Dynamical property of storm-time subauroral rapid flows as a manifestation of complex structures of the plasma pressure in the inner magnetosphere

Y. Ebihara,¹ N. Nishitani,² T. Kikuchi,² T. Ogawa,² K. Hosokawa,³ M. -C. Fok⁴ and M. F. Thomsen⁵

1. Institute for Advanced Research, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8601, Japan
2. Solar-Terrestrial Environment Laboratory, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8601, Japan
3. The University of Electro-Communications, 1-5-1, Chofugaoka, Chofu, Tokyo 182-8585, Japan
4. NASA GSFC, Code 673, Greenbelt, MD 20771, USA
5. Space and Atmospheric Sciences, Los Alamos National Laboratory, Los Alamos, New Mexico, USA

KEYWORDS: Magnetic storms, subauroral plasma flows, ring current, SuperDARN radar

RUNNING TITLE: STORM-TIME SUBAURORAL RAPID Plasma FLOW
Abstract. During the intense magnetic storm of 15 December 2006, the mid-latitude SuperDARN Hokkaido radar observed a dynamical character of rapid, westward flows at 50–56 MLAT. The simulation that couples the inner magnetosphere and the subauroral ionosphere was performed using a realistic boundary condition of the hot-ion distribution determined from four LANL satellites at 6.6 Re. The following results are obtained using the simulation. (1) In general, morphology of the azimuthal component of the ionospheric plasma flow is consistent with that known as the subauroral polarization stream (SAPS). (2) An increase in the hot-ion density in the plasma sheet results in the temporal reduction and subsequent intensification of the rapid flow at certain subauroral latitudes with a delay of ~40 min. (3) Influence of the plasma sheet temperature on the rapid, westward is vague. The simulated line-of-sight velocity is compared with that obtained by the SuperDARN Hokkaido radar. Agreement between them is found in terms of the temporal and spatial variations of the rapid flows as well as the flow velocity. It is suggested that the dynamical character of the subauroral plasma flow is a direct manifestation of the plasma pressure distribution in the inner magnetosphere (the ring current) especially during the magnetic storm.
1. Introduction

Rapid, westward plasma flows are commonly observed in the subauroral ionosphere. In the evening sector, the speed of the rapid flows sometimes reaches 2–3 km/s in a latitudinally narrow channel of ~1°–2° [e.g., Galperin et al., 1973; Spiro et al., 1979]. Such a flow is termed polarization jet (PJ) [Galperin et al., 1973], or subauroral ion drift (SAID) [Spiro et al., 1979]. Associated strong poleward electric fields, termed the subauroral electric field (SAEF) [Karlsson et al., 1998], typically exceed 100 mV/m in the topside ionosphere [Smiddy et al., 1977; Maynard, 1978; Karlsson et al., 1998]. Foster and Vo [2002] introduced a term subauroral polarization stream (SAPS) to include broader and less intense regions of westward plasma flows in the subauroral region. The rapid flows were typically observed during the recovery phase of substorms [Anderson et al., 1991; 1993] as well as during magnetic storms [Yeh et al., 1991; Burke et al., 2000; Huang et al., 2001; Huang and Foster, 2007]. Burke et al. [2000] found that storm-time rapid flows show little systematic correlation with variations of the $AE$ index, suggesting that the storm-time rapid flows are quasi-permanent features that are not strongly coupled to the substorm-associated loading/unloading cycles. Burke et al. [2000] also pointed out that the storm-time rapid flows appear at lower latitudes than during non-storm-time substorms. Later, Huang and Foster [2007] showed that the latitude of the rapid flow channel is correlated well with the $Dst$ index.

Simultaneous occurrence of rapid subauroral flows has been observed in both the hemispheres, and in the ionosphere and the magnetosphere [Burke et al., 2000; Anderson et al., 2001; Makarevich and Dyson, 2007; Puhl-Quinn et al., 2007]. Thus, rapid subauroral flows are most likely formed as a result of magnetosphere-ionosphere coupling processes. One natural interpretation of the formation of the rapid subauroral flows is suggested by, e.g., Southwood and Wolf [1978], Spiro et al. [1979], and Anderson et al. [1993], in terms
of a closure of the electric current: Plasma sheet ions tend to drift inward, further than electrons, in the evening sector [c.f., Figure 12 of Ejiri et al., 1980]. Thus, the inner edge of the ion plasma sheet is located at a lower $L$-value than that of the electron plasma sheet. Plasma sheet electrons can undergo quasi-strong pitch-angle diffusion. As a result, the precipitating electrons enhance the ionospheric conductivity (formation of the main auroral oval). A longitudinal gradient of the ion pressure results in field-aligned current. In the evening sector, the downward field-aligned current tends to flow to the ionosphere equatorward of the main auroral oval. The upward field-aligned current flows out of the ionosphere poleward of the auroral oval [e.g., Rich et al., 1980; Anderson et al., 2001]. As a result, poleward electric fields occur in between these current sheets. In the narrow channel between the equatorward edge of the auroral oval and the downward field-aligned current, the poleward electric field is enhanced because the ionospheric conductivity is low [e.g., Maynard, 1978; Karlsson et al., 1998]. All of these characteristics are consistent with comprehensive observations of the rapid flows [e.g., Anderson et al., 2001; Goldstein et al., 2005; Huang and Foster, 2007; Puhl-Quinn et al., 2007].

The Super Dual Auroral Radar Network (SuperDARN) is a powerful facility for investigating the temporal and spatial variation of ionospheric plasma flows. The data obtained from the King Salmon (57.09 MLAT in AACGM) [Koustov et al., 2006], Wallops (49.03 MLAT) [Oksavik et al., 2006], TIGER (–54.68 MLAT) [Makarevich and Dyson, 2007], and Hokkaido (36.45 MLAT) [Kataoka et al., 2007] radars have revealed the fact that rapid subauroral flows have very dynamical characteristics. Dynamical characteristics of the sub-auroral rapid flow will be a direct manifestation of the temporal and spatial variations of the plasma pressure in the inner magnetosphere if the above interpretation is correct. To date, there was no confirmatory study on the influence of the plasma pressure in the inner magnetosphere on the dynamical character of the storm-time subauroral rapid flow. In this paper, we verify the interpretation by using the data obtained from the
SuperDARN Hokkaido radar (36.45 MLAT) during the magnetic storm of 15 December 2006 and carrying out the simulation that couples the inner magnetosphere with the subauroral ionosphere.

2. Observation

We focus on the intense magnetic storm that occurred on 14–15 December 2006. Figure 1 summarizes the time-shifted solar wind condition obtained from the ACE satellite, the $Dst$ index, and the subauroral plasma flows observed using the SuperDARN Hokkaido radar (MLT = UT + 9.3 h). This magnetic storm was led by a fast solar wind stream and a magnetic cloud accompanied with a large southward component of the interplanetary magnetic field (IMF). $Dst$ started decreasing significantly around 2100 UT on 14 December 2006 and reached its minimum value around 0700 UT on 15 December 2006 (c.f., Figure 1d).

The line-of-sight (LOS) velocity of the Hokkaido radar along beam 7 is drawn in Figure 1e. The field of view of the radar is indicated in Figure 2. The blue-to-red colors indicate the Doppler velocity that is most likely associated with the horizontal drift motion in the ionosphere. Positive values indicate the direction toward the radar (south-westward direction). Thus, blue color indicates rapid, westward plasma flows in the ionosphere. The gray color stands for the ground/sea scatter echo, which is negligible for this particular study. At a glance, the ground/sea scatter echo occupies a large part of the data during the storm’s main phase (from 2100 UT on 14 December to 0700 UT on 15 December). Ionospheric echoes were received at 0519–0533 UT and 0627–0637 UT on 15 December, which are attributed to overshielding [Ebihara et al., 2008]. In addition, persistent ionospheric echoes with relatively high Doppler velocity appears at 50–56 MLAT from
1000 UT to 1300 UT on 15 December 2006. We focus on this period, which is marked by a solid rectangle in Figure 1.

3. Simulation

The comprehensive ring current model (CRCM) [Fok et al., 2001] was used to solve the spatial and temporal evolutions of the four-dimensional phase-space density of the hot ions in the inner magnetosphere. The boundary conditions for the simulation were determined from the LANL satellite measurements performed at 6.6 Re. The bounce-averaged drift velocities of the ions were calculated under the magnetic and electric fields that were respectively determined using the T96 empirical model [Tsyganenko, 1995; Tsyganenko and Stern, 1996] and the requirement of the continuity of the electric current in the coupled magnetosphere-ionosphere system. The electric potential predicted by the convection electric field model of Weimer [2001] (dependent on the solar-wind condition) was imposed as a boundary condition for the simulation. The corotation electric field was also included. The other parameters used in the simulation were the same as those used by Ebihara et al. [2008].

4. Results

Figures 3a and 3b show the plasma sheet density and temperature of hot ions (0.13–40 keV) measured by the four LANL satellites at 6.6 Re. Magnetosheath-like or lobe-like ions were excluded by applying the criterion that $T_i \geq 3$ keV and $N_i \geq 0.05$ cm$^{-3}$, where $T_i$ and $N_i$ are the ion temperature and ion density, respectively. The ion density and temperature were linearly interpolated with respect to MLT and time for the purpose of identifying the boundary condition of the simulation. We admit that only the four satellites are insufficient to provide an accurate boundary condition of the simulation. We believe that this is one of
the best ways to estimate the hot-ion distribution at 6.6 Re, and that the boundary condition provided is still useful for the purpose of demonstrating how the hot-ion distribution at 6.6 Re influences the plasma pressure distribution in the inner magnetosphere. It is not our intention to reproduce exactly all the aspects of nature.

The plasma sheet ions are brought by the large-scale convection electric field from 6.6 Re to a low $L$-value with their drift trajectories depending on the kinetic energy and the equatorial pitch angle. The spatial and temporal evolutions of the plasma pressure in the inner magnetosphere are displayed in Figure 3d–m. The complex structures of the plasma pressure are prominent. The complexity is primarily due to the variation of the hot-ion distribution at 6.6 Re, rather than the variation of the convection electric field because the strength of the convection electric field remains to be relatively stable throughout the period indicated. The plasma pressure can be as thin as the full width at half maximum (FWHM) of ~0.5 in the radial direction. Each of the thin structure of the plasma pressure is accompanied with the azimuthal pressure gradient (as shown in Figure 3d–m) that generates the field-aligned current.

To trace the evolution of the plasma pressure, the plasma pressure as a function of $L$ and time at a meridian of 2200 MLT is shown in Figure 3c. When the plasma sheet density increases at 6.6 Re at ~1050 UT, the information is gradually propagated by the convection electric field to low $L$-values. Eventually, the plasma pressure at $L \sim 3$ shows a gradual increase at ~1130 UT with a delay of ~40 min. A solid line indicates the approximate earthward motion of the plasma sheet ions from 6.6 Re to low $L$-values. On the other hand, the influence of the plasma sheet temperature on the plasma pressure in the inner magnetosphere is not simple as is discussed by Ebihara and Ejiri [2000], Ebihaira and Fok [2004], and Lavraud and Jordanova [2007]. When the plasma sheet temperature is high, the relative number of high energy ions is increased. High energy ions tend to drift azimuthally due to grad-B and curvature drifts rather than the E×B drift. Thus, the plasma pressure in the inner magnetosphere is not simply related to the plasma sheet temperature.
It should be noted that not all the variations of the hot-ion distribution at the simulation boundary results in the complicated structures of the plasma pressure in the inner magnetosphere. Drift trajectories of the ions depend on energy, pitch angle and time. Thus, short-lasting variations of the plasma sheet are easily smeared as the ions drift earthward. Only long-lasting variations are effectively responsible for the formation of the prominent structures of the plasma pressure in the inner magnetosphere.

Figure 4 shows the field-aligned current (top) and the azimuthal component of the ionospheric plasma flow (bottom). In the simulation, the field-aligned current presented is primarily generated by the azimuthal pressure gradient [Vasyliunas, 1970; Wolf, 1970; Fok et al., 2001]. Thus, the complicated distribution of the field-aligned current reflects the complicated distribution of the plasma pressure. The space charge deposited by the field-aligned current tends to be canceled out by the Pedersen current, influencing in the ionospheric electric field (ionospheric plasma flow). Note that in general, morphology of the azimuthal component of the ionospheric plasma flow shown in the bottom of Figure 4 is consistent with that known as SAPS [Foster and Vo, 2002]. As MLT increases from dusk, the westward flow region tends to move equatorward. In the midnight-dawn sector, the eastward flow region lies poleward of the westward flow region.

Figure 5a shows the observed LOS velocity along beam 7 of the Hokkaido radar in the premidnight sector during the period between 1000 UT and 1300 UT on 15 December 2006. The LOS velocity appears to increase occasionally up to 400 m/s and more at 48–55 MLAT at 1030–1050 UT, 1055–1100 UT, 1130–1155 UT, and 1210–1220 UT. If the flow velocities were aligned with the $L$-shell, the corresponding westward flow would exceed 800 m/s. According to the data from GUVI aboard the TIMED satellite, the equatorward boundary of the auroral oval was determined to be ~58 MLAT at ~2300 MLT at 1120 UT (as indicated by a thick line). Thus, the rapid flows observed are considered to be a class of SAPS [Foster and Vo, 2002; Koustov et al., 2006].

Note that backscatter echo received is from the ionospheric point at which high-frequency
(HF) radar wave vector is orthogonal to the ambient magnetic field. Thus, the region where backscatter echo from the ionosphere is received appears patchy and variable as shown in Figure 5a. Nishitani and Ogawa [2005] show examples of ray paths of the radio wave emanating from the SuperDARN Hokkaido radar.

In Figure 5b, the simulated LOS velocity along beam 7 is displayed. In order to directly compare the observation and the simulation results, the abscissa, the ordinate, and the color code are the same as those shown in Figure 5a. The rapid flows appear occasionally with their speed being up to 400 m/s within a latitudinally confined region with a typical thickness of ~3°–5°. The simulation result agrees well with the observation in terms of the LOS velocity, the location, and timing. The temporal disappearance of the rapid flow between 1100 and 1130 UT can be explained as follows: When the ion density is enhanced at 6.6 Re at ~1050 UT (Figure 3a), the intensity of the field-aligned current is subsequently enhanced at 60–65 MLAT (Figure 4c). On the duskside, a downward field-aligned current is enhanced, resulting in charge accumulation. The resultant electric field tends to impede the poleward electric field that results in the persistent westward flow (Figure 4n). As a consequence, the rapid, westward flow disappears. The downward field-aligned current region moves equatorward with its intensity gradually decreasing (as indicated by arrows in Figure 4c–h) in accordance with the earthward drift motion of magnetospheric ions. When the downward current is located equatorward of the upward current region indicated by an open arrow in Figure 4f, the poleward electric field (the westward flow) is then intensified near the field-of-view of the Hokkaido radar as shown in Figure 4p–q. As a consequence, the rapid, westward flow is then enhanced.

Figure 5c is the same as Figure 5b except that the plasma sheet density and temperature at 6.6 Re were held constant at 0.57 cm⁻³ and 6 keV, respectively. The density and temperature were determined on the basis of a statistical study of the hot-ion measurements at 6.6 Re [Thomsen et al., 1996]. For this particular case, the plasma pressure distribution appears to be broader, and the LOS velocity is almost persistent in comparison with Figure 5b. By comparing Figure 5b with Figure 5c, it is concluded that the enhancement of the plasma
sheet density could have resulted in a temporal reduction and subsequent intensification of the rapid, westward flow with a certain delay depending on the strength of the convection electric field. The influence of the plasma sheet temperature on the plasma pressure in the inner magnetosphere (and the rapid, westward flow) is vague as shown in Figure 3b and 3c.

In order to assess the longitudinal movement of the rapid flows, the LOS velocities observed by all the beams (from 0 to 15) of the Hokkaido radar were averaged over the region from 48 to 58 MLAT. Figure 6a shows the averaged LOS velocity as a function of the magnetic longitude (MLON) and time. The rapid flow regions seem to drift westward, particularly for the first and second rapid flows at 1020–1110 UT. However, as shown in Figure 6b, they tend to stay at almost the same position in MLT. Figure 6c is the same as Figure 6b except that it shows the simulated LOS velocity. The rapid flow regions also stay at almost a fixed MLT, which are consistent with the observation. Figure 6d is the same as Figure 6c, except that the plasma sheet ion distribution was held constant, indicating that the LOS velocity does not show a significant temporal variation. This particular result is inconsistent with the observation.

It should be noted that Figure 6 does not represent correctly the azimuthal extent of the rapid flows because Figure 6 is compiled from the LOS velocities along the 16 beams of the radar. The simulated azimuthal distribution is correctly displayed in the bottom of Figure 4 in an earth-fixed frame of reference, and is mentioned above.

5. Discussion

Relation to substorms: First, we discuss the relationship between rapid flows and substorms. Nowadays, the term substorm encompasses many different physical processes. Here, we focus on (1) substorm-associated local acceleration of plasma sheet ions, and (2) substorm-associated transport process.
A fairly good agreement between the observation and simulation justifies the simulation and the use of the outer boundary conditions of the hot ions. The primary source of the temporal variation of the hot ions at 6.6 Re is unknown and beyond the scope of this study. Perhaps, substorm-associated processes, including stretching and dipolarization, may have caused some of the variation of hot ions [e.g., Baumjohann et al., 1991, Birn et al., 1997]. Complicated processes, other than substorm-associated processes, could also have acted on the hot-ion distribution at 6.6 Re because the temporal variation of the hot-ion distribution occurred at a shorter interval than typical interval during the substorms.

Although substorm-associated magnetic and electric fields are excluded in the simulation, the simulation result shows a good agreement with the observation. This probably implies that substorm-associated magnetic and electric fields are less important in the formation of the rapid ionospheric flows observed by the Hokkaido radar at $L \sim 2–3$, probably due to relatively high magnetic pressure in comparison with the plasma pressure. Anderson et al. [1993] showed that at $L < 4$, SAID typically occurs during the substorm recovery phase, after more than 30 min of the substorm onset. According to Figure 3c, the traveling time of ions from 6.6 Re to 4.0 Re is estimated to be $\sim 30$ min, which is consistent with their observation. The traveling time probably depends on the distance between the source of ions and the high-pressure region. This notion is supported by the observations made by Mishin and Puhl-Quinn [2007] who showed the traveling time of $\sim 10$ min from $L = 6.8$ to 4.9 by using the data from Cluster and DMSP. Of course, the traveling time should also depend on the intensity of the convection electric field. Thus, the actual situation should not be so simple.

**Morphology of the storm-time ring current:** The result provides an important insight into the morphology and dynamics of the storm-time ring current. Direct observations made by satellites have revealed that the plasma pressure exhibits a single peak around $L = 3$ during the quiet period [e.g., Lui and Hamilton, 1992] and sometimes multiple peaks during the storm time [e.g., Hoffman, 1973; Lui et al., 1987]. *In-situ* satellite measurements hardly distinguish a spatial change from a temporal one. The global morphology of the ring
current has been intensively studied using energetic neutral atoms (ENAs) emitted from ions constituting the ring current [e.g., Pollock et al., 2001; C:son Brandt, 2002]. Unfortunately, most of the ENA emissions occur at low altitude, and in general, it is difficult to reconstruct a spatial distribution of the ions in the equatorial plane. SuperDARN radar observations will be able to supplement inherent limitations of satellite observations to globally monitor the storm-time ring current if one-to-one correspondence between the spatial distribution of the ring current and the rapid ionospheric flows is observationally confirmed.

6. **Summary**

The mid-latitude SuperDARN Hokkaido radar observed a dynamical character of rapid ionospheric flows on the nightside during the 15 December 2006 magnetic storm. We performed a simulation that couples the inner magnetosphere and the subauroral ionosphere. The plasma sheet parameters (density and temperature of hot ions) observed at the geosynchronous orbit were employed as a boundary condition of the simulation. Highly variable nature of the plasma sheet parameters caused the complicated distribution of the plasma pressure in the inner magnetosphere, resulting in the dynamical character of the subauroral plasma flow. The simulated flow shows a good agreement with the observed one. It is suggested that the dynamical character of the subauroral plasma flow could be a direct manifestation of the plasma pressure distribution in the inner magnetosphere especially during the magnetic storms, although some other processes should also influence the subauroral plasma flow. Using global network observation of the ionospheric plasma flow will be a promising avenue toward deeply understanding the spatial and temporal evolution of the storm-time coupling processes among the solar wind, the outer magnetosphere, the inner magnetosphere, and the ionosphere.

**Acknowledgements**
The IMF and solar wind data were provided by Norman Ness (ACE/MFI) and David J. McComas (ACE/SWEPAM) through NASA/GSFC/CDAWeb. The authors thank Nikolai A. Tsyganenko for the empirical magnetic field model. This study was supported by the Program for Improvement of Research Environment for Young Researchers from the Special Coordination Funds for Promoting Science and Technology (SCF) commissioned by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan. This study is also supported by Grant-in-Aid for Scientific Research (B) (19340141) by Japan Society for the Promotion of Science (JSPS).

References


Galperin, Y.I., V.N. Ponomarev, and A.G. Zosimova (1973), Direct measurements of drift rate of ions in upper atmosphere during a magnetic storm. II. Results of measurements
during magnetic storm of November 3, 1967, Cosmic Research, 11, 249-258.


Pollock, C. J., et al. (2001), First Medium Energy Neutral Atom (MENA) Images of Earth’s


Vasyliunas, V. M. (1970), Mathematical models of magnetospheric convection and its coupling to the ionosphere, in Particles and Fields in the Magnetosphere, edited by


Figure 1: (a) Solar wind density, (b) solar wind speed, (c) Z-component of the IMF in the GSM coordinates, (d) the Dst index, and (e) LOS Doppler velocity of the ionospheric plasma flow along beam 7 of the SuperDARN Hokkaido radar (positive toward the radar).
Figure 2: Field of view of the SuperDARN Hokkaido radar in the geographical coordinates. Thick contour lines indicate magnetic latitude at 300 km altitude.
Figure 3: (a) Plasma sheet density, (b) plasma sheet temperature, (c) meridional distribution of the simulated plasma pressure at 2200 MLT, (d-m) simulated plasma pressure in the equatorial plane at 1030, 1045, 1100, 1115, 1130, 1145, 1200, 1215, 1230, and 1245 UT on 15 December 2006. In panels (a) and (e), the position of the LANL satellites (1994–084, LANL–97A, LANL–01A, and LANL–02A) is indicated by a black line. In the panels from (d) to (m), the Sun is to the left. The contour stands for the equipotential of the convection electric field. The outer boundary plotted is $L = 4$. The distorted fans with blue color indicate the equatorial mapping of the field-of-view of the Hokkaido radar.
Figure 4: (top) Field-aligned current at the ionosphere altitude (blue color for upward current, and red color for downward current), and (bottom) azimuthal component of the ionospheric plasma flow (blue color for westward current, and red color for eastward current). The Sun is to the left. The contour stands for the equipotential of the convection electric field. The fans indicate the field-of-view of the Hokkaido radar.
Figure 5: LOS Doppler velocities along beam 7 of the Hokkaido radar (positive toward the radar) generated by (a) an observation, (b) and (c) a simulation. In (c), the plasma sheet ion distribution is constant in time. A white line indicates the local magnetic midnight.
Figure 6: Observed LOS velocity at 48–58 MLAT as a function of (a) magnetic longitude (MLON) and time and (b) magnetic local time (MLT) and time. Simulated LOS velocity at 48–58 MLAT (c) as a function of MLT and time (d) with the plasma sheet ion distribution being constant in time.