1. Introduction

The fundamental physical process in the Earth's space is the magnetic reconnection that merges two domains of plasma with antiparallel magnetic field relative to each other at their contacting site (Dungey, 1961, 1963). The Earth's magnetosphere is thus mainly affected by the direction of the interplanetary magnetic field (IMF) embedded with solar wind plasma, as the main geomagnetic dipole field is very stable in both direction and strength.

When IMF is southward, it is well known that there are two reconnection processes that mainly form the magnetosphere's magnetic configuration. First, IMF field lines interconnect with geomagnetic field lines at dayside magnetopause when solar wind plasma hits on the Earth's magnetosphere, creating two sets of open field lines that are consequently convected toward nightside of the Earth due to the frozen-in condition of collisionless plasma and form two plasma domains which are the northern magnetic tail lobe and the southern magnetic tail lobe. Second, when these two plasma domains contact with each other, the northern open field lines reconnect with the southern open field lines and create new IMF field lines and new closed field lines.
When IMF is northward, there are two magnetic reconnection sites at the nightside of the cusps of the Earth's dipole field, as indicated by the northern point M1 and the southern point M2 in Figure 1. At these two sites, a draped IMF field line is antiparallel with an open field line or a closed field line. Such reconnection is called cusp reconnection, lobe reconnection, or high latitude reconnection (Cowley, 1981; Dungey, 1963; Fuselier et al., 2000; Lavraud et al., 2006; Li et al., 2008, 2005; Onsager et al., 2001; Phan et al., 2003; Russell, 1972). However, the scenario of cusp reconnection has more variations than the dayside magnetopause reconnection, because there are two reconnection sites and two types of geomagnetic field lines that a draped IMF field line may encounter.

In theory, there are two main scenarios as follows. A draped IMF field line may only merge with the geomagnetic field at one of the two merging sites, resulting in a new open field line draping the dayside magnetopause and a new open field line or a new IMF field line in the tail depending on what type of geomagnetic field line merging at M1 or M2. Or a draped IMF field line merges with the geomagnetic field at both merging sites, resulting in a new closed field line draping the dayside magnetopause and new open field line(s) and/or new IMF field line(s). The newly created field lines then are all convected tailward. However, it is not clear how such open field lines are distributed in the tail.

In this study, we use two different global magnetosphere magnetohydrodynamics (MHD) models to simulate two events, whose IMF is northward with a significant By, and study the configuration and evolution of the magnetotail. We also discuss the possible magnetotail reconnection and substorm that may occur during northward IMF conditions.

2. Method

We use global magnetosphere models BATS-R-US and Open-GGCM hosted on NASA Community Coordinated Modeling Center (CCMC) to simulate two northward IMF events. We also use the plotting services provided by CCMC to analyze the simulation results. Therefore, all our simulation output data sets are stored in CCMC and can be openly analyzed through CCMC portal (http://ccmc.gsfc.nasa.gov).

On an adaptive mesh refinement grid, BATS-R-US solves the global MHD equations for the magnetosphere using numerical methods related to Roe's Approximate Riemann Solver (Powell et al., 1999; Tóth et al., 2012). Its built-in ionospheric potential solver provides electric potentials and conductances in the ionosphere from magnetospheric field-aligned currents. On a stretched Cartesian grid, OpenGGCM solves the global magnetosphere MHD equations using second order explicit time integration with conservative and flux-limited spatial finite differences (Raeder, 2003). It is coupled with Coupled Thermosphere Ionosphere Model (CTIM) (Fuller-Rowell et al., 1996). More detail information about these models can be accessed through CCMC portal.

We use BATS-R-US 20140611 version and OpenGGCM 4.0 version without coupling ring current or radiation belt model. CTIM is used in OpenGGCM simulations. The run numbers on CCMC are Wenhui_Li_062216_1, Wenhui_Li_062216_2, Wenhui_Li_081516_1, and Wenhui_Li_081516_2. Solar wind and IMF data from NASA OMNI are used to drive the models. High resolution grid of 9.0 million cells is used for both models. The two simulated events are event-1 from September 17, 2000 at 20:00:00 UT to September 18, 2000 at 08:00:00 UT and event-2 from August 12, 2000 at 20:00:00 UT to August 13, 2000 at 02:00:00 UT.

Figure 2 and Figure 8 show the solar wind and IMF conditions near dayside magnetopause for event-1 and event-2, respectively. In these figures, $By = \sqrt{B_y^2 + B_z^2}$ IMF clock angle is arctan ($B_y/B_z$), and flow pressure or dynamic pressure equals $2 \times 10^{-6} \times N_p \times V_p^2$ where $N_p$ is proton number density in cm$^{-3}$ and
Vₚ is proton flow speed in km/s. During event-1, the IMF is first southward for about 3 h and then changes to northward from 00:00 UT to 08:00 UT. For event-2, the IMF is northward from 18:00 UT to 02:00 UT the next day. Both events have significant IMF \( B_y \) component. IMF \( B_x \) is set to be zero for all the simulations.

In this study, we inspect the magnetosphere by showing the distribution of four topological types of magnetic field lines that are closed geomagnetic field lines connecting both cusps, IMF field lines, open geomagnetic field lines connecting northern cusp with southern IMF, and open geomagnetic field lines connecting southern cusp with northern IMF. For a point on the equatorial plane, we trace the magnetic field line passing through it, and color it according to the topology of this field line: red for closed field line, blue for IMF field line, green for open field line rooted in southern cusp, and yellow for open field line rooted in northern cusp.

3. Simulation Results

3.1. Magnetotail Under Southward or Northward IMF Conditions

Figure 3 is a topological map showing a distribution of four types of magnetic field lines on the GSM equatorial plane, and Figure 4 shows some open field lines corresponding to panels (3a) (panel (a) of Figures 3 and 3b). Panel (3a) shows that, at a time (September 17, 2000 at 22:44:00 UT) of southward IMF condition,
only the southern-cusp-rooted open field lines pass through the equatorial plane, because the northern-cusp-rooted open field lines are above the equatorial plane for this time as shown in panels (4a1) and (4a2). This is the typical structure of the magnetotail for southward IMF conditions. Note that at another southward IMF time (September 17, 2000 at 22:00:00 UT), the open field part of panel (3a) becomes yellow (not shown), because all the southern lobe field lines are below the equatorial plane at this moment.

When IMF is northward, the magnetotail configuration changes dramatically. Both panel (3b) and panel (3c), which are results from different models for the same event and have the same simulation time stamp, show that there are two different domains of open field lines passing through the equatorial plane at the time of September 18, 2000 at 04:20:00 UT corresponding to northward IMF conditions. Some of the open field lines from these two domains are shown in panel (4b1) and panel (4b2). In contrast to the open field lines under southward IMF conditions, which stay in northern (southern) part of the tail for northern-cusp-rooted (southern-cusp-rooted) open lines, these open field lines always extend a domain from northern (southern) cusp toward the southern (northern) IMF and thus always pass through the equatorial plane.

3.2. Magnetotail Under Northward IMF Conditions With Dominant By

Figure 5 shows a topological distribution of magnetic field lines when IMF is northward and has a dominant dawn-dusk component $B_y$. During the time from September 18, 2000 at 00:12:00 UT to September 18, 2000 at 00:30:00 UT, $|B_y|$ is much greater than $|B_z|$, and the corresponding IMF clock angle is about $80°-90°$, as shown in Figure 2. During this time period, two long open field domains form along the dawnside and duskside of the magnetotail, respectively. Here, the duskside (dawnside) domain is composed of open field lines that root in southern (northern) cusp and connect to the northern (southern) IMF.

The BATS-R-US simulation results of panels (5a1) and (5a2) show that these two open domains are separated by IMF, while the OpenGGCM simulation results of panels (5b1) and (5b2) show that these two open domains contact with each other or are very close to each other. At the same time, the BATS-R-US results show a small closed field domain, while the OpenGGCM results show a stretched and elongated closed field domain.

3.3. Magnetotail Under Northward IMF Conditions With less Significant By

Figure 6 shows a topological distribution of magnetic field lines when IMF is northward and has a less significant $B_y$. This figure shows the minimal open status of the magnetosphere during this event. The time stamp of panels (6a1) and (6b1) is September 18, 2000 at 03:58:00 UT corresponding to an
IMF clock angle of −36°. Before this time stamp and during the time period from September 18, 2000 at 03:44:00 UT to September 18, 2000 at 03:48:00 UT, IMF $|B_y|$ is much less than IMF $B_z$, and the corresponding IMF clock angle is about 3°–10°, as shown in Figure 2. The time stamp of panels (6a2) and (6b2) is September 18, 2000 04:32:00 UT corresponding to an IMF clock angle of −25°. Before this time stamp and during the time period from 04:14:00 UT to 04:27:00 UT, IMF $|B_y|$ is much less than IMF $B_z$, and the corresponding IMF clock angle is about −2°–−15°, as shown in Figure 2. Considering that there is a time delay between the arrival of an IMF field line at the nose of the magnetopause and the forming of a new open field line in the tail from this IMF field line, it seems that the magnetosphere is mostly closed when IMF clock angle is between $\sim −10°$ and $\sim 10°$.

Panels (6a1) and (6a2) resulted from BATS-R-US simulation show a nearly closed and much shrunk magnetosphere. The corresponding OpenGGCM simulation results panels (6b1) and (6b2) also show a nearly closed, but significantly stretched magnetosphere.

**3.4. Magnetotail Under Northward IMF Conditions With Significant $B_y$**

Figure 7 shows a topological distribution of magnetic field lines when IMF is northward and has a significant $B_y$ at September 18, 2000 at 06:00:00 UT or 07:00:00 UT. During the period from 05:00:00 UT to 08:00:00 UT, IMF clock angle is about $−50°$–$−20°$, as shown in Figure 2. Figure 7 shows a fairly open magnetosphere and a magnetotail with a dawnside lobe and a duskside lobe. The OpenGGCM results also show
an elongated closed field as in other IMF clock angle conditions shown in Figures 5 and 6.

3.5. Magnetotail Under Northward IMF Conditions With Decreasing IMF Clock Angle

Event-2 is an event during which the IMF clock angle almost linearly changes from $\sim 90^\circ$ to $\sim 10^\circ$, as shown in Figure 8. Figure 9 shows the topological distribution of magnetic field lines for different IMF clock angle conditions during event-2. The time stamps for panels (9a1), (9a2), and (9a3) are 21:20:00 UT, 22:20:00 UT, and 23:50:00 UT, respectively, on August 12, 2000 UT; and the time stamps for panels (9a4), (9a5), and (9a6) are 00:50:00 UT, 01:50:00 UT, and 01:26:00 UT, respectively, on August 13, 2000 UT. All these time stamps are indicated by the green vertical lines in Figure 8.

For each topological map of magnetic field lines in Figure 9, the average IMF clock angle and the standard deviation for the period $[T-00:15:00, T-00:05:00]$, where $T$ is the corresponding time stamp, is plotted on the bottom of the map. This period has 10 data points. For each map of field line topology, the position of an open field line indicates its creation time relative to the time stamp of the map considering its time to convect from dayside magnetopause to its current position. Therefore, we estimate that the magnetotail is mainly formed by open field lines created in the period $[T-00:15:00, T-00:05:00]$ for this event. This estimation is mainly based on the solar wind speed.

Figure 9 indicates that a larger IMF clock angle leads to a wider and longer magnetotail. During this event in the simulation, the IMF magnitude, which equals to $B_{xy}$ in Figure 8, since $B_x$ is set to be zero, varies only slightly. The solar wind dynamic pressure for panel (9a1), (9a2), or (9a3) is much greater than the dynamic pressure for panel (9a4), (9a5), or (9a6). According to magnetotail model (Petrinec & Russell, 1996; Wang et al., 2018), panel (9a4), (9a5), or (9a6) should show a wider magnetotail than that in panel (9a1), (9a2), or (9a3). However, Figure 9 shows opposite results. During event-2, solar wind $|V_y|$ is less than 50 km/s except for times of panels (9a4), (9a5), and (9a6), where the magnetotail is skewed toward the dayside. OpenGGCM results shown in panels (9b1), (9b2), (9b3), (9b4), (9b5), and (9b6) show similar properties, but have longer tail and longer closed field.

3.6. Possible Magnetotail Reconnection Under Northward IMF Conditions

The figures of topological distribution of magnetic field lines indicate that the two tail lobes may touch each other at a region near the $x$ axis in the tail beyond the closed field. This contacting site may create an opportunity for reconnection, since these two tail lobes are mainly opposite in magnetic direction.

The magnetic field lines shown in Figure 10 display such a reconnection process. They are computed from starting points locating near the mid-night at a thin region of the contacting area of these two open domains shown in panel (3b) or panel (3c), using the 3D simulation output for the time stamp of 04:20:00 UT.

In panel (10a1), a northern-cusp-rooted open field line reconnects with a southern-cusp-rooted open field line at a location above the equatorial plane and subsequently creates an IMF field line (blue) and a closed field line (black). The location pointed by a red arrow in Figure 10 indicates
a magnetic reconnection site. Panel (10a2) shows that the field lines spread out at the reconnection site, because the magnetic field at this location becomes turbulent, resulting in these computed magnetic stream lines changing directions significantly at this turbulent site.

Panels (10b1) and (10b2) display a similar process except that it occurs at a location below the equatorial plane. Panels (10c1) and (10c2) also display a similar process, but occurring at a location near the equatorial plane. One should note that the kinked sections of the field lines indicated by the black arrows in Figure 10 are results of the cusp reconnection occurring at the nightside of cusps.

As a result of this magnetotail reconnection process, the magnetotail should form a convection region. Figure 11 shows various distributions of the plasma convection, corresponding to panels (4b1) and (4b2) for cut planes at $Z=-3$ RE (panels (a1) and (b1)), $Z=0$ RE (panels (a2) and (b2)), and $Z=3$ RE (panels (a3) and (b3)). A significant long and narrow mild convection zone is shown in Figure 11 as a pink-red area. All the field lines in panels (10a2), (10b2), and (10c2) show that the magnetotail is twisted for a significant angle, relative to the midnight meridian plane. Therefore, the distribution of the convection region is also aligned with the twisted tail such that the southern (northern) part is at the duskside (dawnside). However, this effect is not obvious for OpenGGCM results.

Plasma fast flows are also expected if magnetic reconnection occurs in the magnetotail. After searching for fast flows from all the simulation runs, we found three earthward flow channel events from OpenGGCM results, but not from BATS-R-US results as shown in Figure 12. Panel (12b1) shows a high speed flow channel with a speed up to 800 km/s at September 18, 2000 01:10:00 UT, which is after about 1 h of northward IMF
conditions with dominant IMF \( B_y \). This high speed flow event lasts from \( \sim 01:06:00 \) UT to \( \sim 01:14:00 \) UT in the simulation. Panel (12b2) shows a flow channel with a speed of 200–300 km/s at September 18, 2000 at 04:30:00 UT, a time with \( \sim -10^\circ \) IMF clock angle. This flow event lasts from \( \sim 04:24:00 \) UT to \( \sim 04:36:00 \) UT. In event-2, a fast flow channel appears from \( \sim 00:16:00 \) UT to \( \sim 00:26:00 \) UT on August 13, 2000 UT. Panel (12b3) shows this flow channel with a speed of 400–500 km/s at August 13, 2000 00:22:00 UT, a time with \( \sim 34^\circ \) IMF clock angle.

**4. Discussion**

In this study, we show a magnetotail configuration that looks significantly different from the one developed under southward IMF conditions. It is interesting to discuss how this configuration forms and what magnetospheric or ionospheric effects it may cause.
4.1. Cusp Reconnection

Obviously magnetotail configuration is mainly affected by magnetic reconnection occurring in the magnetosphere. To understand the magnetotail configuration, we need to understand the reconnection process that occurs under northward IMF conditions.

Figure 10. Magnetic reconnection in the magnetotail under northward IMF conditions. These field lines are computed from points at the border between the green area and yellow area in Figure 3. The blue, red, and black lines represent IMF, open field lines, and closed field lines, respectively. The left panels are views from GSM dawnside, and the right panels are views from dayside magnetopause. Panels (a1), (a2), (b1) and (b2) are BATS-R-US results, and panels (c1) and (c2) are OpenGGCM results. A red arrow indicates a magnetotail reconnection site, and a black arrow indicates an open field line created by cusp reconnection. IMF, interplanetary magnetic field.
The most well-known reconnection process for northward IMF is the cusp reconnection or high-latitude reconnection first proposed by Dungey (1963), who suggested that a northward IMF would be antiparallel to the Earth’s field at points poleward of the cusps and makes reconnection possible there, as shown in Figure 1. The IMF field lines may interconnect with open tail lobe field lines (Russell, 1972), or with closed geomagnetic field lines (Cowley, 1981, 1983).

Observations have provided evidences for cusp reconnection (e.g., Fuselier et al., 2018, 2000; Gosling et al., 1991; Kessel et al., 1996; Lavraud et al., 2002; Lavraud, Fedorov, et al., 2005; Le et al., 2001; Onsager et al., 2001; Phan et al., 2003), and global MHD models have reproduced this process (Fedder & Lyon, 1995; Gombosi et al., 1998; Guzdar et al., 2001; Ogino et al., 1994; Raeder et al., 1997).

Observations have show that cusp reconnection may occur at a broad local time range of locations (Onsager et al., 2001) and can occur for IMF clock angles between −90° and 90° (Twitty et al., 2004). When geomagnetic dipole tilts sunward (antisunward), an IMF field line may first interconnect with a geomagnetic field line at northern (southern) cusp, and then at southern (northern) cusp (Lavraud, Thomsen, et al., 2005).

Onsager et al. (2001) reported that cusp reconnection may create new closed field lines and new open field lines with footprints in either northern or southern cusp. They also identified high-latitude closed field lines participating in cusp reconnection.

As shown in Figure 4, an open field line created by cusp reconnection always connects northern (or southern) cusp to southern (or northern) IMF and passes through the equatorial plane, in contrast to an open field line created by dayside magnetopause reconnection, which always connects northern (or southern) cusp to northern (or southern) IMF.

4.2. Magnetotail Formation Under Northward IMF Conditions

4.2.1. Effect of IMF Clock Angle

This study suggests that magnetotail configuration is mainly affected by the IMF clock angle when IMF is northward. When IMF is nearly due northward, the magnetosphere is nearly closed, and the magnetotail is minimal or disappears. When IMF is northward and has a significant dawn-dusk component By, the mag-
netosphere is fairly open and the magnetotail usually forms into a dawnside tail lobe and a duskside tail lobe, instead of a northern tail lobe and a southern tail lobe under southward IMF conditions. When IMF is northward and has a dominant $B_y$, the magnetotail is much large and very long with a width of more than 60 RE and a length of more than 100 RE.

Since the magnetotail is mainly a topological structure, the geometric and topological property of the geomagnetic field and the IMF thus plays a dominant role in determining how cusp reconnection process occurs and consequently forms the magnetotail.

In an ideal condition in which the IMF is pure northward in GSM coordinates and the Earth’s dipole tilt angle is zero, an IMF field line most likely merges with geomagnetic field at both cusps simultaneously as shown in Figure 1. This process then forms a closed field line draping the dayside magnetopause and then

Figure 12. Distribution of plasma flow velocity $V_x$ component on GSM equatorial plane. Panels (a1) and (b1) have a time stamp of September 18, 2000 at 01:10:00 UT, panels (a2) and (b2) have a time stamp of September 18, 2000 at 04:30:00 UT, and panels (a3) and (b3) have a time stamp of August 13, 2000 at 00:22:00 UT. The blank area indicates tailward flow. GSM, Geocentric Solar Magnetospheric System.
integrating itself into the closed field. In the nightside, this process creates one new IMF field line if the reconnecting geomagnetic field line is a closed field line connecting both reconnection sites, or creates two new IMF field lines if the reconnecting geomagnetic field lines at both reconnecting sites are two open field lines, eroding the previously existing open field lines. After a period of purely northward IMF conditions, the magnetosphere may become completely closed.

However, when the IMF at the nose of the magnetopause has a significant $B_y$ (or clock angle), the symmetric field line distribution as shown in Figure 1 does not likely exist. Assuming that the IMF turns a clock angle of 60°, the whole draped IMF field line does not likely also turn ∼60° such that this IMF field line reconnections with the same closed field line at both cusps, because an IMF field line always drapes around the magnetopause antisunward and aligns with the solar wind velocity direction instead of the IMF clock angle. Therefore, with a significant clock angle, the probability for an IMF field line draping on northern (southern) cusp also drapes on southern (northern) cusp on the same local time location is reduced. The larger the clock angle magnitude, the less probability of reconnecting with the same closed field line or reconnecting with geomagnetic field at both cusps simultaneously, thus the more probability of creating open field lines. Such open field lines are then convected antisunward and form a tail as shown by panels (4b1) and (4b2) in Figure 4. A larger IMF clock angle magnitude thus leads to a wider and longer magnetotail, as shown by Figures 5–7 and 9.

The open field lines all pass through the equatorial plane, because they always connect northern (southern) cusp with southern (northern) IMF. The open field lines created by cusp reconnection usually form a tail lobe in the dawnside and another tail lobe in the duskside, since the IMF field lines draping at northern magnetopause most likely are convected to one side of the magnetotail, and the IMF field lines draping at southern magnetopause most likely are convected to the other side. Figures 5 and 7 indicate that the southern-cusp-rooted tail lobe is in the duskside (dawnside) for positive (negative) IMF $B_y$ and the northern-cusp-rooted tail lobe is in the other side. Therefore, if IMF $B_y$ changes its sign frequently (for example, less than 1 h), the magnetotail may not be able to form a stable dawn-dusk tail lobe structure.

The field lines shown in Figures 4 and 10 suggest that a neutral sheet with a significant angle relative to the equatorial plane may form in the tail if IMF clock angle is significant. Observations show that neutral sheet twists a larger angle for northward IMF than for southward IMF when IMF $B_y$ is significant (Case et al., 2018; Maezawa & Hori, 1998; Xiao et al., 2016). Analyzing data from Cluster, Geotail, and Interball, Petrukovich et al. (2003) found that the plasma sheet twists a very large angle under northward IMF conditions with a significant $B_y$.

### 4.2.2. Effect of Other IMF and Solar Wind Parameters

In this study, IMF $B_x$ is set to be zero for all the simulations. We thus cannot find any effect of IMF $B_x$ on magnetotail formation. The dipole tilt is updated with time in event-1 simulation, but is fixed in event-2 simulation. It seems that dipole tilt does not affect the magnetotail dependence on IMF clock angle. Lavraud, Thomsen, et al. (2005) found that dipole tilt angle mainly controls which merging site (M1 or M2 in Figure 1) is the first one for a draping IMF field line to reconnect with geomagnetic field, but IMF tilt angle arctan($B_x/B_z$) has only marginal impact. Therefore, a significant dipole tilt is likely to significantly enhance the formation of the dawn-dusk tail lobes, since it may significantly increase the probability of generating open field lines by cusp reconnection, while IMF $B_x$ has only marginal impact on magnetotail formation.

The total magnitude of IMF equals $\sqrt{B_y^2 + B_z^2}$ ($B_{yz}$) in the simulation. As shown in Figure 2, $B_{yz}$ of Figure 5 is approximately equal to $B_{yz}$ of Figure 6 or panel (3b), and is greater than $B_{yz}$ of Figure 7. During event-2, $B_{yz}$ only varies slightly as shown in Figure 8. It seems that the total magnitude of IMF has little effect on the dimension of the magnetotail.

Magnetotail model (Petrinec & Russell, 1996; Wang et al., 2018) suggests that the y or z dimension of the magnetotail is in inverse relation with solar wind plasma dynamic pressure, which is proportional to solar wind number density and square of speed. However, the magnetotail topological maps shown in Figures 5–7 and 9...
and their corresponding dynamic pressure values shown in Figures 2 and 8 indicate that this inverse relation is not valid for the two events in this study. Such inverse relation should be valid if the IMF clock angle is fixed.

Figure 7 shows that the dawnside lobe seems to be pushed toward duskside. It may relate to solar wind velocity $V_y$ component since $V_y$ is on 100 km/s level from September 18, 2000 at 04:00:00 UT to September 18, 2000 at 08:00:00 UT, but is mainly less than 50 km/s before this period. In event-2, the magnetotail seems to skew toward the dawnside, while $V_y$ is about $-80\text{--}50$ km/s. $V_y$ seems to have a significant impact on the direction of the magnetotail.

4.3. Magnetotail Reconnection and Substorms Under Northward IMF Conditions

4.3.1. Observations

From WIND data, Øieroset et al. (2000, 2004) reported five fast flow events occurring in the tail about 25–60 RE during a four-day period with mainly northward IMF conditions. The analysis of these fast flows suggests that quasi steady reconnection can occur in the mid-magnetotail region during periods of persistent northward IMF.

It is usually believed that substorm is not likely to occur under long period of northward IMF conditions. However, some substorm events occurring during long period of northward IMF conditions have been reported.

After studying more than 50 auroral substorms, Akasofu et al. (1973) found that, during quiet periods, auroral substorms are quite common along the contracted oval even when the IMF $B_z$ is positive. Petrukovich et al. (2000) investigated 43 small substorms and found that typical IMF direction during substorm growth phases was azimuthal (with dominating $B_y$ and small positive or negative $B_z$), and that no small substorms associated with definitely northward IMF ($B_z > |B_y|$).

Lee et al. (2010) reported several substorms observed under northward IMF conditions. The two event periods in this study are also the events reported by Lee et al. (2010). They reported substorm onsets at August 13, 2000 at 00:00:05 UT, September 18, 2000 at 04:10:00 UT, September 18, 2000 at 06:20:00 UT, and September 18, 2000 at 10:07:00 UT. These time stamps are at a time that northward IMF conditions with significant clock angle has lasted for at least 4 h.

Miyashita et al. (2011) reported 11 very weak to moderate substorm expansions occurred during a period of more than 20 h of northward IMF conditions on January 19, 1998. They suggested that the large IMF $|B_y|$ is a very important factor.

A statistical study performed by Peng et al. (2013) suggests that duration of northward IMF, IMF $B_y$ component, dynamic pressure, storms, and presouthward IMF conditions are related to the occurrence of substorm under northward IMF conditions. Zhang et al. (2015) reported X lines in the tail for northward IMF with AE index in a range of 50–70 nT. Du et al. (2008) reported an anomalous geomagnetic storm, whose main phase occurred during northward IMF conditions.

4.3.2. Magnetic Reconnection in the Simulation

Although magnetic reconnection process in the simulation is created by MHD equations in the global magnetosphere model and may not completely reflect the true reconnection process, which involves kinetic processes and wave-particle interactions, it helps us to shed light on how magnetic reconnection and substorm may occur during northward IMF conditions.

If the northward IMF with significant $B_y$ persists for a substantial time period and $B_y$ stays in one direction (positive or negative) for this period, a dawnside tail lobe and a duskside tail lobe will form and continuously grow in the magnetotail to a certain dimension mainly limited by solar wind dynamic pressure, as shown in Figures 4, 5, 7, and 9. The magnetic energy is thus stored and enhanced continuously in the magnetotail. The two tail lobes may contact with each other near the noon-midnight meridian plane and result in magnetic reconnection processes, since their magnetic field directions are mainly antiparallel, as shown in Figures 4 and 10. The magnetic energy stored in the tail lobes is thus released. If such energy is strong enough, earthward fast plasma flows, as shown in Figure 12, will be created, and even a substorm may occur.
The field lines shown in Figures 4 and 10 suggest that magnetic pressure pushes open field lines toward the reconnection center, where magnetic pressure is low, mainly from dawnside and duskside of the tail. It thus does not have much pressure on the newly closed field lines from the north and the south. Therefore, the prereconnection field lines and the newly closed fields are not stretched significantly and can only result in a weak convection region. In contrast, the prereconnection field lines and the newly created closed field lines formed during a magnetotail reconnection process under southward IMF conditions, are usually greatly stretched. Therefore, magnetotail convection and substorm, if any, are usually weak under northward IMF conditions.

While earthward fast flows may appear, significant tailward fast plasma flow is not likely to appear, because the newly created detached field lines (blue lines in Figure 10) are most likely not stretched significantly to convert significant magnetic energy to kinetic energy of the plasma flow. As a result, we only found earthward fast flow channels shown in Figure 12 but not tailward fast flow channels in the simulation. Although IMF magnitude may not have significant impact on the dimension of the magnetotail, it may have significant impact on the formation of fast flows, since stronger magnetic field of the newly closed field lines should lead to stronger earthward convection.

Our simulation results suggest that magnetotail configuration is rather sensitive to IMF clock angle. Since IMF rarely has a stable clock angle, it is not often for such dawn-dusk tail lobe reconnection to occur for a substantial time. The low probability of occurrence and the resulting weak convection explain why it is not often to observe magnetotail reconnection or substorm under northward IMF conditions.

To explain the Geotail observations of magnetotail convection for periods of quiet time and northward IMF with |By| ≥ Bz, Nishida et al. (1998) proposed a model (see Figure 9 in their paper) that is similar to the magnetotail reconnection process presented here. Here, we present a more realistic view of this model using simulation data.

This magnetotail configuration and the related reconnection process also provide a way for solar wind plasma entry into the plasma sheet in the mid-tail region, since the newly closed field lines catch the solar wind plasma on the reconnecting open field lines.

Note that the grid resolution of the simulation runs in this study is not high enough to create a substorm in the magnetotail, although there are substorm onsets at August 13, 2000 at 00:00:05 UT, September 18, 2000 at 04:10:00 UT, and September 18, 2000 at 06:20:00 UT (Lee et al., 2010). Future high-resolution simulation studies focusing on substorms under northward IMF conditions will be very interesting for studying the magnetotail.

### 4.4. Ionosphere Observations Related to Northward IMF With Significant By

Although this study does not inspect ionosphere effects from simulation results, we would like to point out some ionosphere observations under northward IMF conditions with significant By since the magnetotail configuration presented here may provide an alternative perspective for the observed phenomenon.

Using the Dynamics Explorer (DE) 2 data, Taguchi et al. (1992) examined By-controlled convection and field-aligned currents in the midnight sector for northward IMF. Their findings are quoted as follows.

“When IMF is stable and when its magnitude is large, a coherent By-controlled convection exists near the midnight auroral oval in the ionosphere having adequate conductsivities. When By is negative, the convection consists of a westward (eastward) plasma flow at the lower latitudes and an eastward (westward) plasma flow at the higher latitudes in the midnight sector in the northern (southern) ionosphere. When By is positive, the flow directions are reversed” (Taguchi et al., 1992). Grocott et al. (2005) presented interhemispheric radar observations interpreted as the ionospheric response to tail reconnection during northward IMF intervals. SuperDARN observations for days on February 21–22 and April 26–27, 2000 showed bursts of flow in the midnight sector for both hemispheres of ionosphere during northward IMF with a significant By. The bursts were westwards (eastwards) in the Northern (Southern) Hemisphere during the negative By interval. Their directions were reversed during the positive By interval.

These ionosphere phenomena seem to relate to the formation of dawn-dusk tail lobes and the resulted reconnection process, when IMF is northward with a significant By. For example, the twisted newly created
closed field lines shown in Figure 10 most likely create the dawn-dusk ionospheric convection, when they adjust themselves into normal closed field lines.

4.5. BATS-R-US Versus OpenGGCM

For this study, we use two different global magnetosphere models through NASA CCMC portal. One is the BATS-R-US which has been chosen by NOAA Space Weather Prediction Center to be part of the operational space weather model. The other is the OpenGGCM which has been used in simulating some events with well agreement with observations, especially for events under northward IMF conditions (Li et al., 2005, 2009, 2017; Raeder et al., 1995).

In this study, both models simulate the same events, but have significant differences in results due to their differences in implementing methods and different coupled ionosphere models (Raeder, 2000). For example, BATS-R-US seems to have smaller closed field and more regular shape of the magnetosphere, while OpenGGCM has longer closed field and longer magnetotail with a more irregular form. Fast plasma flow channels appear in OpenGGCM simulation, but not in BATS-R-US simulation. This may be a result of the characteristics of OpenGGCM grid setting, where the grid near x axis has highest resolution. If grid resolution is high enough, fast plasma flow channels may also appear in BATS-R-US simulation. Since we do not compare simulation results with observations directly in this study, we do not know which model is more reliable.

In spite of the differences, they have three basic common results. One is that a domain of open field lines connecting northern cusp to southern IMF will form in one side (dawn or dusk) of the magnetotail, while another domain of open field lines connecting southern cusp to northern IMF will form in the other side of the magnetotail under northward IMF conditions with significant positive or negative By. This result is determined by the geometry and topology properties of the Earth's dipole field and the IMF in front of the magnetopause. The second common result is that these two open domains may contact each other at some point and trigger a magnetic reconnection process. The third common result is that the width and length of the magnetotail increase if the magnitude of the IMF clock angle increases.

5. Conclusions

On the one hand, when the IMF in front of the magnetopause is southward, the reconnection process at dayside magnetopause creates a northern open field tail lobe and a southern open field tail lobe with opposite magnetic field direction. On the other hand, when the IMF is northward with a significant dawn-dusk component By, cusp reconnection is possible to create a dawnside open field tail lobe and a duskside open field tail lobe with opposite magnetic field direction. Such a tail lobe is an open field line root in northern (southern) cusp and connects with southern (northern) IMF. The larger the magnitude of IMF clock angle, the longer and wider the magnetotail. A magnetic reconnection process may occur in the magnetotail when the dawnside and duskside tail lobes contact with each other. A substorm is also possible to occur due to such reconnection process.

Data Availability Statement

The simulation data sets in this study are Wenhui_Li_062216_1, Wenhui_Li_062216_2, Wenhui_Li_081516_1, and Wenhui_Li_081516_2 from NASA Community Coordinated Modeling Center (https://ccmc.gsfc.nasa.gov/results/). The solar wind and IMF data are from NASA CDAWeb OMNI data sets (https://cdaweb.gsfc.nasa.gov/). This work was carried out using the OpenGGCM tools developed at the University of New Hampshire and the SWMF/BATS-R-US tools developed at the University of Michigan's Center for Space Environment Modeling (CSEM). Simulation results and analysis tools have been provided by the NASA Community Coordinated Modeling Center (CCMC) at Goddard Space Flight Center through their public Runs on Request system (http://ccmc.gsfc.nasa.gov). All the simulation data can be accessed through CCMC website (https://ccmc.gsfc.nasa.gov/results/). The solar wind and IMF data are from NASA CDAWeb OMNI data sets (https://cdaweb.gsfc.nasa.gov/).
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