IMAGE and FAST observations of substorm recovery phase aurora

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[1] Images from the IMAGE Wide-band Imaging Camera (WIC) and Spectrographic Imager (SI) channel SI12, were compared to in situ data taken by FAST. The IMAGE data segment began during the expansive phase of a substorm and a double oval configuration evolved, consisting of a set of discrete poleward auroral forms and a separate more diffuse oval. The FAST data showed that a narrow (~1.5° latitude) region of downward currents separated the two ovals. The SI-12 optical observations showed a single oval of precipitating protons located on the equatorward side within the diffuse aurora. In agreement with IMAGE, the highest intensity proton flux measured by FAST was concentrated on the equatorward region although low flux protons were present throughout the entire double oval. In the lower latitude diffuse oval occasional structured auroras were embedded. These structured auroras were mostly created by inverted V type electrons but there were narrow regions in which intense beams of accelerated electrons were seen whose energy/pitch angle distribution and accompanying electric field data were consistent with Alfven wave acceleration. The poleward oval consisted of an intense inverted V precipitation event poleward of which a weak region of Alfven wave accelerated electrons was located. From the images it appears that the Alfven wave accelerated electron event in the diffuse auroral regions and the poleward features were part of short lived or rapidly moving auroral forms. *INDEX TERMS:* 2788 Magnetospheric Physics: Storms and substorms; 2704 Magnetospheric Physics: Auroral phenomena (2407); 2716 Magnetospheric Physics: Energetic particles, precipitating; 2455 Ionosphere: Particle precipitation

1. Introduction

[2] Spaceborne ultraviolet auroral imagers often observe a double auroral oval distribution in the substorm recovery phase [*Elphinstone et al.*, 1995a, 1995b]. The equatorward main UV auroral oval is associated with the inner portion of the central plasma sheet. The aurora in this region is diffuse or discrete depending on the state of substorm development. The second auroral oval consisting of a poleward discrete arc system is connected to the PSBL near the open and closed field line boundary. The association of the PSBL with this region was derived through the observation of velocity dispersed ion signatures (VDIS) [*Elphinstone et al.*, 1995b]. Observations from the FAST spacecraft show that the high latitude aurora can be separated into three different regions. First there is a downward current region containing, diverging electric field structure, up going field aligned electrons, small scale density cavities and B perpendicular ion heating. The second part is an upward current region containing converging electric field structures, large-scale density cavities, down-going inverted V electrons and up-going ion beams and conics. These two regions are generally consistent with quasi-static potential structures [e.g., *McFadden et al.*, 1999]. The third region is characterized by filamentary currents containing Alfvenic electric fields, field aligned counter streaming electrons and ion heating transverse to B with associated large ion outflow. This region is assumed to be associated with intense Alfven waves propagating from the magnetosphere that are most likely produced by rapidly moving field lines. Therefore we would expect that this type of aurora would be associated with either nightside substorm activity or dayside merging. The mechanism associated with this type of aurora on the dayside is described by *Chaston et al.* [1999]. We will examine a case of double oval configuration aurora in terms of the auroral regions described by data from a FAST pass and by the simultaneous global imaging from IMAGE between 1450 to 1600 UT on June 11, 2000 (day 163).

2. Data Presentation

[3] WIND ($X = 6R_e$, $Y = -33\ R_e$, $Z = -4\ R_e$ solar magnetospheric coordinates) magnetic field data show that during the period of interest the IMF z component was weakly negative with a strong positive y component. The GOES 10 geo-synchronous satellite magnetometer data (provided courtesy of H. Singer) showed sudden dipolarization occurring at 1445 UT indicating that the data sequence started in the expansive phase of a substorm. IMAGE orbit is highly elliptic with perigee at 1000 km (south) and apogee at 44,000 km (north) providing the most favorable close up view of the northern auroral oval shortly after instrument turn on following perigee pass. Pairs of FUV images are presented from 1516 to 1538 UT in Figure 1. The left Wideband Imaging Camera(WIC) image, is sensitive to auroral and dayglow LBH N_2 and N emissions in the wavelength region from 140 to 170 nm. The right SI12 image, shows proton induced Lyman alpha [*Mende et al.*, 2000]. Dayglow was removed from the raw WIC images by subtracting a 40 pixel Gaussian smoothed version of the image. The subtraction removed the slowly varying large-intensity dayglow and allowed the presentation of fine scale aurora simultaneously in the sunlit and dark regions. Without this correction the dynamic range spanned 14 bits. The SI12 instrument responds only to emissions produced by charge exchanged protons of energy

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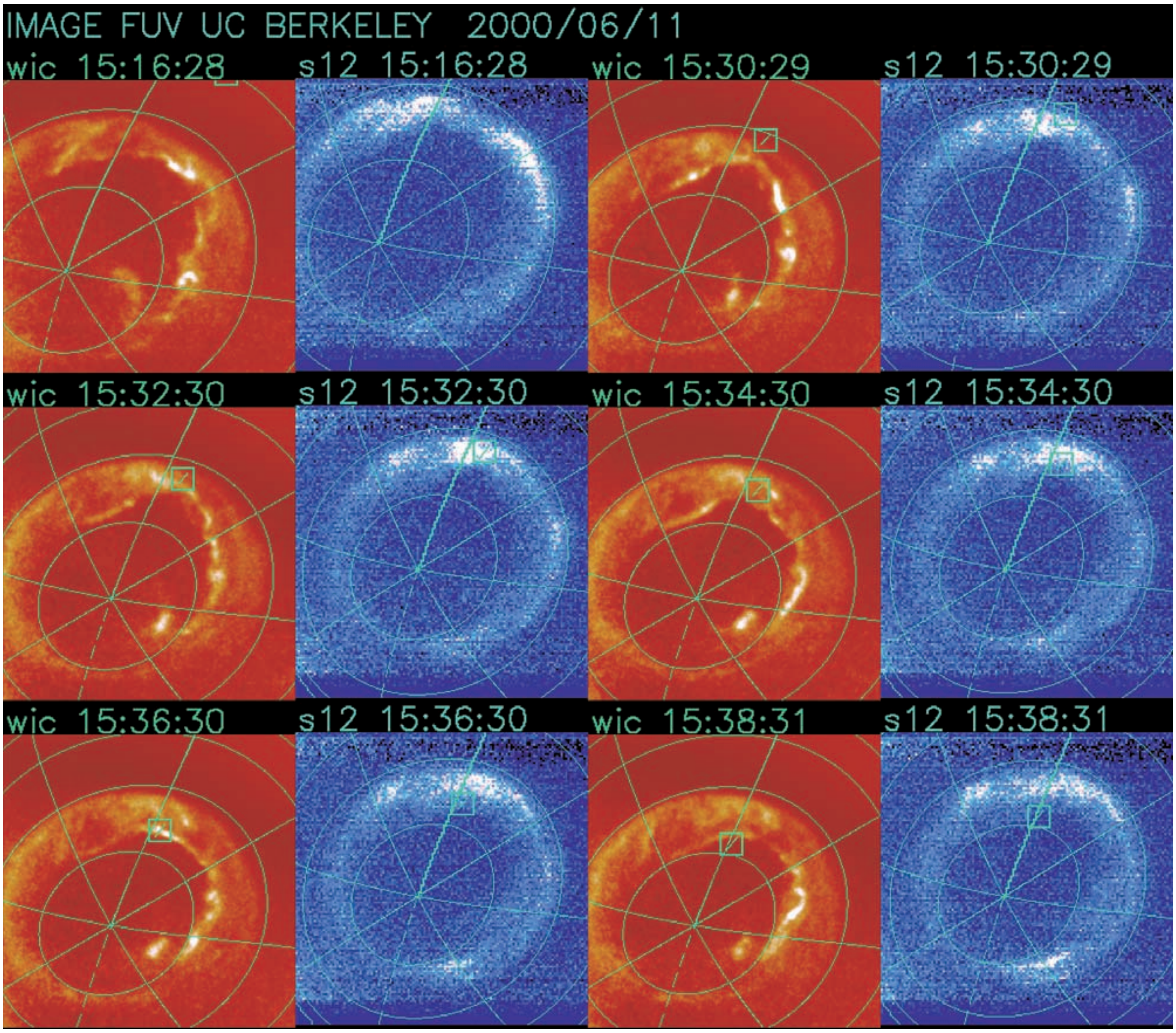

Figure 1. Collage of simultaneous WIC and SI12 images with superimposed geomagnetic latitude (45, 60, 75 and 900) and magnetic local time (midnight, 0300, 0600, 0900, 1500, 1800, 2100) green solid lines, and magnetic midday with dashed line.

greater than 1 keV and it needed no dayglow contamination correction [*Mende et al.*, 2000; *Frey et al.*, 2001]. Geomagnetic latitude (45, 60, 75 and 90) and magnetic local time (midnight, 0300, 0600, 0900, 1500, 1800, 2100) was superimposed with green solid lines. Magnetic noon was indicated with a dashed line.

3. Discussion

[4] The situation in Figure 1 is characteristic of the latter part of a substorm expansive phase followed by the recovery phase and leading to a "double auroral oval" [*Elphinstone et al.*, 1995a, 1995b]. The first image of the sequence (not included in Figure 1) showed a significant part of the nightside auroral oval including a hook like feature, the substorm surge (near 2000 MLT). Later (1458 UT) the remainder of the surge was located at 1930 MLT. After 1504 (not shown) the surge faded and a double oval configuration was seen by WIC consisting of a poleward region of discrete poleward auroras and a second more diffuse equatorward oval. At the start of the sequence (Figure 1) the proton aurora is seen (Right side blue-white images), collocated with the diffuse region. There is a bright patch near midnight which is just equatorward of the substorm surge and presumably located at the substorm onset location [*Mende et al.*, 2001]. The other duskward more intense proton precipitation is longitudinally coincident with the vestiges of the substorm surge but located equatorward of it. The intensity of the protons also faded with the remains of the substorm surge. After 1530 UT the proton auroras were located in the equatorward diffuse aurora. Between 1530 and 1538 the FAST satellite traversed the midnight auroral oval as illustrated by the small green box and a three minute (one minute prior to the image time and two minutes after) satellite track within the box. The WIC images at 15:36:30 and 15:38:31 are almost identical to the recovery phase situation described by *Elphinstone et al.* [1995a] in their Figure 1 top panel. In the FAST (Figure 2 top panel) magnetic field data negative gradients signify regions of upward current (downward electron flow). The second panel is the spectrogram of downward electrons showing diffuse electron precipitation with embedded structures below latitudes of 67° ILAT, (15:35 UT). The structures are either mono-energetic peaks (15:33:20, 15:34:40 and 15:35:10 UT) with high fluxes in both B parallel and perpendicular detectors consistent with isotropic pitch angle distribution or beams with monotonically decreasing energy spectra

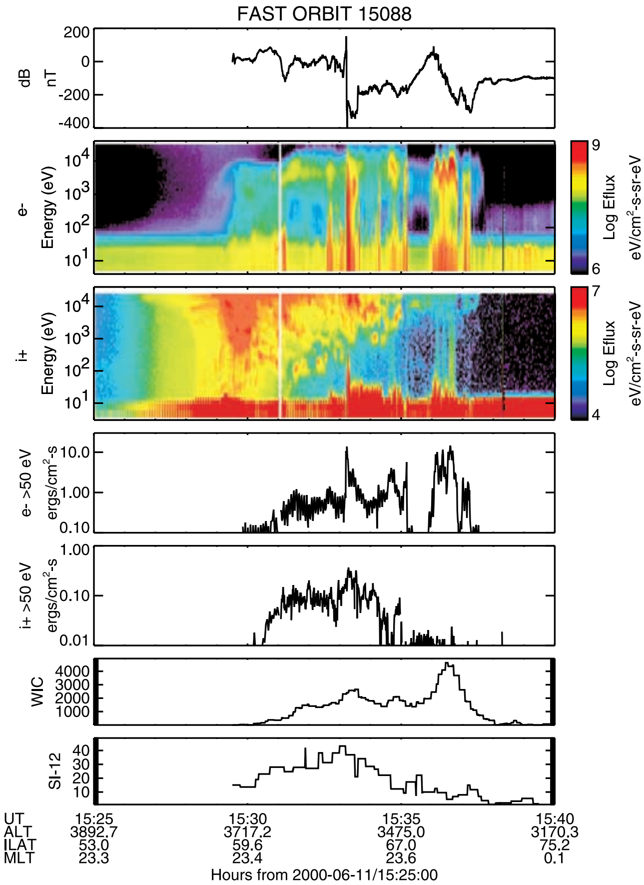

Figure 2. Fast data for the overpass shown in Figure 1. Panels are magnetic field, Downward (pitch angle 0–30) electron energy flux spectrogram, downward proton energy flux spectrogram, electron energy flux, ion energy flux, WIC counts and SI-12 counts.

(15:33:15 UT). The most remarkable feature is the one at 15:33:15 which represents a particularly intense current sheet and large fluxes of precipation. In this region the electric field wave data (not shown) has an amplitude greater than 100 mV/m and the phasing is consistent with a propagating Alfven wave. These observations are consistent with Alfven wave accelerated particles [*Chaston et al.*, 1999]. The downward current region [*Carlson et al.*, 1998] coincides with a region of no electron precipitation between 15:35:10 and 15:36:00. Poleward of the gap there is a large flux of 5 to 10 keV electrons also exhibiting mono-energetic peaks with enhancements at low energy due to reflected secondary electrons, typical of inverted V electron distribution produced by a quasi-static DC parallel electric field. At 15:37:10 there is another less intense batch of electrons with lower mean energy characteristic of Alfvenic wave accelerated electron distribution. Figure 2 Panel 3 and 5 show the downward ions (pitch angle = 0°–30°) energy spectra and and total energy respectively. At lower latitudes the protons have significant fluxes and they can be seen by the imager. The electron energy flux (Panel 4) shows a significant peak, of >10 erg cm^{-2} s^{-1}, at 15:33:15 due to the Alfvenic feature and at 15:36–37 in the region of the poleward mono-energetic inverted V structures. In the most poleward Alfvenic structure seen at 15:37:10 the energy flux is of the order of only 1 erg cm^{-2} s^{-1}. The protons (bottom panel) peak at lower latitude reaching an energy flux of 0.3 ergs cm^{-2} s^{-1}. The IMAGE satellite imagers take one exposure (10 and 5 sec duration for WIC and SI respectively) every two minutes. The intensity of pixels which were located on the orbit track during the two minute interval bracketing the exposures are plotted on Panel 6 and 7 for the IMAGE WIC and SI-12 detectors. This assures that the satellite data and the time when the image is taken, is within one minute of each other. The WIC image shows the aurora with the intense electron precipitation centered at and coincident with the poleward bright features, a darker region coincident with the zone of downward current and two brighter regions coincident with FAST electron precipitation enhancements. There is also excellent agreement between the FAST ion energy flux and the SI-12 measurements. The image 15:30:29 (Figure 1) shows FAST entering the nightside aurora. In the 15:32:30 image the satellite is about to traverse a bright feature which is presumably the electron precipitation seen on the FAST plot at 15:33:15. In the 15:34:30 image the satellite is poleward of the bright feature that seems to have also moved westward and became much weaker at the satellite trajectory. In agreement with the satellite proton data FAST is also at the poleward edge of the proton aurora at this time. The 15:36:30 WIC image shows that FAST should be on top of a bright feature. This is precisely the time when FAST sees the bright poleward inverted V feature. In the next image (15:38:31) the satellite is already in the polar cap. The bright feature, which was seen by FAST at 15:36:30, is substantially diminished in the 15:38:31 WIC image. The peak of intensities of the IMAGE FUV emissions represent an electron and proton energy flux of about 13 and 1 ergs cm^{-2} s^{-1} respectively [*Gérard et al.*, 2001] which is consistent with FAST measurements projected to 100 km altitude considering the energy responses of the instruments. If we assume that inverted V type auroras are the signature of steady state convection boundaries and Alfven wave accelerated auroras are of substorm related magnetic field dynamics then the relative weakness of this auroral component compared to the inverted V component signifies the late phase of the substorm recovery. Our optical observations show that the poleward bright auroral feature, which contains these auroral types, is very dynamic. In the strong upward current region where the energy flux was >10 erg cm^{-2} s^{-1} we estimated the current from the precipitating flux, (~1 μA m^{-2}) and the current sheet thickness (~400 km) and we found reasonable agreement with dB >200 nT decrease. On the other hand in the downward current region the ion flux is insufficient to account for the measured dB and the current must be carried by cold electrons. Most of the WIC images presented in Figure 1 show double oval configuration with an equatorward diffuse region, a bright poleward edge separated by a darker band. Although the images usually show dynamic behavior, some of these images look very similar to a typical double oval drawn by *Elphinstone et al.* [1995a, 1995b]. The WIC intensity plot in Figure 2 Panel 6 shows that along the FAST track there is a diffuse equatorward zone and a very bright poleward region separated by a broad dimmer region with one discrete structure in it. The spacing of the two bright regions bordering the central less intense middle region is on the scale of the double oval (>5°). The downward current region detected by FAST, located on the poleward side of the central dim region, which contains no electron precipitation, was relatively narrow in latitude (~1°).

4. Conclusions

[5] We conclude from simultaneous FAST and IMAGE FUV data taken during a substorm recovery phase that: 1. During substorm recovery phase the nightside oval had two bright regions separated by a dimmer one. The lower latitude region contained the proton aurora and the diffuse electron aurora with embedded structures. The structured auroras were mainly created by inverted V type electrons signifying quasi-static electric fields but in some of the structures intense Alfven wave accelerated electrons were seen. This region was separated from the higher latitude region by a zone containing downward currents exhibiting minimal electron precipitation. The poleward region consisted of an intense inverted

V precipitation structure poleward of which a weak region of Alfven wave accelerated electrons was located. 2. The Alfven wave accelerated electrons were seen in short lived or rapidly moving features. 3. The low latitude part of diffuse electron aurora was collocated with the more intense proton auroras. Although FAST data showed weak proton precipitation throughout the entire oval the bulk of the proton precipitation (with sufficient intensity to be seen by IMAGE) was located in the equatorward part of the double oval. The proton intensity decreased as the recovery phase progressed while maintaining maximum intensity near midnight.

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