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Auroral Surge Currents and Electrodynamics with FAST and VIS

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Abstract. We analyze data from two FAST satellite passes in the vicinity of auroral surges (as seen in the VIS auroral imager on the Polar satellite) to study the large scale ionospheric electrodynamics of the surge, focusing in particular on the configuration of field-aligned and ionospheric currents. While most previous ground and satellite observations have found the surge to be a region of predominantly upward field-aligned currents (FACs), some satellite observations have found evidence for equal downward and upward FACs near the surge, suggesting that the FACs close locally as opposed to globally through the substorm current wedge. Our observations show that while regions of both upward and downward FACs are present near the surge, there is a significant net upward FAC in the northern portion of meridians passing through the surge and just east of the surge. Current continuity requires that these upward currents be fed by downward currents traditionally thought to be in the eastern portion the auroral substorm bulge. Such a current configuration requires a westward ionospheric current to connect the two FAC regions, and this is supported by our observations of a significant southward electric field in the high Hall conductance surge region, which drives a strong westward Hall electrojet connecting the upward surge FACs and the presumed downward FACs east of the surge.

INTRODUCTION

The auroral surge is arguably the most visually spectacular and electrodynamically complicated auroral form. However, due to its usually short-lived nature, ground-based and satellite electrodynamic observations of this phenomena are rather sparse. Surge electric fields, currents, and precipitation-produced ionization have been observed from the ground with all-sky cameras, magnetometers, and the STARE radar [*Inhester et al.*, 1981; *Opgenoorth et al.*, 1983] and with the Chatanika incoherent scatter radar [*Robinson and Vondrak*, 1990]. Satellite observations of the surge include measurements of the magnetic field deviations and energetic particles along a pass through an active auroral surge with DMSP satellites [*Bythrow and Potemra*, 1987], and detailed particle and field observations from the Dynamics Explorer (DE) [*Weimer et al.*, 1994] and Freja [*Marklund et al.*, 1998] satellites. Surge electrodynamics have also been studied statistically from a careful analysis of DE-1 images and DE-2 particle and field observations [*Fujii et al.*, 1994; *Gjerloev and Hoffman*, 1998].

The variability of individual auroral surges makes it difficult to compare directly the above-listed observations of different events. However, some features are common to most of these surge observations and we take these to be general characteristics of auroral surges. The surge head is a region of high ionospheric Hall

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conductivity typically produced by energetic inverted-V electron precipitation, and it contains broad and intense upward field-aligned currents (note that this does not preclude additional regions of downward field-aligned current). Radar and satellite observations also show that the electric field in the vicinity of the surge generally converges to the surge head, indicating negative space charge associated with this region which is consistent with models of surge electrodynamics [*Inhester et al.*, 1981; *Opgenoorth et al.*, 1983]. Lastly, the satellite electric field measurements consistently show a "stagnation region" of low electric fields (and therefore low ionospheric convection) south of the surge and extending somewhat to the east.

Despite these similarities, there remain some open questions regarding the structure of the field-aligned currents (FACs), ionospheric electric field, and ionospheric currents in the vicinity of the surge. Freja observations [*Marklund et al.*, 1998] showed an intense downward current northwest of a surge which balanced the upward current in the surge, from which it was concluded that the upward currents in the surge may be fed locally by equal downward currents surrounding the surge. Other observations [*Bythrow and Potemra*, 1987; *Weimer et al.*, 1994] and models [*Opgenoorth et al.*, 1983] do not produce equal downward currents nearby, suggesting that the upward currents in the surge are closed through downward currents elsewhere in the auroral bulge. Also, radar [*Inhester et al.*, 1981; *Opgenoorth et al.*, 1983] and satellite [*Fujii et al.*, 1994] observations have found significant southward electric fields near and to the east of the surge that drive strong westward Hall currents in the ionosphere, thereby feeding the net upward FACs associated with the surge head from downward currents distant from the surge. The same Freja observations [*Marklund et al.*, 1998], however, showed weak electric fields east of the surge, implying weak westward Hall currents and necessitating local closure of surge FACs through ionospheric currents in the immediate vicinity of the surge. The surge current configuration has important implications, as local field-aligned current closure precludes the presence of a substorm current wedge [*McPherron et al.*, 1973], which is generally thought to play an important role in substorm magnetosphere-ionosphere coupling.

To try to resolve these inconsistencies regarding surge electrodynamics, we have examined data from the FAST satellite [*Carlson et al.*, 1998] and the VIS instrument on the Polar satellite [*Frank et al.*, 1995] during the approximately three month period of late 1997 and early 1998 when FAST was in local time sectors (∼18–24 MLT) where surges are expected to occur and the VIS Low Res visible wavelength camera was in operation. We found two FAST passes in the vicinity of significant auroral surges, and we analyze the electrodynamic parameters observed on these two passes to compare them to models and previous observations, focusing in particular on the relationship of ionospheric and field-aligned currents.

FAST AND VIS OBSERVATIONS

Possible substorm auroral surges were identified by bright x-ray auroral emissions (corresponding to intense, >3 keV precipitation) seen by the Polar Ionospheric X-ray Imaging Experiment (PIXIE) [*Imhof et al.*, 1995] in the ∼18–24 local time sector. The FAST passes through these possible surge regions were then examined for the precipitating electron signature of the surge, namely intense and energetic ($\gtrsim$5 keV) inverted-V precipitation at the northern edge of the auroral zone [*Meng et al.*, 1978]. Lastly, VIS images at a wavelength of 557.7 nm were examined to see whether the FAST footprint passed through or near a region with the optical signature of a surge, namely a bright emission at the northern edge of the auroral zone containing a noticeable curl [*Akasofu*, 1964]. We purposely avoid auroral morphologies containing multiple surges or spirals [e.g., *Johnson et al.*, 1998], as the electrodynamics of these cases may be quite different than for the single surges considered here. The two events that met these criteria are discussed below.

Event 1: 17 Jan 98

The top of Plate 1 shows an image of 557.7 nm auroral emissions taken by VIS on 17 January, 1998 at 17:04:46 UT with a 44 second integration time. The global aurora can be described as a typical well-developed substorm, with a bulge shape and a well-defined surge at the northwestern edge of the bulge. The image is overlayed with a grid of corrected geomagnetic (CGM) latitude and local time, and with the footprint of the southward-moving FAST satellite. FAST did not pass through the surge head but rather passed through the bright arc connecting to the surge about 1.5 hours of local time to the east.

The lower panels in Plate 1 show the electrodynamic parameters observed by FAST and calculated from the FAST data along its path through the auroral bulge. The electrons in the loss cone, shown in the time-energy spectrogram, were used to calculate the Hall and Pedersen ionospheric conductivities with an ion-pair produc-

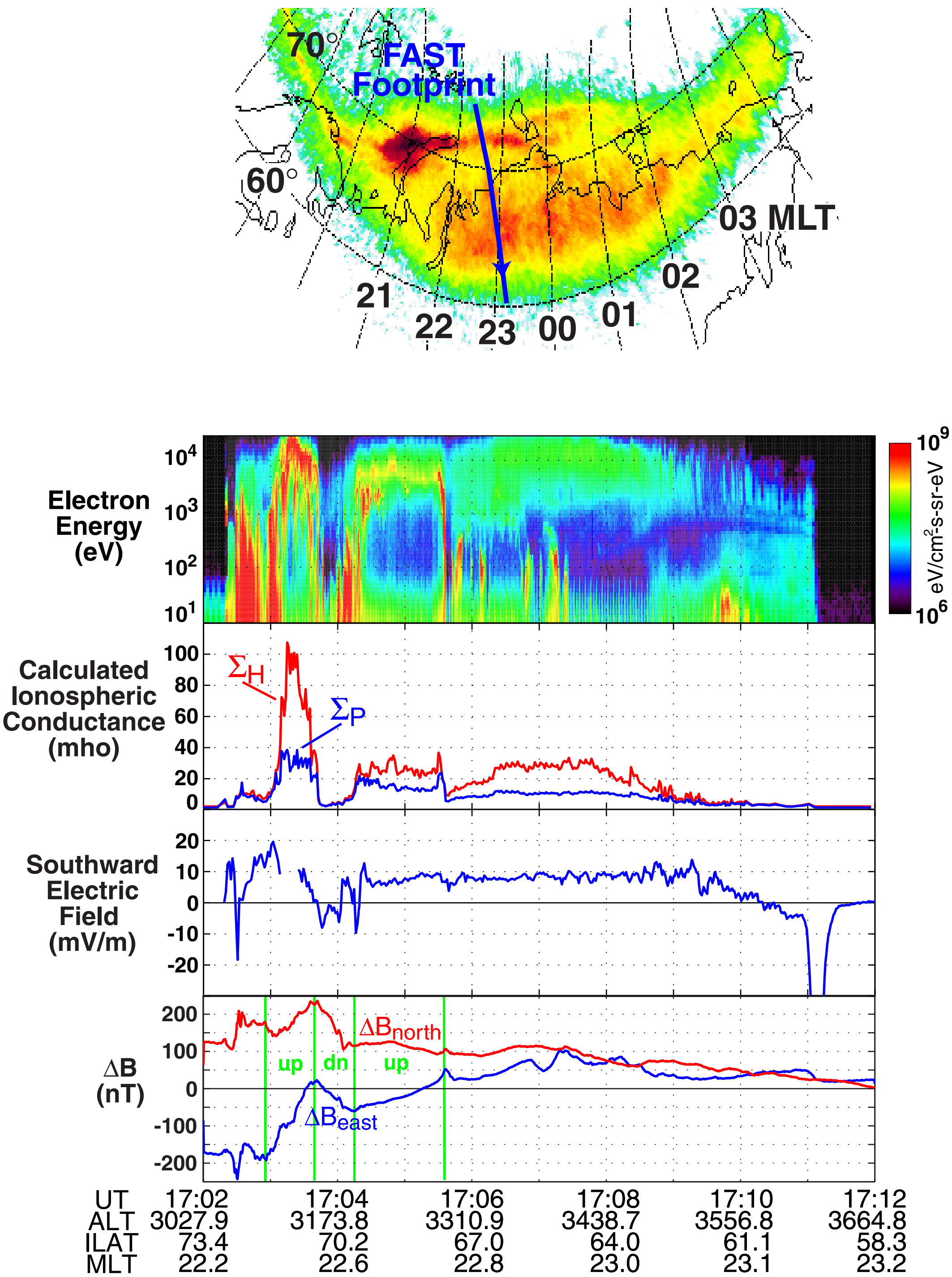

Plate 1. Observations from VIS and FAST on 17 Jan 98 at 17:05 UT. Top: 557.7 nm VIS image of the aurora. The grid coordinates are CGM local time and magnetic latitude. The magnetic footprint of the FAST satellite is overlaid in blue. Bottom: the observed and calculated electrodynamic parameters along the FAST footprint through the surge-connected arc. The panels show, from top to bottom, electron differential energy flux averaged over the loss cone, ionospheric conductances calculated from the precipitating electrons, observed southward electric field, and observed magnetic field deviations. Regions of upward and downward field-aligned currents are marked on the magnetic field deviations.

tion model [*Rees*, 1963]. FAST measured the horizontal electric field only in the direction parallel to the spacecraft velocity, which in this case is almost southward. The electric field data gap corresponds to a period when FAST passed through the low altitude portion of the auroral acceleration region and therefore observed horizontal electric fields associated with parallel particle acceleration which are not present in the ionosphere and thus do not drive ionospheric currents. The magnetic field perturbations observed by FAST, which we assume are produced by FACs, are plotted in the bottom panel.

As expected, the intense and energetic (>10 keV) inverted-V precipitation corresponds to the bright surge-connected arc in the VIS image and produces high Hall and Pedersen conductances in the ionosphere. The meridional electric field varies from primarily southward in the poleward arc, to almost zero just south of the surge-connected arc, and to southward through the rest of the bulge. It turns very strongly northward just south of the auroral oval in association with a subauroral ion drift [*Anderson et al.*, 1993]. The southward electric field and high Hall conductance in the poleward arc produce a strong westward electrojet of magnitude $\sim 1.2 \times 10^5$ A that connects to the surge, in agreement with previous observations of strong westward currents east of the surge [e.g., *Opgenoorth et al.*, 1983].

The magnetic field observations show the expected strong upward current in the surge-connected arc and a region of net downward currents equatorward of this arc. The significant perturbations in the northward magnetic field indicate that the assumed FAC sheets are significantly tilted from their usual east-west alignment [*Fung and Hoffman*, 1992]. Comparing the integrated intensities of the upward and downward currents north of the Harang discontinuity that can connect to the westward electrojet, we find that the downward current is 56% of the upward current, leaving a net upward current of ~0.25 A/m along the northern portion of this meridian. Therefore, since 44% of the upward current does not close locally, current continuity requires that it must close through an ionospheric current that is connected to a net downward current that in turn is either localized or distributed elsewhere in the auroral oval. The strongest electrical connection from the upward current region to elsewhere in the oval is through the high Hall conductance channel at the northern edge of the bulge, and given the observation of southward electric fields in this channel which drive westward ionospheric currents, it is most likely that the net upward current is fed by these westward Hall currents that are connected to net downward currents in the eastern portion of the auroral bulge. This observation is in general agreement with the statistical observations of *Fujii et al.* [1994] and *Gjerloev and Hoffman* [1998] in which the upward surge FACs were closed by a combination of adjacent downward FACs and ionospheric currents connected to downward FACs in more distant regions.

Event 2: 18 Jan 98

Plate 2 shows the FAST and VIS observations from 18 January 98 in the same format as in the previous case. The lack of a latitudinally expanded auroral oval in the 557.7 nm VIS image shown at the top of Plate 2 taken at 13:04:51 UT shows that this is not a bulge-type substorm as was the previous case, but there is a clear and relatively static (as inferred from the sequence of VIS images, which are not shown here) surge structure towards the west of the auroral zone. The 13:08 UT image (not shown) shows more clearly the curling auroral emissions that qualify this event as a surge. The FAST footprint passes through a region of bright auroral emissions close to the surge center.

The lower panels in Plate 2 show the electrodynamic parameters observed by FAST for this pass. The ionospheric conductance was calculated directly from the precipitating electrons while the other parameters are directly measured. As in the previous case, intense inverted-V precipitation corresponds to the bright poleward arc in the VIS image, and the electric field in this surge arc is primarily southward, producing a strong westward electrojet in the surge of magnitude $\sim 2.0 \times 10^5$ A. The apparent electric field data gap is again a result of FAST entering the auroral acceleration region. However, in contrast to the other pass, the electric field is extremely weak and slightly northward in the region south of the surge. This difference between the two passes is consistent with the presence of a Harang discontinuity south of the surge that divides the regions of northward and southward electric fields.

The magnetic field perturbations are also slightly different than in the previous case. There is the expected strong upward current in the surge, but there is less downward current along the portion of this meridian north of the Harang discontinuity. Quantitatively, only 27% of the upward current is closed by adjacent downward currents, leaving a net upward current of 0.53 A/m in the surge meridian. The non-local closure implies that these upward currents in the surge are closed primarily through downward currents elsewhere in the auroral oval.

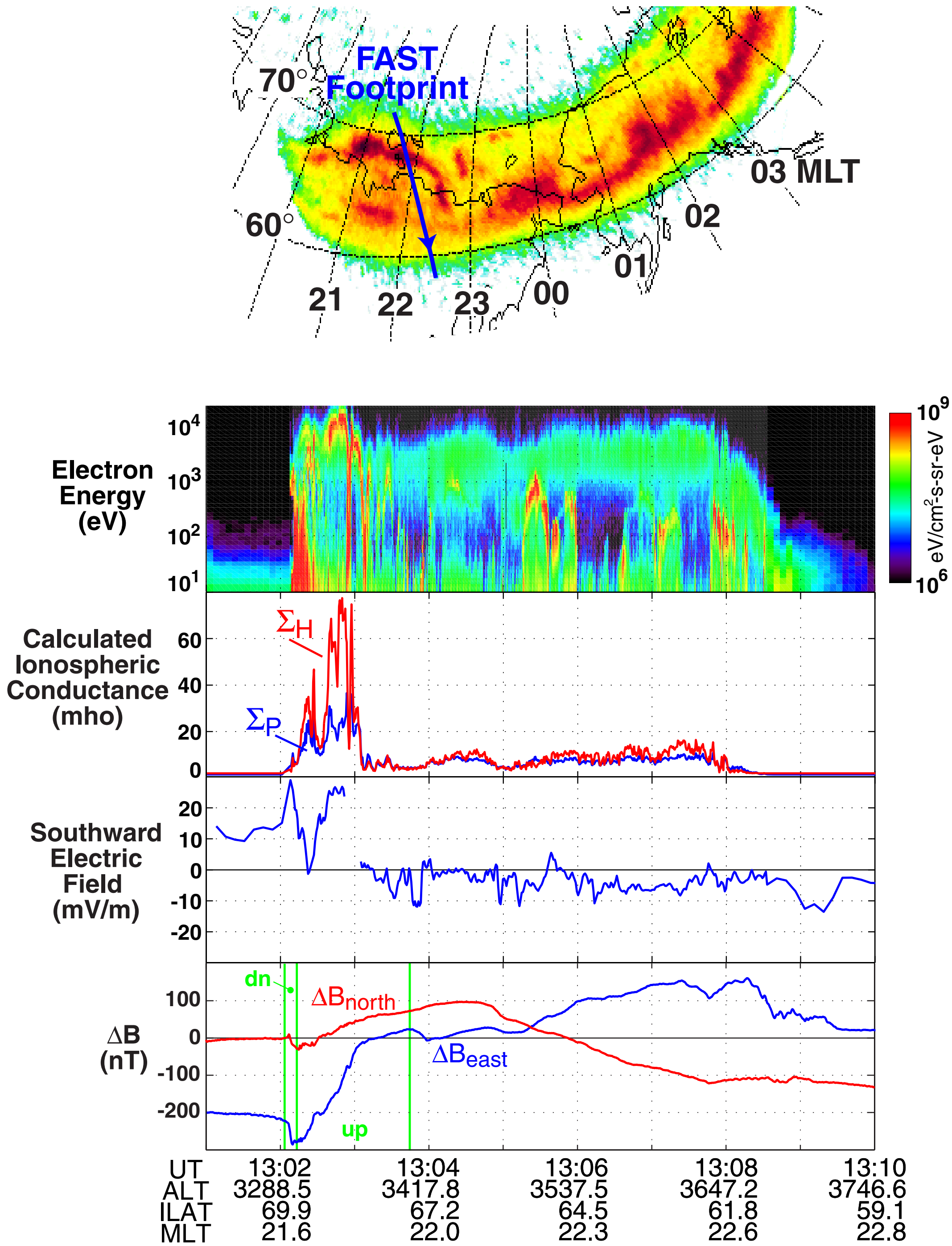

Plate 2. Observations from VIS and FAST on 18 Jan 98 at 13:05 UT in the same format as in Plate 1. Top: 557.7 nm VIS image of the aurora. Bottom: The observed and calculated electrodynamic parameters along the FAST footprint through the surge-connected arc.

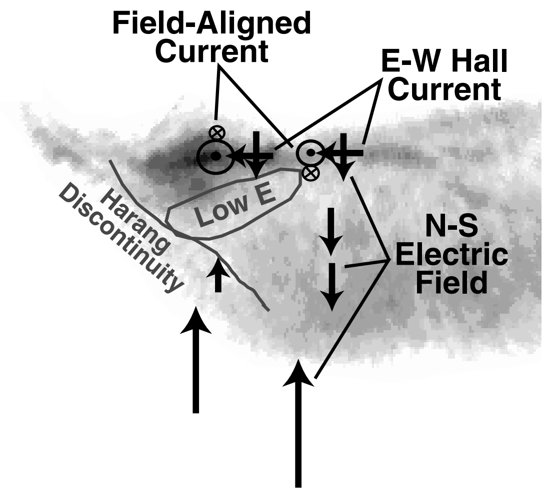

Figure 1. A schematic summary of the field-aligned currents, ionospheric Hall currents, and north-south electric fields observed in the two FAST passes presented herein. The surge and surge-connected arc contain strong upward FACs and adjacent, smaller downward FACs. The southward electric field in the high Hall conductance surge drives a strong westward electrojet which connects to the upward FACs.

DISCUSSION

Figure 1 shows schematically the large-scale electrodynamics of the auroral surge observed in these two passes overlaid on a generic substorm auroral image. The intense upward current and high ionospheric conductivity in the surge and weak electric fields south of the surge, which have been consistently observed in previous surge studies, are found in these measurements as well, and we suggest that these are standard elements of the electrodynamics of the surge.

We find in both passes discussed above a significant southward electric field in the surge and surge-connected arc to the east, which when combined with the high Hall conductance in these regions produces a strong westward electrojet. The FAST FAC observations show that while both upward and downward FACs are present near the surge, the downward FAC is smaller by a factor of 2–4, leaving a significant net upward current in the surge and surge-connected arc. These two facts paint a picture that is generally consistent with the concept of the substorm current wedge [*McPherron et al.*, 1973], in which a downward current in the eastern portion of the auroral bulge passes through the ionosphere as a westward current and leaves the ionosphere as an upward current through the auroral surge. However, our observations suggest that the upward wedge FACs are distributed in local time to a large degree and that significant downward currents are present in the surge and vicinity, as was seen in the statistical DE studies of *Fujii et al.* [1994] and *Gjerloev and Hoffman* [1998]. Our observations are in disagreement to the observations of *Marklund et al.* [1998] in which upward surge FACs were balanced by equal downward FACs in the immediate vicinity and in which weak westward ionospheric currents were observed east of the surge. It should be emphasized that since the surge is such an electrodynamically complicated and variable region, there is likely considerable variability from event to event. Nevertheless, the FAST observations here support the majority of the previous observations and show that the surge is a region of net upward FACs which are fed by a strong westward Hall current.

CONCLUSIONS

We have analyzed the ionospheric electrodynamics observed by the FAST satellite on two passes near auroral surges seen by the VIS Low Res visible imager on the Polar satellite. The southward electric field and vector magnetic field perturbations were directly measured, and the ionospheric Hall and Pedersen conductances were calculated from the precipitating electron measurements. In agreement with most previous surge observations, we find that the surge is a region of strong upward field-aligned currents and high ionospheric conductance, while to the south of the surge is a region of weak electric fields. Our primary goal was to study the configuration of field-aligned and ionospheric currents, as previous surge observations have differed as to the details of this relationship. We find that the surge contains significant net upward currents and that a significant southward electric field in the high Hall conductance region drives a westward current which feeds this upward current. This configuration is consistent with the concept of the substorm current wedge [*McPherron et al.*, 1973] in which a downward current in the eastern portion of the auroral bulge passes through the ionosphere as a westward current and leaves the ionosphere as an upward current through the auroral surge. These observations are consistent with many previous surge observations [*Inhester et al.*, 1981; *Opgenoorth et* *al.*, 1983; *Weimer et al.*, 1994; *Fujii et al.*, 1994; *Gjerloev and Hoffman*, 1998] but are in disagreement with recent Freja surge observations [*Marklund et al.*, 1998] in which it was suggested that the upward surge currents close locally through equal downward currents in the immediate vicinity of the surge. We should emphasize that observations of the auroral surge are still rather sparse, and further simultaneous auroral imaging and electrodynamic observations of the surge will help fill in the gaps that remain in our understanding of the electrodynamics of this complicated and dynamic auroral form.

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