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Possible generation mechanisms of the Pi2 pulsations estimated from a global MHD simulation

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The plasmaspheric virtual resonance (PVR) and the transient Alfvén wave bouncing between the ionospheres in both hemispheres (the transient response, TR) are regarded as the possible generation mechanisms of the Pi2 pulsations. However, the global MHD simulation of a substorm (Tanaka *et al*., 2010) did not reproduce such wave modes because of insufficient ionospheric reflection of the Alfvén wave, numerical transfer of the Alfvén wave across the field lines, and no plasmasphere. Furthermore, it is noted that the substorm current wedge (SCW) which is a driver of the TR is not reproduced in the global MHD simulation. In this study, we search the sources of the Pi2 pulsations in the global MHD simulation, namely, the compressional wave in the inner magnetosphere for the PVR and the Alfvén wave injected to the ionosphere for the TR. In conclusion, there appears a compressional signal in the inner magnetosphere when the high-speed Earthward flow at the substorm onset surges in the inner edge of the plasma sheet. This simulation result suggests that this compressional wave would be trapped in the plasmasphere as the PVR if the model has the plasmasphere. As for TR, the global MHD simulation provides suddenly increasing field-aligned current (the Alfvén wave) associated with sudden appearance of the shear flow which comes from the high-speed flow in the plasma sheet at the onset of the substorm. If the global MHD simulation correctly lets the Alfvén wave be reflected in the ionosphere and transmitted along the field line, the TR would be established. As the ballooning instability is regarded as one of candidates of the Pi2 pulsation sources, we also briefly investigate whether the simulated plasma sheet in the growth phase is unstable or not for the ballooning instability.

Key words: Pi2 pulsation, global MHD simulation, substorm, high-speed plasma flow.

1. Introduction

The Pi2 pulsation is a damped oscillation with a period of 40–150 sec. (Saito, 1969; Olson, 1999). Simultaneous occurrence of the Pi2 pulsation with the substorm onset (e.g., Saito *et al*., 1976) indicates that the Pi2 pulsation is one of the important ingredients in the substorm processes. Thus, when we make a numerical substorm model, it is important to investigate how the Pi2 pulsation is generated at the substorm onset in the model. We have a newly improved MHD simulation model that is believed to reproduce correctly the substorm onset (Tanaka *et al*., 2010). Thus, it is important to consider how the Pi2 pulsation is generated in the simulation. This is the motivation of the present work.

The main features of Pi2 have been summarized in reviews by Olson (1999) and Keiling and Takahashi (2011). There appears to be a latitude distribution of Pi2 spectral properties. After Yumoto *et al*. (2001), the Pi2 pulsation at mid- and low-latitudes tends to have latitudinally-independent and rather higher frequency, while at higher latitudes the high-latitude one shows the lower frequency that gradually decreases. The Pi2 pulsation with the common frequency at mid- and low-latitudes is explained in terms of the plasmaspheric virtual resonance (PVR) mode (Fujita and Glassmeier, 1995; Lee, 1998). Experimental evidence for the PVR was given by Takahashi *et al*. (2003). On the other hand, the Pi2 pulsation at higher latitudes can be regarded as a transiently bouncing wave packet of the Alfvén mode (the transient response, TR) (Baumjohann and Glassmeier, 1984). It is concluded that the Pi2 pulsation shows two different features in high-latitudes and middle- and low-latitudes. Therefore, the model of the Pi2 pulsation should explain behavior of the Pi2 pulsation both at high-latitude and at middle- and low-latitudes. Furthermore, the initial movement of the ground magnetic variation associated with the Pi2 pulsation is consistent with the magnetic variation induced from the Region 1 (R1) field-aligned current (FAC) (Yumoto *et al*., 1990). This result has been believed to support the model that the Pi2 pulsation is associated with the substorm current wedge (SCW) (McPherron *et al*., 1973). Consequently, Fujita *et al*. (2002) performed their numerical simulation of the Pi2 pulsation based on a simplified model of the SCW (the linear MHD-wave simulation). The linear MHD-wave simulation is explained in the next section.

Let us describe briefly the substorm scenario deduced from the global MHD simulation (Tanaka *et al*., 2010). In the growth phase after southward turn of the interplanetary magnetic field (IMF), the magnetic field convection in

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the lobe region and that in the plasma sheet are different. Thus the magnetic fields in the plasma sheet region are configured to be strongly extended tailward in the equatorial plane (the plasma sheet thinning). At the same time, electromagnetic energy is stored in the mid-tail region. As the thinning cannot continue indefinitely, there must be sudden transition of the convection system. The transition starts at time of the reconnection from which the magnetic field tension stored in the growth phase is released. The released tension yields high-speed plasma flow toward the Earth and yields enhanced pressure in the inner boundary of the plasma sheet. The simulation by Tanaka *et al.* (2010) reproduces sudden magnetic field depression (explosive growth phase after Ohtani *et al.* (1992)) and sudden enhancement of the Region 2 (R2) FAC due to enhanced pressure in the inner boundary of the plasma sheet invoked by the high-speed plasma flow from the plasma sheet at the substorm onset. Finally, the R1 FAC is also formed as a part of a loop closure current associated with the R2 FAC in the magnetosphere-ionosphere region. In the simulation, they succeeded in reproducing abrupt decrease in AL indices at auroral onset. However, the simulation does not reproduce the SCW. Therefore, the premise for the linear MHD-wave simulation of the Pi2 pulsation is not realized in the global MHD simulation. Therefore, we need to investigate how the Pi2 pulsation is thought to be produced in the situation reproduced by the global MHD simulation.

In the next section, we discuss how the Pi2 pulsation is regarded to be generated based on both the global MHD simulation of the substorm (Tanaka *et al.*, 2010) and the linear MHD-wave simulation of the Pi2 pulsation (Fujita *et al.*, 2000, 2001, 2002). It is noted that we do not reproduce the Pi2 signals in the coupled model of the global MHD simulation and the linear MHD-wave simulation. We just discuss how the global MHD simulation invokes plasma disturbances that are regarded as sources of the Pi2 pulsations in the linear MHD-wave simulation. In the third section, the ballooning mode that is considered to drive the Pi2 pulsation will be discussed in brief. In the last section, we summarize main results.

2. Numerical Results

First, we note that the oscillations with period of 40–150 sec are not detected at the onset of the substorm in the global MHD simulation. Therefore, we discuss possible generation mechanisms of the Pi2 pulsation based on the plasma behavior revealed from the numerical results of the global MHD simulation.

Although the global MHD simulation solves a full set of the MHD equations, it does not reproduce the Pi2 pulsation explicitly because of several assumptions in modeling the physical system, e.g., numerical transfer of the field-aligned propagating Alfvén wave in the numerical grid is not referenced to the magnetic field lines and imperfect reflection of the MHD waves injected to the ionosphere, and lack of the plasmasphere. On the other hand, the linear MHD-wave simulation (Fujita *et al.*, 2000, 2001, 2002) reproduces the Pi2 pulsation, but it employs the hypothetical SCW as a driver of the MHD waves. Thus, if we prove that the global MHD simulation provides source disturbances necessary for the Pi2 pulsation generation employed by Fujita *et al.* (2002), we suggest that the global MHD simulation may be capable of reproducing the Pi2 pulsation associated with the substorm.

2.1 The Pi2 pulsation simulated by the linear MHD-wave simulation

The linear MHD model of Fujita *et al.* (2002) simulated Pi2 propagation in a non-uniform magnetosphere with the plasmasphere under the realistic ionosphere boundary condition by assigning explicitly a source of the Pi2 pulsation. Refection of the MHD wave incident to the ionosphere is also correctly treated unlike the global MHD simulation. The linear MHD model used a sudden formation of the SCW (McPherron *et al.*, 1973) as a driver of the Pi2 pulsation. However, it was impossible to simulate the SCW self-consistently in the linear MHD-wave simulation. Therefore, it employed a suddenly developing dusk-to-dawn current in the midnight region at $L \sim 10\ R_e$ as an external input of MHD disturbances (an equivalence of the SCW). The dusk-to-dawn current system is confined in azimuthal (local-time) direction. The simulation showed Alfvén wave packets emitted from the east- and west-end regions of the SCW bounce between the ionospheres in both hemispheres; these signals are Pi2 pulsations at high latitudes (the TR). At the same time, the compressional mode (the fast magnetosonic mode) generated by sudden increase of the azimuthal current is launched to the inner magnetosphere. As there is a minimum of the Alfvén speed profile in the plasmasphere, the compressional mode is partly trapped there. This trapping invokes the PVR which has azimuthally non-uniform electromagnetic field because the source of this PVR is limited in the azimuthal direction. Therefore, the coupling resonance between the PVR (the compressional wave) and the field-line resonance mode (the Alfvén wave) occurs in the inner magnetosphere (Tamao, 1965).

2.2 The Pi2 pulsations at high-latitudes

The Pi2 pulsations at high-latitudes are regarded as the TR (Baumjohann and Glassmeier, 1984). Fujita *et al.* (2001, 2002) reproduced the TR in the model where the dusk-to-dawn current is suddenly formed (an equivalence of the SCW). Consequently, the FAC is initially downward and upward in post-midnight and pre-midnight regions (R1 FAC), respectively. Therefore, a sudden increase in the R1 FAC is essential for the high-latitude Pi2 pulsation (TR). If the MHD simulation presents rapid formation of the R1 FAC at the onset of the substorm, the TR would be produced if the ionospheric reflection is correctly reproduced and the Alfvén wave is propagating just along the field lines. Therefore, we need to search such a rapidly growing FAC. Figure 1 shows ionospheric FAC patterns just before and just after the substorm onset in the top panels. The bottom panel illustrates temporal variations of upward FAC intensity (the R1 FAC intensity in the pre-midnight region) at the three points where the upward current increases suddenly in post-midnight ionosphere. This figure indicates sudden increase of the R1 FAC within a couple of minutes. Therefore, we can expect that the wave packet bouncing between ionospheres in both hemispheres will be formed if this FAC is reflected by the ionosphere. Unfortunately, since ionospheric reflection and field-aligned prop-

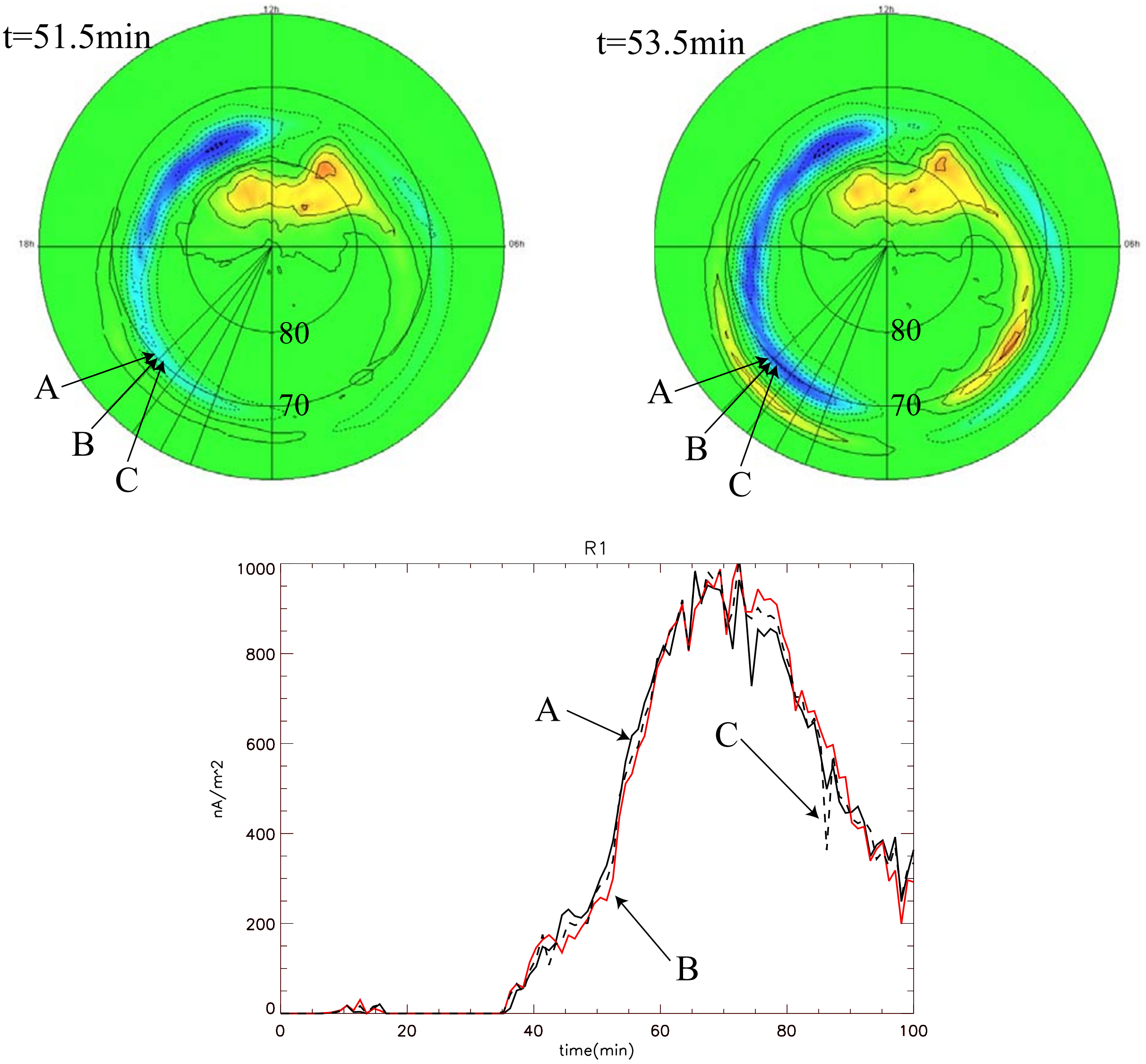

Fig. 1. Ionospheric profiles of FACs (top-left) at 51.5 min and (top-right) at 53.5 min. Blue and red areas indicate upward and downward FACs, respectively. The bottom panel illustrates temporal variations of R1 FACs at the three points in the ionosphere. Latitudes and longitudes (counter-clockwisely from the midnight meridian) are (69.4°, 315°) for A, (69.4°, 319°) for B, and (69.4°, 323°) for C. Positions of the three points are also shown in the top panels.

agation of the Alfvén wave are not correctly reproduced in the global MHD simulation, the simulation does not directly reproduce the TR.

Many previous models of the Pi2 pulsation, even Fujita *et al.* (2001, 2002), assumed the SCW (McPherron *et al.*, 1973) as a working hypothesis. However, it should be noted that the increased FAC at the substorm onset is not related to the SCW after Tanaka *et al.* (2010). Let us investigate why such a fast growing R1 FAC is generated in the global MHD simulation. After Tanaka *et al.* (2010), there appears the high-speed earthward flow in the plasma sheet at the substorm onset. This flow stops at the inner boundary of the plasma sheet (the Ring current region) at midnight and bifurcated into the pre-midnight and post-midnight regions. The top panel of Fig. 2 shows the flow vectors on the surface of $r = 10\ R_e$ when the high-speed flow arrives at the Ring current region. We notice flow shear in the shell as shown with a big white arrow. This shear is related to conversion between a field-aligned current and a cross-tail current. The conversion is recognized in the bottom panel of Fig. 2. In addition, as the auroral breakup (enhancement of the ionospheric conductivity) is associated with the arrival of the high-speed flow at the Ring current region, the ionospheric conductivity is enhanced due to precipitation of high-energy particles from the magnetosphere at the arrival time of the high speed flow at the Ring current region. (Our MHD simulation code assumes the ionospheric conductivities controlled by particle precipitation from the magnetosphere.) This enhanced ionospheric conductivity also contributes to rapid increase in the R1 FAC intensity. It is evident from the bottom panel of Fig. 2 that this current system is different from the SCW. Consequently, even without the SCW, a rapidly growing R1 FAC will lead to conditions that may drive the Pi2 pulsation.

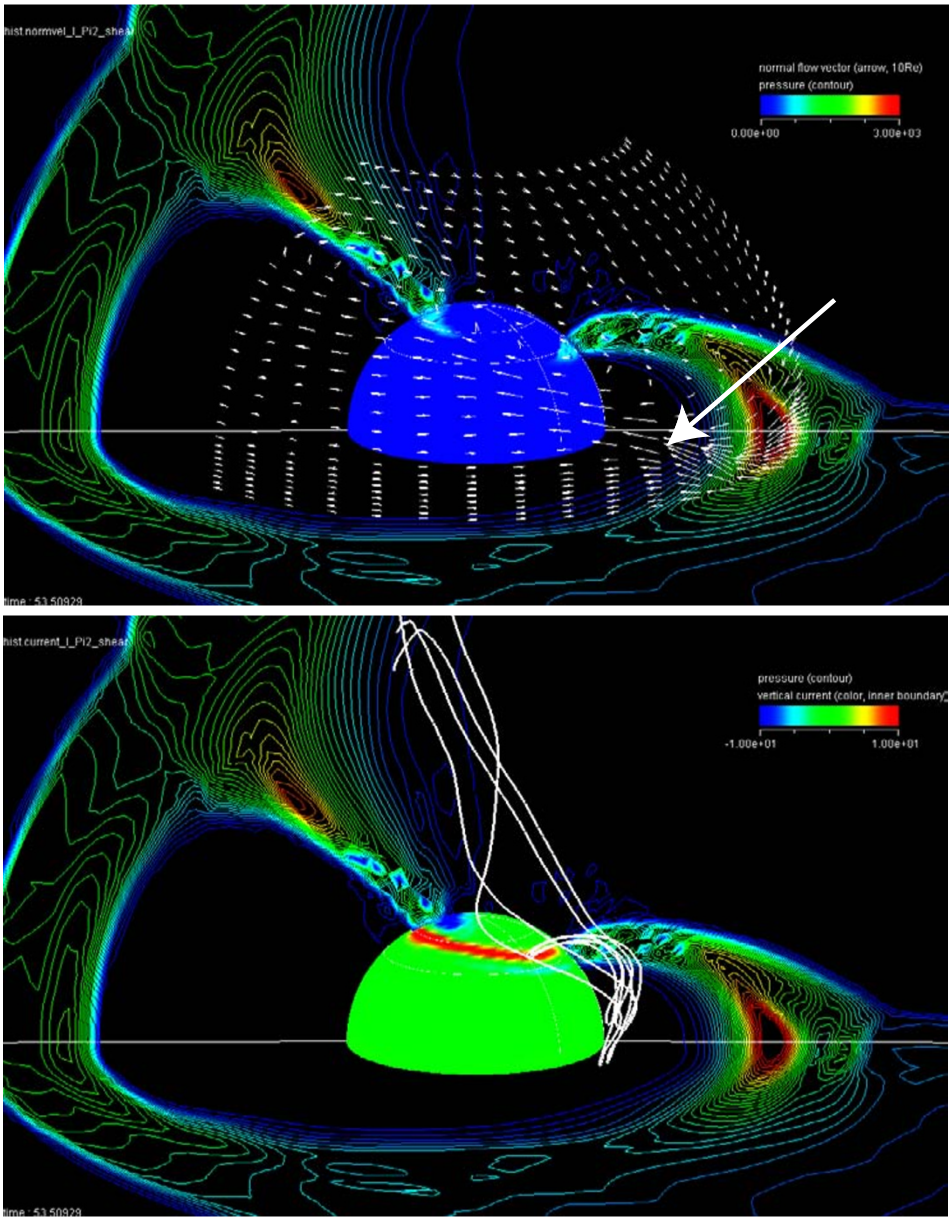

Fig. 2. (Top) Flow vectors at $r = 10\ R_e$ at $t = 53.5$ min and (bottom) current lines of the R1 FAC with their roots on the meridian of 21.3 LT (Region A in Fig. 1). Center spheres in both panels mean the inner boundary (3 R_e). Contours in both panels illustrate pressure profile in the equatorial plane (afternoon $\sim$ evening side) and that in the meridional plane. The big white arrow in the top panel indicates the flow shear invoked by the high-speed plasma flow at the substorm onset. The red region in the inner boundary means R1FAC in the bottom panel. The R1 FAC is connected with the cross-field current to the cusp generator region in the region of the flow shear.

2.3 The Pi2 pulsations at middle- and low-latitudes

Tanaka *et al*. (2010) demonstrated that the high-speed Earthward convection flow at the substorm onset suddenly stops in the region with increased ambient magnetic field intensity (the Ring current region) in the nightside magnetosphere. Then, pressure at $L \sim 7\ R_e$ is suddenly increased. In other words, the inner magnetosphere in the nightside is suddenly compressed. Then, if this sudden compression will invoke a compressional MHD wave in the inner magnetosphere and if there might have been the plasmasphere where V_A (the Alfvén speed) exhibits local minimum, the conditions would be right for the PVR to be generated (Fujita and Glassmeier, 1995; Lee and Kim, 1999). Fujita *et al*. (2002) presented behavior of the compressional wave and that of the field line resonant wave (Alfvén wave) which are consistent with observation of MHD waves at the substorm (e.g, Teramoto *et al*., 2011). As the global MHD simulation does not have the plasmasphere structure, we cannot reproduce the PVR in the simulation. However, if we can detect the compressional wave in the inner magnetosphere in the simulation, this wave may lead to the PVR as obtained by Fujita *et al*. (2002). Consequently, we need to investigate whether the compressional wave is excited by sudden compression of the inner magnetopause at the substorm onset.

Let us investigate the numerical results. Figure 3 illustrates the disturbed part of B_z (the magnetic field generated by the current which is obtained as the residual of the calculated magnetic field from the dipole magnetic field

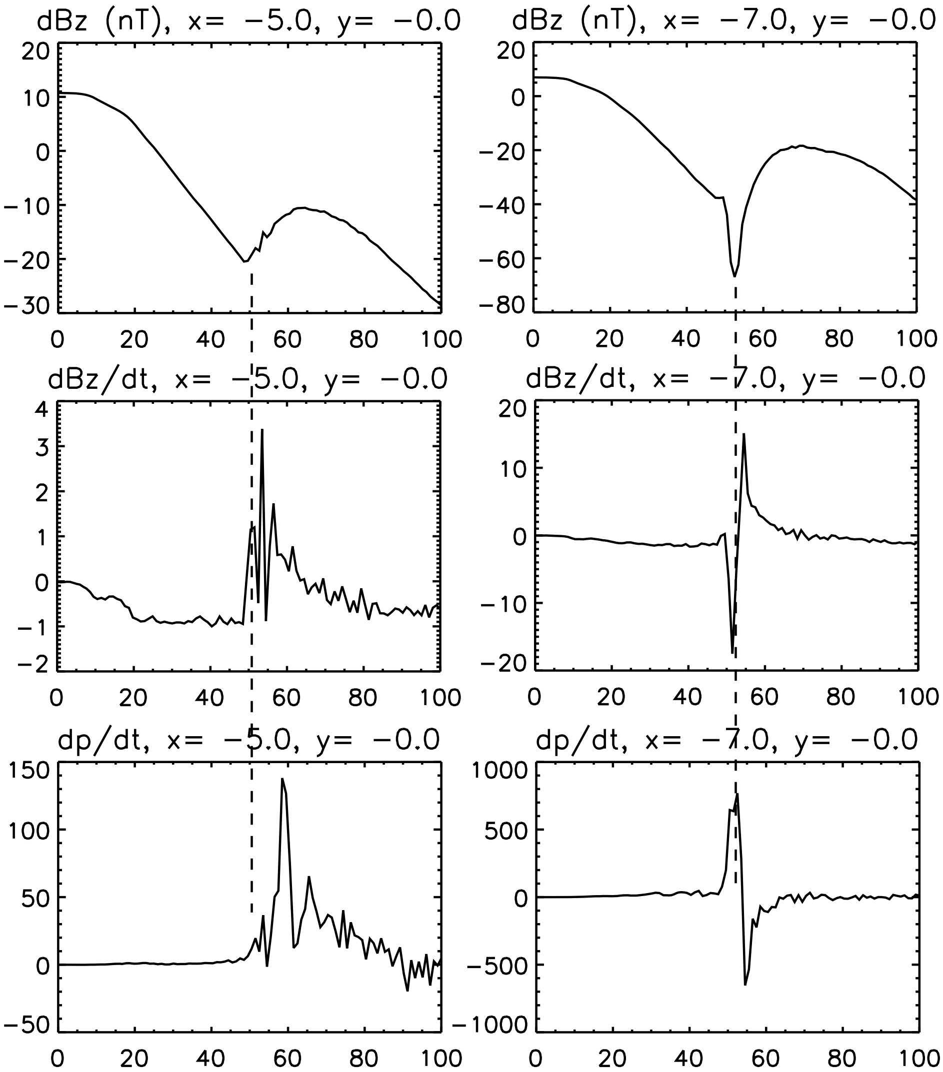

Fig. 3. Temporal changes of (top row) the disturbed part of B_z in nT, (middle row) dB_z/dt, and (bottom row) dp/dt (left column) at $x = 5\ R_e$ and (right column) at $x = 7\ R_e$. The horizontal axis denotes time in minute.

of the Earth), dBz/dt, and dp/dt at $r = 5$ and 7 R_e in the midnight-equatorial line. (As variations in B_z and p are small, we illustrate dBz/dt, and dp/dt instead.) At $r = 7\ R_e$, the magnetic perturbation exhibits diamagnetic feature because dBz/dt and dp/dt are anti-correlated to each other. Namely, the perturbation belongs to the slow magnetosonic mode. On the other hand, at $r = 5\ R_e$, the first movements in dBz/dt and dp/dt are nearly in phase. This fact indicates that the magnetic perturbation belongs to the compressional mode (the fast magnetosonic wave). Note that the small magnetic perturbations shown in the top panel of this figure are not signatures of the Pi2 pulsation in the simulation because the model does not have the plasmasphere. When there is the plasmasphere, the magnetic disturbances may become trapped in the plasmasphere. Consequently, there should appear the Pi2 pulsation in the inner magnetosphere (the PVR). In our simulation, amplitudes of the magnetic perturbation are as small as several nTs. This result is consistent with observed amplitude of the wave observed in the magnetosphere (i.e., Teramoto *et al.*, 2011).

3. Discussion

In the previous section, we have identified sources of the Pi2 pulsations employed in the MHD simulation of the substorm from the numerical results of the global MHD simulation. The candidates of the generation mechanisms—the TR and the PVR may be reproduced in the global MHD simulation if defects of the global MHD simulation (namely, lack of the plasmasphere, numerical diffusion of the Alfvén wave, and imperfect reflection of the MHD wave injected into the ionosphere) are resolved. Meanwhile, resent observations suggest that the high-speed plasma flow in the plasma sheet exhibits the Pi2-like oscillatory behaviors at the onset of the substorm (Kepko and Kivelson, 1999). In particular, Keiling (2012) reported that the Pi2 pulsation which appears before the auroral break-up is possibly generated by the drift ballooning instability (Miura *et al.*, 1989). As for the theoretical study, Cheng and Zaharia (2004) investigated the ballooning instability in the plasma sheet in the growth phase of the substorm based on the ideal MHD magnetosphere model from Tyganenko. After their analysis, low-frequency MHD waves are unstable in

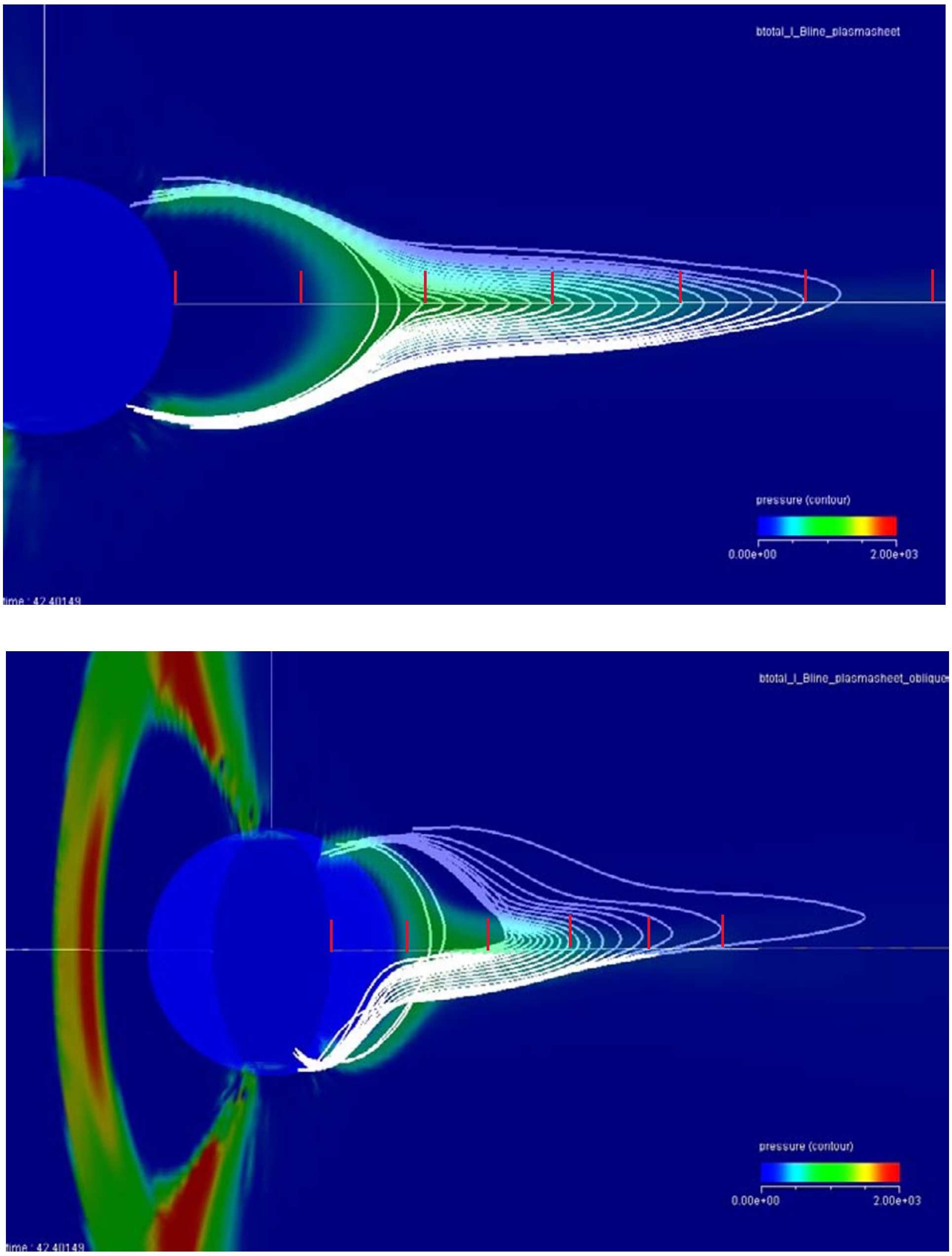

Fig. 4. Configuration of the magnetic field lines in the plasma sheet at $t = 42.4$ min (the late growth phase). Top and bottom panels illustrate the side view and the obliquely back view of the magnetic field lines, respectively. Background color shows pressure in the noon-meridional plane. Each vertical tip indicates 3 R_e distance from the center of the Earth.

the plasma sheet for the ballooning instability in the growth phase. This wave may be a source of the Pi2 pulsation although the nonlinear evolution of the ballooning instability in the magnetosphere has not been studied yet. Therefore, it seems meaningful to investigate that the plasma sheet in the growth phase is unstable or not for the ballooning instability based on the global MHD simulation. It is noted that the present MHD simulation does not reproduce the ballooning instability. This does not mean the plasma sheet stable for the ballooning instability, but insufficient mesh resolution of the present simulation may prevent realization of the instability (Zhu *et al.*, 2009).

The ballooning instability occurs in the region with curved magnetic field lines and high beta plasmas (Miura *et al.*, 1989; Miura, 2004). Thus, we should investigate how the curvature of the magnetic field is developed in the plasma sheet region in the simulation. Figure 4 shows the configuration of the magnetic field lines in the plasma sheet when the radius of curvature becomes the smallest in the simulation at $t = 42.4$ min. It is natural that the smallest curvature appears in the late growth phase of the substorm. It is noted that the magnetic field in the plasma sheet has a significant y component (dawn-dusk direction) as shown in the bottom panel of Fig. 4 because the IMF used in the simulation contains the B_y component.

Stability analysis of the plasma sheet for the ballooning instability requires global energy principle analysis of the plasmas along magnetic field line or the global eigen-

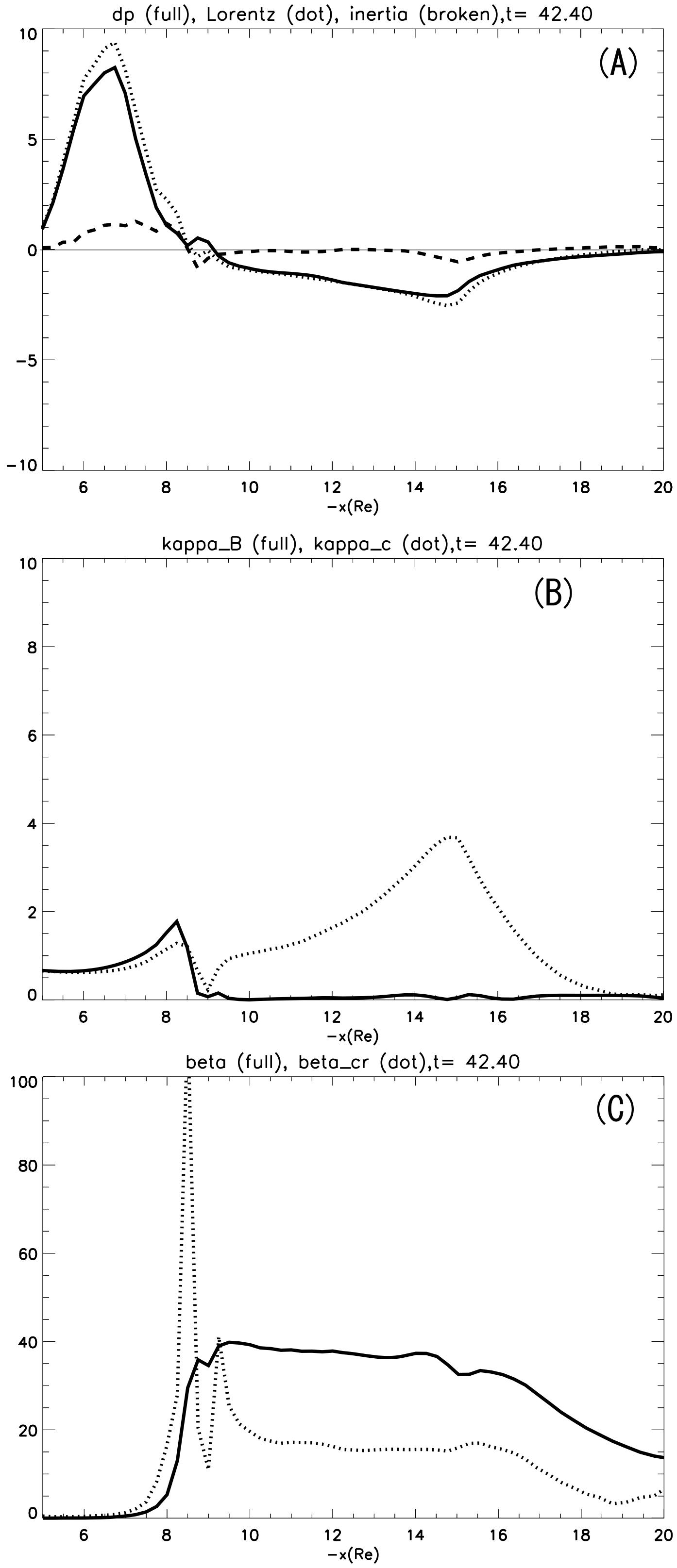

Fig. 5. Radial profiles of quantities related to the ballooning instability in the midnight equatorial plane at $t = 42.4$ min; (A) ∇p (full curve), $\boldsymbol{J} \times \boldsymbol{B}$ (dotted curve), and $\rho d\boldsymbol{u}/dt$ (broken curve); (B) κ_B (full curve) and κ_c (dotted curve); and (C) β (full curve) and β_{cr} (dotted curve).

value analysis of the plasma disturbance along the field line (Miura, 2004; Zhu *et al.*, 2009). However, it is quite difficult to perform such analysis in the realistic plasma sheet configuration shown in Fig. 4. Therefore, we employ a simplified method based on local analysis of the plasma parameters in the equatorial plane where the magnetic field curvature is most enhanced. Miura (2004) presented the criteria about stability of plasmas for the incompressible ballooning instability based on the energy principle. Before we employ this criterion, we need to check that the Lorentz force is balanced by the pressure-gradient force (∇p), namely,

$$\boldsymbol{J} \times \boldsymbol{B} - \nabla p = \rho \frac{d\boldsymbol{u}}{dt} \simeq 0, \tag{1}$$

where $\boldsymbol{J}$ means current vector. As shown in the top panel of Fig. 5, this balance is attained in the plasma sheet region ($L > 10\ R_e$). It is noted that Miura (2004) assumes no background plasma flow. This is not the case of the present simulation. Second, Miura (2004) revealed that the plasma becomes unstable for the incompressible ballooning instability if the plasma β is larger than the critical β denoted as β_{cr} from now. It is roughly estimated as

$$\beta_{cr} = \frac{\kappa_c}{\kappa_p}, \tag{2}$$

assuming that the magnetic field in the plasma sheet is so highly stretched, namely, $\kappa_c \gg \kappa_B$ where κ_c and κ_p are the inverse of radius of magnetic field curvature ($|(\hat{e}\nabla)\hat{e}|$ where $\hat{e} = \boldsymbol{B}/B$) and that of the pressure gradient ($|\nabla p|/p$), respectively. In Fig. 5(B), we confirm that the condition of $\kappa_c \gg \kappa_B$ is satisfied in the plasma sheet region. From this figure, κ_c is maximized at $L \simeq 15\ R_e$, on the other hand, the curvature does not seem to be maximized there from the top panel of Fig. 4. This apparent discrepancy comes from the magnetic field configuration falling sideways due to the B_y component as shown in the bottom panel of Fig. 4. Finally we evaluate β_{cr} indicated in Eq. (2). The result is shown in Fig. 5(C). Concludingly, our rough estimation of the ballooning stability of the plasma sheet in the growth phase of the substorm suggests that the plasma sheet would be unstable for the ballooning instability.

The ballooning instability should be examined with the global energy principle based on the plasma parameters along magnetic field lines or the global eigenvalue analysis. So, the local analysis done in this paper is an approximation. However, the results indicate that the ballooning instability may occur in the growth phase of the substorm.

4. Conclusion

From the linear MHD-wave simulation of the Pi2 pulsation (Fujita *et al.*, 2001, 2002), the Pi2 pulsation is the TR at high latitudes and the PVR in middle- and low-latitudes. As the global MHD simulation does not correctly reproduce reflection of the MHD wave at the ionosphere nor field-aligned propagation of the Alfvén wave, it is difficult to reproduce the TR. In addition, the global MHD simulation does not have the plasmasphere, it is impossible to reproduce the PVR, either. Therefore, we look for plasma disturbances that are regarded as sources of the Pi2 pulsations in the linear MHD-wave simulation. Thus, rapid growth of R1 FAC and generation of the fast magnetosonic mode wave in the inner magnetosphere are two necessary conditions for the Pi2 pulsation. From these considerations, we investigated rapid growth of the R1 FAC and the fast magnetosonic wave in the inner magnetosphere.

Let us summarize the main conclusions here.

1) At the substorm onset, the MHD simulation gives rapid growth of R1 FAC. This would generate the bouncing Alfvén wave between ionospheres in both hemispheres. This rapid growth of the R1 FAC is not related with the SCW. Therefore, the Pi2 pulsation at high latitudes could be generated without the SCW.
2) When the enhanced high-speed convection flow in the plasma sheet at the onset stops in the Ring current region ($L \sim 7\ R_e$), we confirm that the fast magnetosonic wave is generated in the inner magnetosphere. If we consider the plasmasphere, this fast magnetosonic wave would invoke the PVR.
3) The plasma sheet in the growth phase of the substorm might be unstable for the ballooning instability, which might trigger the Pi2 pulsation. To confirm this possibility, we need to perform more rigorous analysis.

This paper describes only possible generation mechanisms of the Pi2 pulsations based on the global MHD simulation. As nobody has attempted such a research yet, we believe that this research is quite important for the Pi2 pulsation research. However, it should be noticed again that the present MHD simulation incompletely reproduces whole processes associated with the substorm because the simulation does not yield the waves with a period of the Pi2 pulsation. Probably, we need to improve the MHD code significantly to reproduce the Pi2 pulsations. The issues to be improved are propagation of the Alfvén wave along magnetic field lines, reflection of the MHD wave by the ionosphere, and inclusion of the plasmasphere.

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