MESO-SCALE STRUCTURES WITHIN THE AURORAL BULGE

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ABSTRACT

We present ground-based optical, riometer, and magnetometer, Polar UVI and GOES magnetic field observations of a substorm on 24 November, 1997. This event involved a clear optical onset followed by poleward motion of auroras, i.e. an expanding auroral bulge. During the first minutes of the expansion phase, there were three distinct meso-scale (10–1000 km) structures embedded in the bulge: a series of equatorward moving auroral arcs, a well-defined spiral pair, and north-south directed auroras. The spirals occurred several minutes after the onset, and indicate either a field-aligned current or a ballooning-type instability. The north-south aligned auroral forms occurred roughly 10 min after the onset implying bursty bulk flow type flows in the central plasma sheet. The riometer data suggest high energy electron precipitation in the vicinity of the poleward moving edge of the auroral bulge, starting at the onset and continuing until the north-south structure. In this paper, we examine this evolving auroral morphology.

Key words: substorm; bulge; meso-scale aurora.

1. INTRODUCTION

When a substorm begins and the dayside reconnection starts, newly opened flux tubes drift downstream to be stored in the magnetotail lobes. During the growth phase the tail stretches, cross-tail current increases and the plasma sheet thins. At the expansion phase onset the often most equatorward auroral arc intensifies and moves poleward. A bulge forms from the breakup region and expands poleward and along the oval. Westward Travelling Surges (WTS) are usually observed at the western edge of the bulge. Ground magnetometers detect Pi2 pulsations and particle injections are seen at the geosynchronous orbit. The stretched magnetotail changes to a more dipolar configuration when the nightside reconnection starts to close the flux tubes of the northern and southern lobes. Such merging leads to the formation of a plasmoid which is finally ejected downstream to the solar wind.

The process starting the substorm expansion in the tail defines the main difference between the two most widely discussed substorm models: the Near-Earth Neutral Line (NENL) (Baker et al., 1996; Shiokawa et al., 1998) and the Current Disruption (CD) model (Lui, 1996, 2001). NENL states that the expansion starts as the reconnection begins at about 20–30R\textsubscript{E} from the Earth. Plasma flows accelerated earthward from the X-line slow down in the stronger and more dipolar magnetic field (6–10R\textsubscript{E}). This results in a pile-up of magnetic flux. The increase in flux corresponds to the dipolarisation and diversion of cross-tail current as Field-Aligned Currents (FAC) into the ionosphere forming the Substorm Current Wedge (SCW). Compressional pulse initiated from the braking point propagates earthward causing Pi2 pulsations and particle injection at the geosynchronous orbit. According to CD, instabilities generate fluctuations in the magnetic and electric fields and increase the resistivity in the cross-tail current region. This leads to the diversion of the current to the ionosphere and associated dipolarisation. Candidates for the near-Earth plasma sheet instabilities are the cross-field current (Lui et al., 1991) and the ballooning instability (Roux et al., 1991). Tailward propagation of the instability thins the plasma sheet resulting in conditions favourable for the reconnection. In CD, the wave propagation shows as poleward expansion of the bulge in the ionosphere, while NENL explains the expansion by the growing pile-up of the magnetic flux at the earthward end of the plasma sheet. In NENL, the dipolarisation of the magnetotail arises from the earthward flows, like Bursty Bulk Flows (BBF), from the reconnection site to the near-Earth pile-up region. The dipolarisation in the CD model follows from the current disruption.

The transition region between the dipolar and tail-like field lines can be unstable for Rayleigh-Taylor type instability\textsuperscript{1}. As coupled to the shear flow Kelvin-Helmholtz instability, ballooning has been used for explaining the formation of large-scale auroral vortices (Voronkov et al., 2000) and the triggering of the expansion phase (e.g. Erickson et al. (2000)).

Poleward Boundary Intensifications (PBI) are brightenings of the aurora near the polar cap boundary, and have

\textsuperscript{1}A surface wave -type perturbation, which creates charge accumulations, and is then neutralised by the FACs diverting the cross-tail current to the ionosphere.
traditionally been identified on keograms of photometer data. Two-dimensional image data (e.g. Zesta et al. (2002)) shows that PBIs can be arcs that aligned east-west or tilted with respect to the polar cap boundary, or appear as more localised structures that often evolve into North-South (N-S) aligned structures. PBIs can remain at the boundary or propagate equatorward. N-S aurora are often related to transient earthward flows in the central plasma sheet (e.g. Zesta et al. (2000)). A connection between equatorward propagating arcs and phase fronts of earthward propagating disturbances in the plasma sheet (Zesta et al., 2002) has not yet been verified.

A bubble model by Pontius and Wolf (1990) described these features as elongated, transient low-density channels. The drift velocities inside and outside the bubble are different causing a charge accumulation, an extra electric field, and thus, the fast earthward flow. The charge separation neutralises by the formation of a FAC loop to the ionosphere and N-S aurora (a streamer). The N-S structures are often observed in the bulge. They form at the poleward boundary of the auroral oval, intrude rapidly equatorward (Amm and Kauristie, 2002) and cause a local brightening at the equatorward part of the oval (Sergeev et al., 2001). They occur roughly 10 min after the breakup and recur periodically. NENL explains streamers by BBFs between the reconnection site and the plasma pile-up region. According to the CD model, the earthward flows are related to convection surges (Lui, 1996) or propagation of the rarefaction wave.

2. INSTRUMENTATION

The locations of the Canadian Auroral Network for the OPEN Program Unified Study (CANOPUS) (Rostoker et al., 1995) stations used in this study are shown in Figure 1. The Gillam (GIL, 265.36°E and 56.38°N) All-Sky Imager (ASI) Field-Of-View (FOV) covers a circular area with a diameter of 600 km at the altitude of 110 km. The average spatial resolution is about 3 km (or 0.75°). The imaging interval is 1 min, exposure time 1.6 s and the filters are for the green (557.7 nm) and red (630.0 nm) emission. Riometers at Rabbit Lake (RAB, 58.22° N, 256.32° E), Eskimo Point (ESK, 61.11° N, 265.95° E), Island Lake (ISL, 53.86° N, 265.34° E) and Fort Churchill (FCC, 58.76° N, 265.92° E) record data at temporal resolution of 5 s and their FOV is 60°. They are sensitive to precipitating particles with energies of 10–100 keV. The Meridian Scanning Photometer (MSP) at GIL monitors the emissions at 557.7 nm, 630.0 nm, 486.1 nm (proton) and 470.9 nm (blue) along north-south scans. Its average latitudinal resolution is 0.2° and the time resolution is 30 s.

Global auroral images from the Ultraviolet Imager (UVI) experiment (Torr et al., 1995) on board the Polar satellite capture global activity. We used images from Lyman-Briggs-Field long (LBHL, at 170 nm) filter at 0319–0342 UT. The images are taken 3 min apart and their FOV cover the whole nightside oval. The National Oceanic and Atmospheric Administration (NOAA) Geostationary satellites GOES 8 and 9 had their footpoints in either side of the substorm. Magnetic field data (keyparameters from CDAWeb) were used to identify the dipolarisation, Keyparameter magnetic field data from the Interball Tail satellite in the tail lobe (X ~ 24 R_E, Y ~ 1 R_E, Z ~ 7 R_E) was also used for this purpose.

3. OBSERVATIONS OF THE SUBSTORM

The substorm occurred over CANOPUS at about 02–04 UT (~1930–2130 MLT) on 24 November, 1997. The IMF B_z had been negative since 2100 UT on the previous day, and small activations had been encountered in the ionosphere. As seen from the Polar UVI images (Figure 2), the oval was wide in the midnight sector and narrow in the evening sector prior to the substorm, but became wider during the activity. Tilted streamers grew and faded in different parts of the oval. The intense precipitation of the breakup arc followed the poleward propagation at the edge of the expanding bulge (0326–0335 UT). Faint arcs and unstructured precipitation were observed inside the bulge until the more intense N-S aurora crossed the polar cap boundary, in-
the oval at 0337UT. Magnetotail observations by GOES 8 and 9 (locations in Figure 2) show an increase in $B_Z$ and decrease in $B_X$ starting at 0332UT indicating the dipolarisation of the tail field at the geosynchronous orbit. The auroral breakup preceded the dipolarisation by about 6min. The Interball Tail satellite, although in the tail lobe, recorded a clear signature of the dipolarisation at 0335UT. According to the Polar UVI images the auroral onset took place west of GIL at about 0326UT, and it was followed by the northward expansion. Figure 3 shows an absorption spike starting at 0328UT (Fig. 4), i.e. a couple of minutes after the onset at GIL. At FCC and ESK the absorption increased rapidly at 0334UT and 0336UT, respectively. The strong signatures of the absorption suggest that a front of hard precipitation ($\geq 30$keV) was related to the poleward moving auroral arc. The proton emission at 486.1nm (Figure 5) comes from the near-Earth plasma sheet, and can be used to monitor the stretching of the magnetotail. The equatorward (poleward) shift of the equatorward edge of the proton band corresponds to an earthward (tailward) shift of the quasi-dipolar field lines (Sergeev et al., 1990). During the growth phase (02–03UT), the equatorward boundary of the proton emission moved equatorward out of the MSP FOV. Thus, the moment of dipolarisation cannot be exactly determined, but it was likely to occur just before 0332UT being consistent with the timing suggested by the GOES data.

4. DISCUSSION

Despite the high level of background activity, the event at 02–04UT can be considered as a substorm because 1) a bulge was formed with streamers inside, 2) dipolarisation signatures were observed at the geostationary orbit and in the tail lobes, 3) growth phase characteristics (equatorward motion of the proton band and increase of $B_X$ in the tail) preceded the expansion phase. However, a typical substorm is not in question since 1) no WTS was observed, 2) spirals occurred inside the bulge and not close to the onset region, 3) intense precipitation was seen only at the poleward edge of the bulge, 4) the dipolarisation took place 6min after the breakup, 5) both equatorward drifting arcs and streamers occurred during the expansion indicating two different modes of energy transport in the plasma sheet (wave fronts and BBFs). The lack of satellites in the plasma sheet beyond the geosynchronous orbit prohibited us from evaluating the substorm in the far-tail.

The spiral pair inside the auroral bulge was very transient. Its growth and decay occurred within less than one minute (the interval between two successive ASI images). Compared to the vortices studied by Voronkov et al. (2000) these spirals were roughly of the same size, but
clearly faster growing and without a visible stage of saturation, at least in the images taken with 1 min time interval. This suggests that the spirals were produced by the FAC instability without coupling to the ballooning mode.

The N-S aurora experienced the stages defined by Sergeev et al. (2001). The poleward edge of the bulge intensified in the electron emissions prior to the equatorward intrusion of the N-S structure, and a local brightening of the equatorward part of the oval was seen in both the proton and the electron emission when reached by the streamer at 0337 UT. The streamers typically occur a few minutes after the onset (Deehr and Lummerzheim, 2001) and are associated with transient dipolarisations (Kauristie et al., 2002). In our case, the streamer formed 10 min after the auroral breakup and 5 min after the dipolarisation. At the beginning of the expansion, the most intense arc separated a few times resulting in new arc propagating equatorward. As stated by Zesta et al. (2002), this tense arc separated a few times resulting in new arc propagating equatorward. As stated by Zesta et al. (2002), this likely indicates earthward motion of a wave front in the plasma sheet. The change in energy transportation mode (wave fronts to BBFs) in the plasma sheet coincided with the dipolarisation and the spiral formation. Simultaneously, the Northern Polar Cap index doubled, which is a strong indicator of an abrupt increase in nightside reconnection. This also suggests that the BBFs are a signature of more efficient reconnection that the wave fronts. This idea is also supported by the UVI images showing that the auroral oval is expanding poleward faster after the change from the arcs to the streamers than before. Such behaviour is not visible in the MSP data (Figure 3) because of the limited FOV of the instrument. In the NENL scenario one could interpret the transition from the arcs and a slower reconnection to the streamers and a faster reconnection as the transition of the merging from closed to open field lines. However, neither the distribution of UVI auroras nor that of 630 nm emission (not shown here) support this interpretation as the poleward edges in these data do not show any significant shifts with respect to the 557.7 nm band.

According to the NENL model, the equatorward motion in the ionosphere (earthward motion in the plasma sheet) should be observed prior to the breakup. However, at the end of the growth phase, the oval was so narrow that even if the equatorward motion existed it could not necessarily be observed. Not supported by the substorm models, the most intense precipitation occurred at the poleward boundary of the bulge. Only faint precipitation was detected inside the bulge, and no signatures of a SCW or a WTS were observed.

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