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FAST EQUATORWARD SEPARATRIX MOTION IN THE NIGHTSIDE IONOSPHERE JUST PRIOR TO SUBSTORM ONSETS (EXTENDED ABSTRACT)

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In our previous paper (WATANABE *et al.*, 1998), we dealt with flow burst features in the nightside ionosphere that were thought to be the ionospheric signature of distant tail reconnection. These were observed just prior to substorm onsets. We explored the flow burst phenomenon with an emphasis on its direct association with the reconnection of magnetic field lines in the magnetosphere. However, the morphology of the flow burst is very important in that it occurs just prior to the substorm expansion phase onset. Since magnetic reconnection is an open/closed boundary layer process, we need to trace the location of the boundary in the ionosphere. As a by-product, we can know the time variation of the boundary, and consequently, of the magnetospheric configuration. The purpose of this paper is to discuss implications of the morphology from the point of view of substorms.

First we briefly describe the morphology. Figure 1 shows the horizontal component (positive geomagnetic north) of ground-based magnetic records obtained on November 16, 1995. A substorm occurred after a long period of a northward IMF (interplanetary magnetic field). The time interval bounded by the two vertical broken lines is the growth phase lasting from 2219 to 2327 UT. The flow burst phenomenon occurred from 2316 to 2332 UT as designated by the horizontal bar in the Tromsø magnetogram. Figure 2 represents a time sequence of Doppler velocities observed by the Goose Bay radar from 2310 to 2334 UT in the $\approx$2030 MLT (magnetic local time) sector. As designated by the yellow arrows, an equatorward bursty flow region with velocities greater than 750 m/s emerged abruptly at $\approx$2316 UT (Fig. 2d) and migrated equatorwards with time; it started to degenerate at the substorm onset (2326 UT, Fig. 2i) and finally faded away at 2332 UT (Fig. 2l). During the flow burst interval, DMSP F12 passed over the field-of-view of the radar flying poleward and observed the polar cap boundary (open/closed boundary or separatrix) at 2324 : 34 UT. The orange curve in Fig. 2h shows the spacecraft's trajectory with the blue triangle marking the polar cap boundary. We can conclude from Fig. 2h that the flow burst occurred at or a little

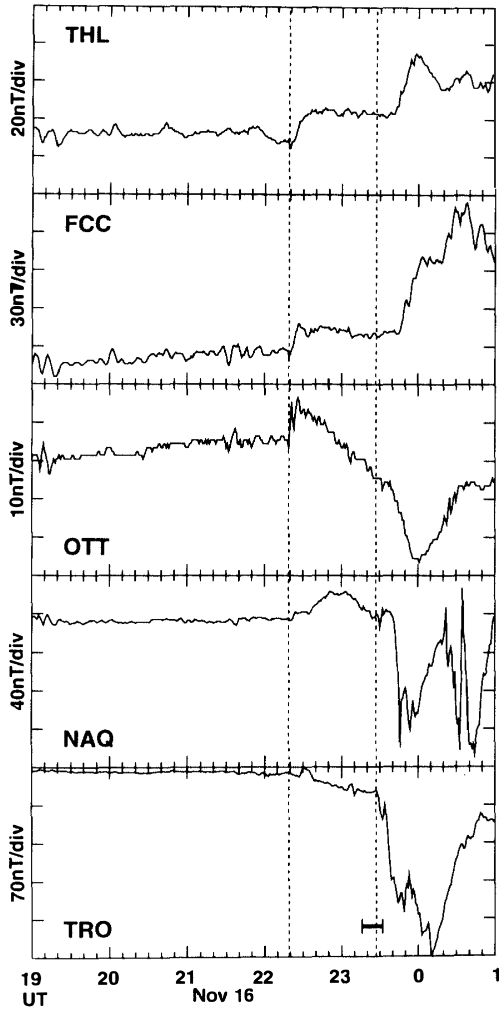

Fig. 1. The horizontal component (positive geomagnetic north) of the geomagnetic field observed on November 16, 1995, at Thule (THL, near geomagnetic pole), Fort Churchill (FCC, auroral zone in the evening sector), Ottawa (OTT, mid-latitude in the evening sector), Narssarssuaq (NAQ, premidnight auroral zone), and Tromsø (TRO, midnight auroral zone). The vertical broken lines show the start of the substorm growth phase (2219 UT) and the onset of the expansion phase at Tromsø (2327 UT). The bursty flow occurred during the time interval designated by the horizontal bar in the bottom Tromsø magnetogram.

equatorward of the polar cap boundary, showing that the bursts of flow are consequences of a boundary layer process. If we assume that the distance between the region of accelerated flow and the open/closed boundary shown in Fig. 2h remains constant, we can trace the separatrix location in the ionosphere. The equatorward boundary motion speed is about 580 m/s, whereas the average Doppler velocity in the flow burst region is 880 m/s. Therefore we can prove the presence of a reconnection process (WATANABE *et al.*, 1998). Although we cannot identify the separatrix location other than the enhanced-reconnection-rate part, the equatorward separatrix motion is expected to elongate over a wider local time span than the longitudinal scale of the flow burst.

Figures 3 and 4 give another example of the substorm-associated flow burst phenomenon that occurred on October 27, 1995. The substorm followed after a long period of the quiet magnetosphere associated with a northward IMF. Magnetograms in Fig. 3 show that the growth phase started at 0037 UT characterized by enhancements of the auroral (DAW/MEA) and polar cap (THL) electrojets and continued up to 0203 UT when a small negative bay commenced at Narssarssuaq. A flow burst phenomenon occurred from 0136 to 0158 UT as designated by the horizontal bar in the Narssarssuaq magnetogram. Figure 4 represents a time sequence of Doppler velocities observed by the

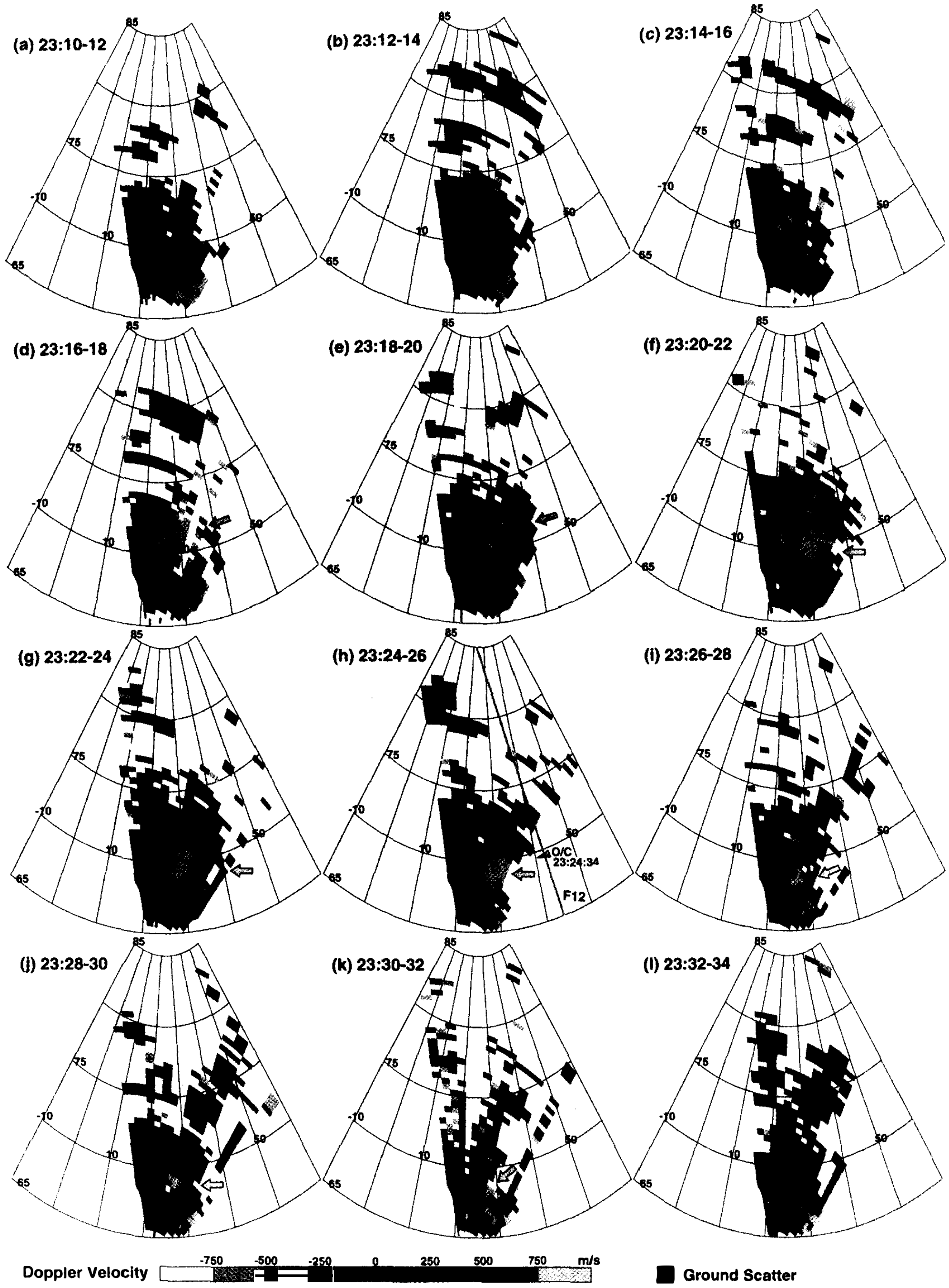

Fig. 2. A time sequence of line-of-sight Doppler velocities observed by the Goose Bay radar during 2310–2334 UT on November 16, 1995. Two-dimensional maps were obtained every 2 min. Blue color is used for velocities toward the radar (i.e., equatorward flows), whereas red is for velocities away from the radar (i.e., poleward flows). The bursts of flow, designated by yellow arrows, emerged at ≈2316 (panel d) and started to degenerate at ≈2326 (at the onset of the substorm expansion phase, panel i), and finally faded out at ≈2332 (panel l). DMSP F12 passed over the field-of-view during this interval and observed the polar cap or open-closed boundary at 2324:34 UT (69.5°N, 42.5°E in AACGM (altitude adjusted corrected geomagnetic) coordinates). The trajectory of the satellite is shown in panel h by an orange curve with the blue triangle marking the open-closed (O/C) boundary.

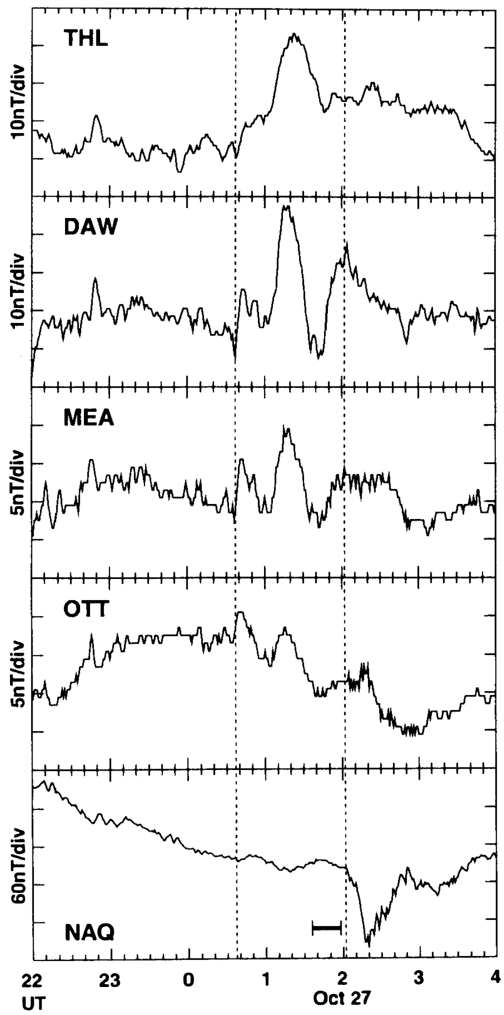

Fig. 3. The horizontal component (positive geomagnetic north) of the geomagnetic field observed on October 27, 1995, at Thule (THL, near geomagnetic pole), Dawson (DAW, auroral zone in the evening sector), Meanook (MEA, auroral zone in the evening sector), Ottawa (OTT, mid-latitude in the evening sector), and Narssarssuaq (NAQ, premidnight auroral zone). The vertical broken lines show the start of the substorm growth phase (0037 UT) and the onset of the expansion phase at Narssarssuaq (0203 UT). The bursty flow occurred during the time interval designated by the horizontal bar in the bottom Narssarssuaq magnetogram.

Goose Bay radar from 0130 to 0154 UT in the $\approx$2300 MLT sector. As designated by the yellow arrows, an equatorward bursty flow region with velocities greater than 750 m/s emerged abruptly at $\approx$0136 (Fig. 4d) and grew while migrating equatorwards with time; it started to weaken at 0152 UT (Fig. 4l) and finally disappeared at 0152 UT (not shown here). During the flow burst interval, DMSP F10 passed over the field-of-view of the radar flying poleward and observed the polar cap boundary at 0142:51 UT. The orange curve in Fig. 4g shows the spacecraft's trajectory with the blue triangle marking the open-closed boundary. We can see that the center of the flow burst is associated with the open-closed boundary. (In backscattered-power plots (not shown here), the center of the flow burst is more clearly defined than in the Doppler velocity.) Accordingly, as in the previous event, we can trace the separatrix location in the ionosphere. The equatorward separatrix motion speed in this case is about 670 m/s.

Thus the equatorward separatrix motion just prior to the substorm onset is several hundred m/s. One may doubt whether the polar cap boundary can move at such a high speed. For example, if we backtrack the boundary with the same constant speed, we find that there is almost no polar cap at the start of the growth phase. We note, however, that the high speed boundary motion is supported by previous observations. At present, the most reliable way to find the location of the separatrix on the nightside from

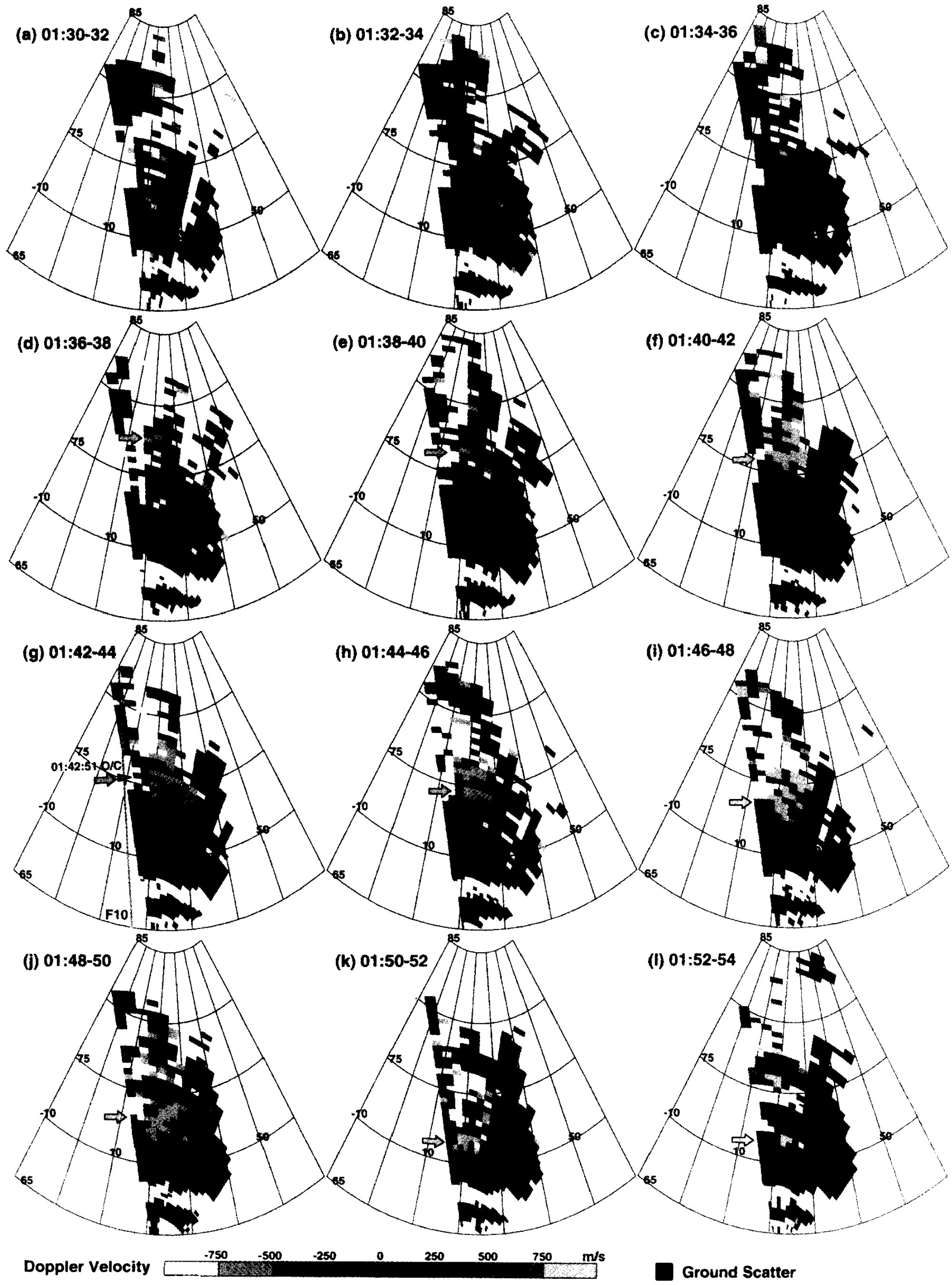

Fig. 4. A time sequence of line-of-sight Doppler velocities observed by the Goose Bay radar during 0130–0154 UT on October 27, 1995, in the same format as Fig. 2. The bursts of flow, designated by yellow arrows, emerged at ≈0136 (panel d) and started to degenerate at ≈0152 (panel l), and finally faded out at ≈0158 (not shown here). DMSP F10 passed over the field-of-view during this interval and observed the polar cap or open-closed boundary at 0142:51 UT (75.1°N, 9.0°E in AACGM coordinates). The trajectory of the satellite is shown in panel g by an orange curve with the blue triangle marking the open-closed (O/C) boundary.

the ground observation is to use latitudinal profiles of 630 nm auroral emission (BLANCHARD *et al.*, 1997). SAMSON *et al.* (1992) demonstrated for a well-isolated substorm on December 7, 1989, that the poleward boundary of 630 nm emission moved equatorward gradually with an average speed of several tens m/s from the beginning of the growth phase up to about 5 min before the expansion phase onset. For the last 5 min of the growth phase prior to the expansion phase onset, the equatorward motion of the emission boundary increased steeply to a speed of several hundred m/s. These results suggest that the polar cap boundary on the nightside moved much faster (several hundred m/s) for the 5 min prior to the expansion phase onset than for the preceding early and middle growth phases. Although the time scale (several minutes) is somewhat shorter than the lifetime of the flow burst in this study (10–20 min), we infer that this auroral morphology is another manifestation of the same phenomenon examined in this study.

Is the fast-moving boundary at the end of the growth phase a feature at all local times? The ionospheric projection of the separatrix is often modeled as a circle for simplicity. The polar cap expands equatorward during the growth phase due to an enhanced rate of dayside reconnection. Let us assume for a moment that the expansion of the polar cap is independent of local time, namely, open flux added at the dayside cusp is uniformly redistributed over all local times to form a circular polar cap. If the dayside reconnection rate is constant, the incremental change of the polar cap radius will diminish with time (since the area of the circular polar cap is proportional to the radius squared), which does not agree with the observation. In reality, the solar wind parameters are not constant, and consequently the dayside reconnection rate would not be constant. Although we do not know exactly how the dayside reconnection rate depends on solar wind parameters, the southward component of the IMF seems to contribute most sensitively to the dayside reconnection rate. A rapid expanding of the polar cap at the end of the growth phase would require a steep increase in the southward IMF during the flow burst period. However, such a signature was not observed for both events; in the October 27 event the IMF B_z during the flow burst period (Wind observation at $X = 178\,R_E$) was nearly constantly ≈ -2.5 nT for the first half and decreased gradually in magnitude for the second half to a value of -0.9 nT at the end, whereas in the November 16 event the IMF B_z for the first half of the flow burst period (IMP 8 observation at the dawnside) was ≈ -5.0 nT (data dropouts for the second half). In addition, a circular polar cap expansion with 500 m/s will require a dayside reconnection voltage of 210 kV when the polar cap boundary is at 78° MLAT (magnetic latitude) and 380 kV at 68° MLAT. Such a high reconnection voltage is impossible for the observed IMF B_z. Thus, the observational facts suggest that the circular polar cap model, *i.e.*, a uniformly expanding polar cap, is no longer valid for the fast-moving boundary at the end of the growth phase. Instead, considering the proportionality of the polar cap area to the total amount of open magnetic flux, we must interpret that the fast-moving boundary feature is confined to the nightside.

Why does the polar cap expand non-uniformly? There are at least two factors that control the shape of the separatrix: one is the magnetic flux budget through the separatrix by the reconnection processes, and the other is the magnetic field configuration itself. The fast-moving boundary at the end of the growth phase on the nightside would be attributable to the latter factor. The change of magnetospheric configuration really means the change of electric current distribution. The most plausible cause of the configuration change would be a more rapid intensification and/or earthward movement of the cross-tail current at the last stage of the growth phase. It is well-known that during the growth phase, magnetic fields at geosynchronous altitude are distorted progressively to a more tail-like configuration until the expansion phase onset (*e.g.*, SAUVAUD and WINCKLER, 1980). However, at geosynchronous altitude there seems to be no abrupt configuration change 10–20 min prior to the expansion phase onset as reported in this study.

Using AMPTE/CCE data in the near earth magnetotail ($|X| = 6$–$9\ R_E$), OHTANI *et al.* (1992) found that an "explosive growth phase" characterized by a sudden enhancement of growth phase perturbation (reduction of B_z) preceded the full onset of substorms. However, the time scale of their explosive growth phase is normally less than one minute and is much shorter than that (10–20 min) of the flow burst phenomenon studied in this paper. We infer that the explosive growth phase is a phenomenon associated with the expansion phase onset and essentially different from the global magnetotail configuration change in the late growth phase.

BAKER and MCPHERRON (1990) and with more observational support BAKER *et al.* (1993) proposed a model in which slow reconnection in the mid-magnetotail ($|X| =$ 15–$20\ R_E$) begins late in the growth phase (*i.e.*, ≈ 10–30 min prior to the expansion phase onset) and the cross-tail current is enhanced non-linearly earthward of a limited region in the magnetotail near the near-Earth neutral line. ANGELOPOULOS *et al.* (1994) and SERGEEV *et al.* (1995) pointed out in their report on a substorm event on April 15, 1979, that an activity reminiscent of near-Earth neutral line formation started in the mid-tail plasma sheet ($|X| \approx 16\ R_E$) 2–4 min prior to the expansion phase onset observed on the ground, which is consistent with the BAKER and MCPHERRON (1990) conjecture. Near-Earth reconnection is one possible cause of the non-linear growth of the cross-tail current.

It is certain that the magnetotail configuration change happens non-linearly at the end of growth phase, although we do not know the details of the process discussed in the present study. However, we show that the non-linear growth starts about one hour after a southward turning of the IMF. This time span corresponds to the time scale on which slow expansion fans from the dayside cusps fill the magnetotail lobes (CORONITI, 1985), which we think is important for future modeling of substorms.

Acknowledgments

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