electron momentum equation

$$\frac{\partial v_{\parallel e}}{\partial t} + v_{\parallel e} \nabla_{\parallel} v_{\parallel e} + \frac{e}{m_e} E_{\parallel} + \frac{1}{m_e n_0} \nabla_{\parallel} (n T_e) = -\nu_e v_{\parallel e}, \quad (1)$$

the density continuity equation

$$\frac{\partial n}{\partial t} + \nabla \cdot (n_0 v_{\parallel e} \hat{\mathbf{b}}) = 0, \quad (2)$$

and the current continuity equation

$$\nabla \cdot \left(\frac{1}{v_A^2} + \frac{1}{c^2} \right) \frac{\partial \mathbf{E}_{\perp}}{\partial t} = e \mu_0 (1 - \rho_i^2 \nabla_{\perp}^2) \nabla \cdot (n_0 v_{\parallel e} \hat{\mathbf{b}}). \quad (3)$$

Here the subscripts “ $\parallel$ ” and “ $\perp$ ” denote vector components in the directions parallel and perpendicular to $\hat{\mathbf{b}} = \mathbf{B}_0/B_0$ respectively; $v_{\parallel e}$ is the parallel component of the electron velocity; T_e and T_i are the electron and ion temperatures; $\rho_i = (T_i/m_i)^{1/2}/\omega_{ci}$ is the ions Larmour radius; n_0 is the background plasma density; $v_A = B_0/(\mu_0 n_0 m_i)^{1/2}$ is the Alfvén speed, and $\nu_e = \nu_{ei} + \nu_{en}$ is the total electron collision frequency. Collisions are included in the model because they may cause absorption of very small-scale (< 1 km) waves at altitudes below 1000 km (Lysak & Song, 2002).

Equation (3) includes the perpendicular component of the displacement current, which is important when the Alfvén speed locally approaches the speed of light (e.g. when the plasma density is strongly depleted). The model also includes finite electron inertia and a full dispersive ion Larmour radius correction to the ion polarization current.

This correction allows the model to be valid even for the waves with a perpendicular scale size comparable or less than the ion Larmour radius ($\rho_i^2 k_{\perp}^2 \geq 1$) (Streltsov et al., 1998).

Equations (1)-(3) are implemented numerically in a dipole magnetic field geometry, which is a quite appropriate approximation of the geometry of the magnetic field at mid and low latitudes. The code relies on the Finite-Difference Time-Domain (FDTD) numerical approach, which implies that all temporal and spatial derivatives in the equations are approximated with finite differences. A fourth-order “predictor-corrector” method is used to time-advance the numerical solution. The Adams-Bashforth four-step method is used as a “predictor”, and the Adams-Moulton (AM) three-step method is used as a “corrector”.

The computational domain is a two-dimensional region bounded by $L_1 = 2.45$ and $L_2 = 2.95$ magnetic shells on the lateral sides and by the conducting bottom of the ionosphere (≈ 110 km altitude) on top and bottom boundaries. The computational grid is uniform in the direction across the ambient magnetic field and highly non-uniform along the field. The distance between adjacent grid points along the field decreases by a factor of 30-50 from the equatorial plane toward the ionosphere.

The code includes effects of the active ionospheric feedback on structure and amplitude of field-aligned currents interacting with the ionosphere. The basic idea of these interactions is that field-aligned currents change the ionospheric conductivity by precipitating or evacuating electrons from the ionosphere, and these changes in the conductivity, in turn, alter the reflection of the small-scale currents from the ionosphere. If the large-scale background electric field exists in the ionosphere, then changes in the conductivity also affect Joule dissipation of this field, which serves as the energy source for the small-scale FACs generated in the ionosphere. These new FACs add to the reflected currents and cause a so-called “over-reflection” of the small-scale currents from the ionosphere. Under a favorable condition (which includes low ionospheric conductivity and large electric field in the ionosphere) this mechanism leads to an instability, which is called the Ionospheric Feedback Instability (IFI).

In the simplest form, IFI can be implemented by considering the ionosphere as a thin conducting slab with a uniform in the vertical direction plasma density and the electric field (Streltsov & Mishin, 2020). Mathematically, this model can be written with two

equations connecting variations of the electric field and plasma density in the ionosphere with the field-aligned current density, $j_{\parallel}$, above the ionosphere:

$$\frac{\partial n}{\partial t} = \frac{j_{\parallel}}{eh} + \alpha(n_0^2 - n^2), \quad (4)$$

$$\nabla \cdot (\Sigma_P \mathbf{E}_{\perp}) = \pm j_{\parallel}. \quad (5)$$

Here e is the elementary charge; $h = 10 - 20$ km is the effective thickness of the E-region; α is the coefficient of recombination; and n_0 is the equilibrium plasma density in the ionosphere; $\Sigma_P = ehnM_P/\cos\psi$ is the height integrated Pedersen conductivity; M_P is the ion mobility in the ionosphere, and ψ is the angle between the normal to the ionosphere and the magnetic field. The + sign in Equation (5) is used in the Southern hemisphere and the - sign in the Northern hemisphere.

The Hall current is not included in Equation (5) because this 2D model does not include any azimuthal variation in the plasma density. In general, the Hall current may affect the development of the ionospheric feedback instability (Jia & Streltsov, 2014). For example, it may cause coupling between shear and compressible modes in the ionosphere (Yoshikawa & Itonaga, 2000). However, this effect has little impact on the dynamics of small-scale dispersive Alfvén waves at low altitudes for typical ionospheric conditions (Pokhotelov et al., 2000). The form of the active ionospheric boundary conditions given by Equations (4) and (5) has been successfully used in a number of studies of active magnetosphere-ionosphere interactions (Sato, 1978; Miura & Sato, 1980; Trakhtengertz & Feldstein, 1984; Lysak, 1991; Watanabe et al., 1993; Lysak & Song, 2002; Streltsov & Mishin, 2018, 2020).

The external driver and the initial conditions for this model are described in detail in several papers, e.g., Streltsov and Lotko (1995), Streltsov et al. (1998), and Streltsov and Foster (2004). The simulations start by assuming that there are no fields, waves, and currents in the magnetosphere or ionosphere. In the model these fields and currents are expressed via scalar potential ϕ and the parallel component of the vector potential $A_{\parallel}$, namely, $\mathbf{E}_{\perp} = \nabla_{\perp}\phi$, $\mathbf{B}_{\perp} = \nabla \times A_{\parallel}\hat{\mathbf{b}}$, and $j_{\parallel} = -(1/\mu_0)\nabla_{\perp}^2 A_{\parallel}$. Thus, the initial conditions for ϕ and $A_{\parallel}$ are set equal to zero.

The model is driven by the “generator” localized on the right lateral boundary ($L = 2.95$) in the equatorial region. There $\phi = \phi_0 e^{-|\ell/\ell_0|} \sin(\omega t)$ and $\partial A_{\parallel}/\partial t = -\nabla_{\parallel} \phi$. Here ℓ is the distance along $L = 2.95$ magnetic shell measured from the equator and $\ell_0 = \mathcal{L}/4$, where $\mathcal{L}$ is the total length of $L = 2.95$ field line. Both ϕ and $A_{\parallel}$ are kept equal to zero on the left lateral boundary of the domain.

The amplitude of the driver linearly increases in time from zero to some specified magnitude during the first three periods of the pump wave. This is done to provide a smooth temporal transition from the initial zero state to a state when large-amplitude fields and currents form near the plasmopause. The temporal behavior of the driver is qualitatively the same as the dynamic of the large-scale current measured in the ionosphere in the simulations with the passive ionosphere. That dynamic is shown with a blue dashed line in Figure 6.

This type of generator corresponds to the electromagnetic disturbances propagating in the equatorial plane from the magnetotail during substorms. It has been successfully used by Streltsov et al. (1998) and Streltsov and Foster (2004) in studies of large-scale surface Alfvén waves generated on strong plasma gradients in the equatorial magnetosphere at high latitudes. The effect of the solar wind is added in the model via the frequency of the driver. In the simulations present in this paper this frequency is 1.1 mHz, which is one of the common frequencies of the largest PSD amplitudes detected in the solar wind and on ground at high and mid latitudes.

3.2 Background Parameters

The main background parameters of the model are the ambient magnetic field and the plasma density. The magnetic field is assumed to be dipole: $B(r, \theta) = B_*(1/r^3)(1 + 3 \sin^2 \theta)^{1/2}$, where r is the geocentric distance measured in $R_E = 6371.2$ km and θ is the magnetic latitude. This assumption is quite reasonable at low latitude shells modeled in this paper.

The plasma density should be specified in the ionosphere and magnetosphere. The density in the ionosphere defines the ionospheric conductivity which, in turn, defines the development of the ionospheric feedback instability. The mass density in the magnetosphere defines the period of standing Alfvén waves. Together they define dynamics and the thresholds for the ionospheric feedback instability.

The plasma density used in the simulations is calculated using SAMI2 model. SAMI2 is “Another Model for the Ionosphere” developed in the Naval Research Laboratory to describe plasma density in the mid- and low-latitude ionosphere (Huba et al., 2000). It calculates the dynamics and chemical evolution of seven ion species: H^+ , He^+ , N^+ , O^+ , N_2^+ , NO_2^+ , and O_2^+ . Ion inertia is included in the ion momentum equation for motion along the geomagnetic field, which is important in describing plasma dynamics in the topside ionosphere and the magnetosphere. SAMI2 uses a dipole geometry of the Earth’s geomagnetic field and a non-orthogonal non-uniform computational grid.

For the date and time corresponding to the substorm event occurring on 09/28/2016 at 1600 UTC, SAMI2 provides density of $1.75 \times 10^3 \text{ cm}^{-3}$ in the ionospheric E-layer, $2.75 \times 10^5 \text{ cm}^{-3}$ in the F-layer and $5.5 \times 10^3 \text{ cm}^{-3}$ at the equator. Figure 4A shows the electron density and the corresponding Alfvén velocity, v_A , along $L = 2.7$ between the conjugate locations in the ionosphere in the Southern and Northern hemispheres.

Figure 4B shows the profile of the electron density across the ambient magnetic field in the equatorial plane. This density profile is based on the RBSP-B observations and the SAMI2 model, with a steep gradient at $L = 2.7$ and relatively large difference between the density values across the plasmopause. The density profile shown in Figure 4B is defined as

$$n(L) = \frac{n_2 + n_1}{2} \left(1 - \frac{n_2 - n_1}{n_2 + n_1} \tanh \frac{L - L_0}{\delta L} \right). \quad (6)$$

Here n_1 and n_2 are the densities on two sides of the plasmopause ($n_2 > n_1$, see Figure 4B) and δL is the characteristic width of the plasma pause. Parameter $1/\delta L$ defines the transverse gradient in the density and $(n_2 - n_1)/2$ defines the amplitude of the density variation across the plasmopause.

4 Results and Discussions

Figure 5 illustrates evolution of the parallel current density in the simulations with the passive ionosphere (panels on the left) and with active ionosphere (panels on the right). The frequency and the amplitude of the driver are the same in both simulations. Specifically, the frequency of the driver is 1.1 mHz and the amplitude of the driver is chosen to provide maximum electric field of 100 mV/m in the ionosphere in the simulations with

the passive ionosphere. The simulation with the passive ionosphere differs from the simulation with the active ionosphere by “turning-off” Equation (4) in the model. In other words, the field-aligned current does not change the ionospheric density in the simulation when the ionosphere is passive and changes it when the ionosphere is active.

Three different time periods were chosen to demonstrate how the intense small-scale ULF waves are developed throughout the simulations. At the first moment of time, $t = 1118$ s, both passive and active cases are similar. At the second moment of time, $t = 2850$ s, the passive ionosphere case has been observed to have only increased maximum amplitude of the current density, whereas the active case shows the development of small-scale current structures. They start near $L = 2.7$ and propagate in the perpendicular directions from the plasmapause in the direction of the large-scale electric field in the ionosphere. The asymmetry around $L = 2.7$ is explained by the fact that the driver acts from the right lateral boundary of the simulation domain in the direction of the left lateral boundary, and that the density inside the plasmasphere ($L < 2.7$) is larger. Therefore, the dynamics of the current density is different w.r.t $L = 2.7$.

The structure of this field was first investigated analytically by Hasegawa (1976) and later confirmed with simulations by Streltsov and Lotko (1995). It is shown with red lines in the upper panels in Figure 5. This field has a very specific dipole structure: zero on the plasmapause and different signs on two sides from the plasmapause. This structure is quite different from the structure of the large-scale electric field observed near the plasmapause in the subauroral zone (Streltsov & Mishin, 2018, 2020). This difference suggests that the large-scale electric fields at high and middle latitudes are produced by different mechanisms. Indeed, in studies of the ULF waves near the plasmapause in the subauroral zone, it was suggested that this field is generated by the fluxes of the energetic particles penetrating into the plasmasphere from the reconnection site in the tail. In this study, the large-scale field is associated with the surface waves excited on the plasmapause by the fast magnetosonic waves generated in the magnetosphere by the fluctuations in the solar wind.

In each case the large-scale electric field drives the ionospheric feedback instability in the ionosphere when and where the conditions for the instability are satisfied. These conditions include low ionospheric conductivity and large amplitude of the electric field. The background conductivity is uniform in the ionosphere at the initial moment of time,

so the conditions for the instability are satisfied first in the locations where the electric field reaches maxima, which happens not on the field line where the gradient in density has its maximum (plasmopause).

It should be mentioned here, that the external driver used in the simulations produces symmetrical relative to the the magnetic equator electric field and asymmetrical magnetic field. The magnetic field in the surface wave produces an asymmetrical field-aligned current. So, at every moment of time, this generator produces large-scale field-aligned currents which are upward or downward in both hemispheres. This fact explain the symmetry relative to the magnetic equator of the small-scale currents in both hemispheres.

Figure 6 shows the temporal behavior of the amplitude of the current density in the southern ionospheric E-layer (110 km altitude) at $L = 2.7$ magnetic field line. The solid black line shows results from the simulation with the active ionosphere and the blue dashed line shows results from the simulation with the passive ionosphere. The moments of time when the snapshots of $j_{\parallel}$ shown in Figure 5 are taken from the simulations are marked in Figure 6 with red dashed lines. At $t = 1118$ s, the difference of the current density amplitudes in both cases is quite small, which means that IFI does not start working yet. At $t = 2850$ s, the magnitude of $j_{\parallel}$ in the upward current reaches its maximum in the ionosphere and at $t = 3355$ s the magnitude of the downward current reaches its maximum.

The frequency of oscillations of $j_{\parallel}$ in the simulation with the passive ionosphere is 1.1 mHz, which corresponds to the frequency of the driver. These oscillations are shown with the blue dashed curve in Figure 6. It should be noticed that the dynamics of $j_{\parallel}$ in this simulation corresponds to the “non-resonant” behavior of the system. The amplitude of $j_{\parallel}$ increases until t_2 , and this corresponds to the linear increase of the driver’s amplitude. As soon as the driver’s amplitude becomes constant, the amplitude of $j_{\parallel}$ in the large-scale waves on the plasmopause also becomes constant. This type of behavior is expected because the frequency of the driver (1.1 mHz) is much less than the fundamental eigenfrequency of the system (≈ 15 mHz). A similar dynamics of the surface waves driven by the sub-resonant driver on the density gradients in the sub-auroral zone was reported by Streltsov and Foster (2004).

Figure 6 also shows a strong difference in the amplitude of the positive and negative field-aligned currents in the simulation with the active ionosphere. This difference is explained by the fact that the positive current flows in the direction of the ambient magnetic field and this is the upward current in the Southern hemisphere. It precipitates electrons into the ionosphere and locally increases the ionospheric conductivity. The negative field-aligned current is the downward current in the Southern hemisphere. It evacuates particles from the ionosphere and decreases the conductivity. The change in the conductivity, in turn, alters the reflection coefficient of the field-aligned currents from the ionosphere and produces asymmetry in the amplitudes of upward and downward $j_{\parallel}$ shown in Figure 6.

Because the ionospheric feedback mechanism involves self-consistent dynamics of the magnetospheric field-aligned currents, the plasma density and the electric field in the ionosphere, the last two quantities also change dynamically when the ionosphere is active. Dynamics of all these quantities in the simulations with the active ionosphere are shown in Figure 7. Particularly, Figure 7A shows dynamics of the perpendicular electric field in the ionosphere in the Southern hemisphere. It demonstrates that the magnitude and the geometry of this field is very different between the cases when the upward and the downward field-aligned currents interact with the ionosphere. Namely, the upward (positive) FAC increases the conductivity and reduces the electric field (particularly, near the plasmopause). The downward (negative) FAC decreases the conductivity and increases the electric field in the ionosphere. Because this field is the main energy source for IFI and IFI develops better when the density in the ionosphere is low, more intense, small-scale structures appear in the domain when the downward current interacts with the ionosphere.

Figure 7B illustrates dynamics of small-scale field-aligned currents above the ionosphere. It shows that the appearance and dynamics of these currents are modulated by the electric field in the ionosphere (Figure 7A), which means that they are indeed produced by the IFI driven by this field. It also shows that the small-scale FACs can be detected in a range $\pm 0.15 L$ around the plasmopause.

Thus, simulations confirm that the location of the plasmopause determines the development of the ionospheric feedback instability and generation of intense ULF waves at low latitudes during substorms. The location of the plasmopause defines the magnetic

L-shell where the large-scale field-aligned current is generated by the driver. The interaction of this current with the ionosphere produces large-scale electric field in the ionosphere. This field drives the ionospheric feedback instability in the ionosphere, which generates small-scale ULF waves and currents. Thus, these waves are generated in the vicinity of the plasmopause, as it is shown in Figure 5. If the plasmopause will move to higher or lower L-shells, then the large-scale electric field and the small-scale waves and currents will change their locations accordingly. Figure 5E shows the development of the electric field before and after the plasmopause. These results provide a rationale to investigate how the other parameters of the plasmopause, such as the gradient and the magnitude of the density variation, affect the development of the small-scale structures.

Figure 8 shows the maximum amplitude of the current density in simulations with the passive ionosphere when these parameters are changed. Figure 8A shows the transverse density profiles in the equatorial magnetosphere where the transverse density gradient $1/\delta L$ changes from 16 to 80. In all these simulations the amplitude of the driver and the magnitude of the density variation across the plasmopause, $(n_2 - n_1)/2$, remain the same. The maximum current density obtained in these simulations is plotted on Figure 8B. It shows that there is a direct linear dependence of the maximum amplitude of FAC on the density gradient in the equatorial magnetosphere.

Figure 8C shows the density profiles with the same linear slope, but with different amplitude of the density variation across the plasmopause. We used the linear slope in this case to avoid the effect of varied smoothing of the sharp “edges” of the density profile produced by the tanh function with different amplitudes. Figure 8D shows that in this case the maximum amplitude of the field-aligned current is also linearly proportional to the magnitude of the density variation. The dependencies of the maximum amplitude of $j_{\parallel}$ on the parameters of the density gradient forming the plasmopause shown in Figure 8 are consistent with the results of a similar analysis conducted by Streltsov and Foster (2004).

The last point of our investigation is to compare the frequencies of the waves obtained in the simulations with frequencies of magnetic pulsations observed at Palmer station in Antarctica during the 09/28/2016 substorm event. This comparison is shown in Figure 9. Specifically, Figure 9A shows the power spectral density (PSD) of $j_{\parallel}$ obtained in the simulations with the active ionosphere from around $t = 2000$ s to 5600s in the sim-

ulations to include five period of the oscillations (Figure 6), and that of B_X measured by the ground magnetometer at Palmer in the frequency range from 0 to 40 mHz, taken from around 1500 to 1700 UTC (Figure 1C). Figure 9A emphasizes the frequencies associated with FLR, whereas Figure 9B emphasizes those of IAR. Due to the relatively high sampling rate of Palmer stations magnetic field data (0.5 s, compared to 1s on Poker Flat and ACE, for example), the data is consistently noisy across the whole time of observation. Thus, the PSD data turns out to be noisy as well. To remediate this issue to a degree, for Figure 9 we sampled the Palmer station data in such a way that PSD precision of Palmer data and simulation data is almost the same (0.30 mHz). However, the PSD data from Palmer magnetic field in the range of 500 to 1000 mHz still looks very noisy due to abundance of data points.

Both PSDs show significant presence of waves in the frequency range from 5 to 25 mHz and both PSDs demonstrate a sharp amplitude decrease after 25 mHz. Both spectra have almost matching peaks at frequencies of 17, 21, 23 mHz, and frequencies of 15 mHz and 21 mHz correspond to the “natural” Alfvén frequencies at $L = 2.7$ (the L shell of the plasmapause) and $L = 2.46$ (the L shell of the Palmer station), respectively. The natural Alfvén wave frequency at specific L-shell is calculated using the parameters of that L-shell and the Alfvén velocity profile (shown in Figure 4A as red dashed line). First, the period is calculated, $T_{VA} = \int_0^d (1/V_A) dx$, where d is the distance along the L-shell (around 3.4×10^4 km for $L = 2.7$). Then the frequency of the waves is calculated using two such periods, because one period is only from one end of the L-shell to another, $f_{VA} = 1/(2T_{VA})$.

Thus, both simulations and observations suggest that the waves detected on the ground at Palmer station are indeed produced by the ionospheric feedback instability developed in the global magnetospheric resonator and driven by the electric field in the vicinity of the plasmapause.

In the frequency range from 500 to 1000 mHz, both PSDs are quite noisy due to the abundance of data for such a large frequency range; however some amplitude peaks are still distinguishable. For instance, the PSD of B_X has such peaks at 560, 660, 700, 835, 930 mHz, whereas the PSD of $j_{\parallel}$ has peaks with close frequencies at 550, 640, 720, 810, 935 mHz. This frequency range is the range of the Ionospheric Alfvén Resonator (IAR). Therefore, simulations and observations suggest that the IAR also plays a role in the electromagnetic coupling between the ionosphere and magnetosphere at low lat-

itudes, as it was suggested in the pioneering papers about IAR by Polyakov and Rapoport (1981) and Belyaev et al. (1990).

The reason why the spectra of the experimental and numerical data show signals in some frequency bands rather than the discrete frequencies associated with some particular resonant harmonics is the fact that these resonances are driven by the electric field changing in time. Because the amplitude of the large-scale field is one of the main parameters determining the eigenfrequency of the IFI, the temporal variation of this field affects the frequencies of the resonant waves in the observations and simulations.

5 Conclusions

The results from the numerical study presented in this paper demonstrate that the plasmopause plays a very important role in the generation of ultra-low frequency waves detected with ground magnetometers at middle latitudes. The strong gradient in the plasma density associated with the plasmopause converts the electromagnetic energy of the fast magnetosonic waves propagating across the magnetic field to the energy of the field-aligned surface Alfvén waves. The efficiency of this mode conversion depends on the parameters of the plasmopause. In particular, the time-dependent simulations of the two-fluid MHD model show that the amplitude of the surface waves is linearly proportional to the gradient of the plasma density and the magnitude of the variation of the density across the plasmopause.

The paper uses the observations from the ground magnetometers at Palmer station in Antarctica to identify the frequency of the driver and frequencies of the waves generated by the ionospheric feedback instability. It also uses the observations of the plasma density conducted by the the NASA Van Allen Probes satellite in the equatorial magnetosphere on the same date. The satellite observations confirm that during substorms the plasmasphere can be strongly eroded away and the plasmopause moves to middle latitudes.

The model uses the observed frequency of 1.1 mHz to drive the surface waves on the plasmasphere. The simulations show that the large scale electric field modulated with this frequency drives the ionospheric feedback instability generating waves with frequencies < 25 mHz. The waves with the same frequencies are also observed in the measurements of the Palmer magnetometer. The numerical results and the ground observations

also reveal waves with the frequencies in the range 0.5-1.0 Hz, which correspond to the frequencies of the ionospheric Alfvén resonator. This is a very expectable outcome because the main driver of the waves inside the IAR is the same ionospheric feedback instability as the one used in our study to drive the waves in the global magnetospheric resonator. The simulations also demonstrate that the instability develops quite efficiently from the small-scale ionospheric irregularities associated with the numerical noise in the simulations which can be considered as a proxy for the random thermal fluctuation of the plasma density in the real ionosphere.

Acknowledgments

The research was supported by the NSF award AGS 1803702. We thank Joe Huba for his help with the SAMI2 model. Van Allen Probes satellite data was obtained from <https://cdaweb.gsfc.nasa.gov/index.html/> and <http://www.space.umn.edu/rbspefw-data/>. ACE magnetic field and solar wind parameters data were taken from <http://www.srl.caltech.edu/ACE/ASC/>. Poker Flat magnetometer data were taken from <http://www.gi.alaska.edu/magnetometer/>. Palmer magnetometer data were taken from <http://magnetometers.bc.edu/>.

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Figure 1. Magnetic field data from ACE satellite, Poker Flat station and Palmer station on 09/28/2016. Substorm was observed at around 1600 UTC. ACE satellite data is shifted by 0.75 hours w.r.t. ground time, according to the respective solar wind speed. Panels (A), (B), (C) show recorded magnetic field data (red line) along with its trend-line (black line) of the three data sources, respectively. Panels (D), (E), (F) show respective de-trended magnetic field wavepacks. Panels (G), (H), (I) show the Power Spectral Density (PSD) of the de-trended wavepacks.

Figure 2. The Van Allen Probe RBSP-B satellite data on 09/28/2016. Black line is the electron density data, with its axis on the left. Blue line is the L -shells of the satellite trajectory at corresponding time, with its axis on the right. Solid horizontal red line emphasizes the $L = 2.46$ magnetic tube which corresponds to the Palmer station. Dashed vertical red lines with labels A, B, C, D highlight the density gradients at respective L -shells.

Figure 3. The electron density along the L -shell based on RBSP data on 09/28/2016. The time ranges in Panels A, B, C, D correspond to the periods when the satellite passed through $L = 2.46$, as shown on Figure 2.

Figure 4. (A) The electron density profile (solid black line) and Alfvén velocity profile (dashed red line) used in the simulations, along $L = 2.7$, from Southern to Northern ionosphere. (B) The electron density profile in the equatorial plane used in the simulations. The gradient slope, G_1 , and the ratio n_2/n_1 are defined by Equation 6.

Figure 5. (The top row of the panels) The electron density profile and the electric field in the passive ionosphere case (panel A) and the active ionosphere case (panel E). (The rest of the panels) Snapshots of the current density when 1) the Ionospheric Feedback Instability is not developed yet (panels B and F), 2) current density has the largest amplitude in the ionosphere (panels C and G); 3) current density has the smallest amplitude in the ionosphere (panels D and H). The panels on the left show $j_{\parallel}$ in the simulation with the passive ionosphere and panels on the right show $j_{\parallel}$ in the simulation with the active ionosphere.

Figure 6. Evolution of the current density in the ionospheric E-layer (altitude 110 km) during the simulations of the 09/28/2016 substorm event. The driver has the frequency of 1.10 mHz. The blue dashed line shows the dynamics of the current density in the simulation with the passive ionosphere and the solid black line shows the dynamics of the current density in the simulation with the active ionosphere.

Figure 7. The dynamics of (A) the electric field, (B) parallel current density, and (C) conductivity in the Northern ionosphere (altitude 110 km) in the simulation with the active ionosphere.

Figure 8. (A) The transverse electron density profiles with different slopes. (B) The maximum values of the current density in the ionosphere in simulations with gradients shown in the panel (A). (C) The electron density profiles with different amplitudes of the density variation. (D) The maximum values of the current density in the ionosphere in simulations with the gradients shown in the Panel (C).

Figure 9. Power Spectral Density (PSD) of the x -component of the magnetic field measured on Palmer station during 09/28/2016 substorm event (black lines) and of the current density obtained in the simulations (red lines) in the frequency range (A) from 0 to 40 mHz and (B) from 500 to 1000 mHz.