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Aircraft observations conjugate to FAST: Auroral arc thicknesses

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Abstract. Optical observations conjugate to the FAST satellite show good agreement between the widths of auroral structures observed optically and those inferred from the measured electron energy flux. The implication is that these structures are imposed by processes at or above the ~4000 km altitude of FAST. A variety of widths down to about 2 km were observed, but there were no examples of finer scale structures. A pre-breakup weak discrete arc at the poleward edge of the diffuse aurora showed electron produced optical structures located on either side of upward going ion beams. The optical emission in the equatorward part of the diffuse aurora was caused almost exclusively by precipitating ions. The optical observations were made over northern Alaska between Jan 31 and Feb 16, 1997, from a jet aircraft carrying an all-sky and three narrow-field TV cameras.

Introduction.

A characteristic feature seen in plots of electron energy spectra obtained by satellites passing through the auroral oval is an increase and then a decrease of the characteristic electron energy to form the likeness of an inverted V. There can be several inverted-V structures in a pass and they are generally assumed to be associated with visual discrete auroral arcs. While there have been occasional reports of inverted-V structures having widths of 10 km or less [*McFadden et al.*, 1990; *Boehm et al.*, 1994], widths of the order of 100 km are more commonly reported. But visual auroral arcs are most often only a few km and rarely over 10 km wide. Within the arcs, smaller filamentary structures (arc elements) may have widths of order of 100m. The problem was first posed formally by *Evans* [1971] who observed that the distribution of scale sizes observed in rocket observations of total particle energy flux differed from the auroral width measurements made by *Maggs and Davis* [1968]. More width measurements of the auroral fine structure were made by *Borovsky et al.* [1991] followed by an extensive, but inconclusive, review of proposed mechanisms [*Borovsky*, 1993]. The apparent discrepancy has been further discussed recently by *Calvert* [1997]. The unique combination of the FAST satellite particle data with optical auroral observations magnetically conjugate to FAST can address this problem.

The FAST satellite can resolve spatial structures that map to a few tens of meters at the ionosphere with full energy and pitch angle resolution [*Carlson et al.*, 1998]. Optical data taken at points away from the vicinity of the magnetic zenith may cut across the vertical extent of several auroral elements. The effect is that individual structures with a width of a few km or less can be resolved only near the magnetic zenith, where the view direction is parallel to the magnetic field.

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Typically, usable data on such fine structures are confined to within about 6 degrees from the magnetic zenith corresponding to only 10 km at an altitude of 100 km. Imposing such a requirement on an observational program makes the use of ground-based observing sites impractical. For example, a plot of the FAST paths over Alaska shows that during the month of February 1997, the ionospheric footprint of FAST passed within 10 km of the observatory at Poker Flat only once. Moving to another location would not alter this, so the only practical way to obtain auroral images with high spatial resolution conjugate to FAST is to instrument an aircraft. The aircraft can fly above most inclement weather, and it can follow the aurora along the FAST track thus ensuring usable data for a large fraction of the FAST passes covered. The concept is shown in figure 1.

A Sabre-60 business jet aircraft was instrumented with four low-light level TV camera systems: one all-sky camera and three narrow-field cameras, viewing through windows installed in the aircraft ceiling. The 3 narrow-field cameras were aligned along the longitudinal axis of the aircraft covering together a roughly 75x20 degree rectangular area. The vertical camera was an intensified CCD TV system with a 20x16 degree field of view. The cameras front and aft of the ICCD camera were identical SIT cameras having 29x22 degree fields of view. All cameras were operated unfiltered for maximum signal. Observations of overhead auroras conjugate to FAST were made on 16 passes over Alaska between January 31 and February 16, 1997.

The passes were all pre-midnight between ~21:00-23:30 local magnetic time. Auroras were observed under a variety of activity levels with Kp and the College K index ranging from 0 to 5. As would be expected, most of the discrete auroras encountered were single or multiple arcs. Flickering aurora was present in two of the passes, and two passes were through auroral spirals associated with strong upward field-aligned currents. In the last of the passes covered (February 16, 1997), FAST passed through the very bright onset of a local poleward auroral expansion.

We present here FAST auroral electron energy spectra together with optical data for a set of multiple arcs and for an isolated single discrete arc along the poleward edge of the diffuse aurora.

Multiple arcs.

A good example for a general comparison of particle and optical observations of auroral arcs occurred on February 6, 1997. Figure 2 (top) shows an all-sky image of multiple arcs at the time the FAST ionospheric conjugate passed (left to right) through the magnetic zenith. The middle panel shows a standard electron energy spectral plot, i.e. electron energy on a logarithmic scale versus time with flux density (integrated over all pitch-angles) given by the color. Note the rather broad, inverted V structures associated with the aurora. In the bottom panel we extracted the electrons inside the loss cone to calculate the total electron energy flux into the ionosphere and plotted the result on

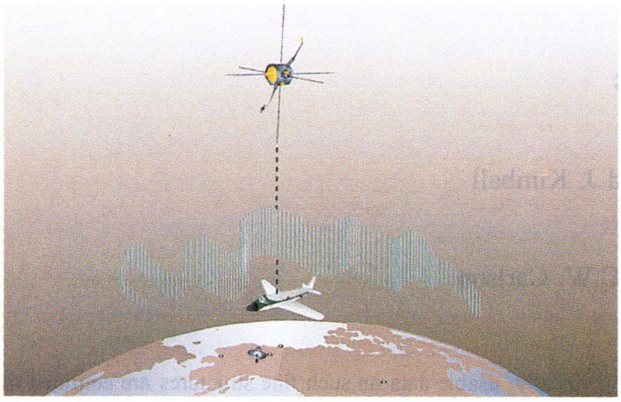

Figure 1. Aircraft can be positioned under the aurora and conjugate to the FAST satellite.

a linear scale. Each individual peak in the energy flux could be matched with an arc in the concurrent optical images. The arc widths observed by FAST vary from about 20 km down to a few km. The auroras, in particular the two arcs to the right (north), did change during the pass. Therefore, a detailed comparison between the energy flux and the one all-sky image shown should not be attempted.

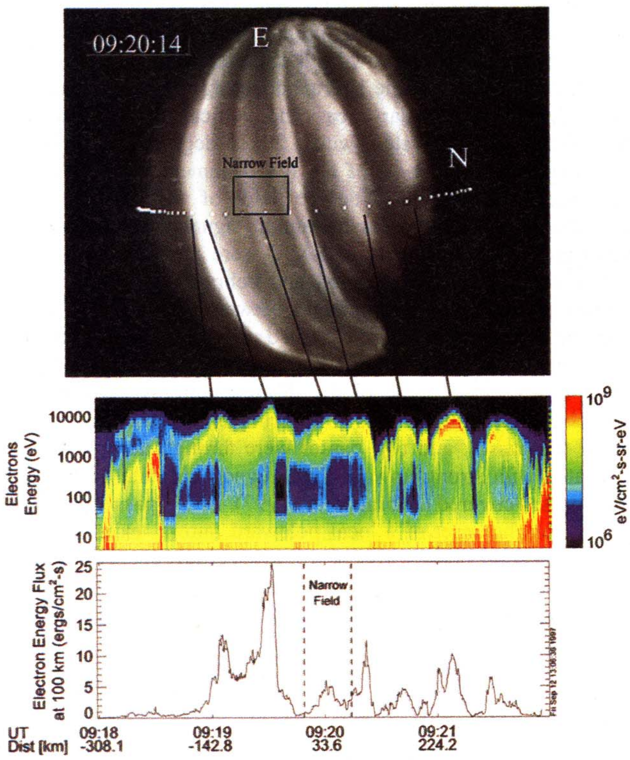

Figure 2. Multiple arcs as seen in the all sky image and by FAST. The 110 km conjugate is shown at 10s intervals as FAST passed across from left to right. The center panel is a "normal" format of the electron energy spectrum (integrated over all pitch angles) and shows a number of inverted-V structures. The bottom panel is the precipitated energy flux on a linear scale. The narrow auroral arcs are clearly displayed here. The auroras, in particular the two arcs to the right (north) did change over the 4 minutes of the pass. The pass was near 21:20 magnetic local time. Dist is the distance along the conjugate track from the left edge of the narrow field image (figure 3).

Figure 3 shows the narrow-field image. The auroras near the magnetic zenith, located towards the right edge of the image, clearly have better spatial resolution. One can separate individual arc structures in contrast to the forms near the center where, due to the vertical extent, arcs overlap. The FAST 110 km conjugate position was calculated each 2 s using IGRF95 with no corrections for perturbations due to auroral currents. The track (left to right) was along the lower edge of the image as shown. Below the image is an intensity trace taken just above the time label to avoid instrumental non-linearities near the edges. The abscissae has been matched to the plot of the energy flux into the ionosphere derived from the FAST energetic electron measurements (bottom). The two traces agree well.

The broad arc in the center of the image shows less structure than seen in the energy flux trace. However, the arc is more than 10 degrees from the zenith and it becomes difficult to separate individual spatial structures within the arc. FAST passed the magnetic zenith at 09:20:10 UT at which time FAST detected a peak in the energy flux that was not present in the luminosity trace. This peak may be a temporal, and not spatial, variation in the aurora. The video has some shear motion within the two arcs to the right in the image with local enhancements moving east-west along the arc. The enhancements appear to be curls (vortices) [*Hallinan and Davis*, 1970] indicating the presence of significant perpendicular electric fields in the acceleration region. The peak in the FAST data (at 09:20:10 UT) is consistent with the passing of a curl through the satellite track. Uncertain east-west displacement of the FAST ionospheric conjugate due to Birkeland currents precludes exact comparison of the time of passage with the video. The sequence suggests

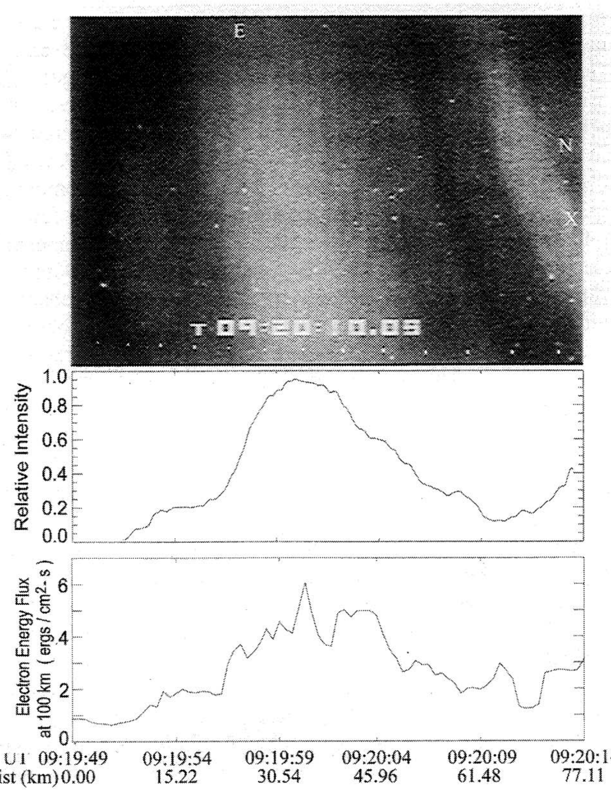

Figure 3. Narrow field image (top) at the time of FAST passing through the magnetic zenith to the right in the image. 110 km conjugate shown at 2s intervals. Center panel shows an intensity trace across the image for comparison with the corresponding precipitated energy flux observed by FAST (bottom).

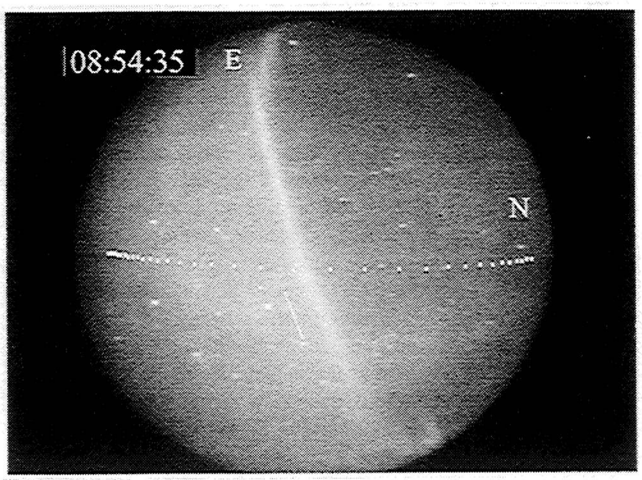

Figure 4. All sky camera image of weak auroral arc (08:54:35 UT, February 5, 1997). Aircraft at 69.60N, 148.54W. Location of faint arc is indicated by the short line.

that the curl structures are present also at the altitude of FAST, and it may provide more insight into the electrostatic Kelvin-Helmholtz process thought to be responsible for the vortex streets [*Hallinan and Davis*, 1970].

Weak auroral arc.

The FAST pass on February 5, 1997, went through a relatively weak single discrete auroral arc located in the poleward edge of the diffuse aurora (08:54:35 UT). Again we find a good agreement between the FAST particle observations and the optical observations from the aircraft. The arc in the all-sky image (figure 4) shows little internal structure, but the higher resolution narrow field cameras (not shown) do show faint indications of multiple structures within the arc. The arc is located near the poleward edge of a broader region of weaker diffuse auroral luminosity to the left (south) of the arc. The discrete arc has an apparent latitudinal width of about 6 km. In addition to the main arc there is a very weak arc 17 km south of the main arc (position indicated on image). It is barely visible in the all sky image, but is identifiable in the aft narrow-field camera. It has no internal structure, and we estimate the width of this arc to be 3 km.

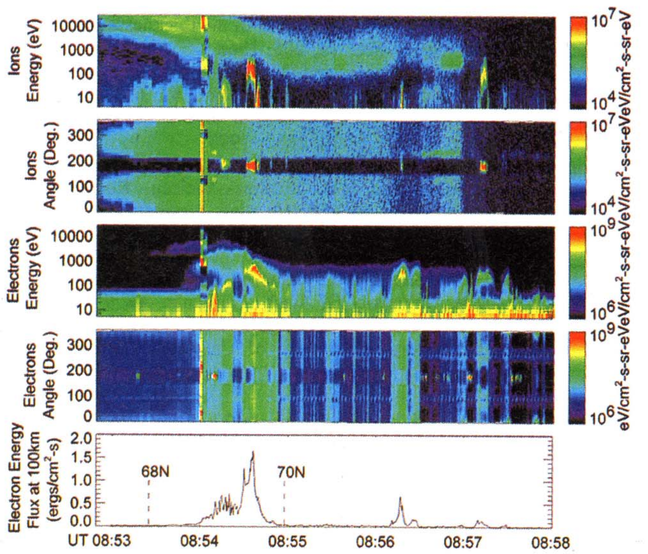

Figure 5. FAST observations corresponding to the auroras shown in figure 4. The four color panels show the ion and electron energy spectra (all pitch angles) and pitch-angle distributions (all energies). The bottom panel shows the electron energy flux into the ionosphere.

The corresponding FAST ion and electron spectra are shown in figure 5. The top two panels show the ion data (energy spectra and pitch-angle distributions, respectively) followed by two similar plots for the electrons. The energy spectra are in the standard logarithmic display format and the electron spectra have a roughly 100 km wide inverted-V type event between 08:54 and 08:55 UT. At the bottom we show the precipitated electron energy flux. The main arc and the weak arc 17 km to the south are clearly associated with the double peak at 08:54:35 UT. The electron and ion spectra indicate that the arcs were located at the poleward edge of the diffuse aurora as also deduced from the optical data.

It is interesting to note that the two arcs observed optically are located on either side of an upgoing ion beam, as can be seen from figure 5. The ion beam suggests that there may have been an accelerating potential below the altitude of FAST which would affect the precipitating electrons, but the acceleration would have been small.

Unfortunately, the main arc straddles the adjoining fields of view of the aft and the zenith cameras and because of the significantly lower camera sensitivity towards the edges of the field of view does not show very well in these images. This effectively limits a more quantitative analysis to the all sky image. Figure 6 shows a comparison between the FAST precipitating energy flux and the relative intensity of the auroral luminosity extracted from the all sky image. The FAST data have been resampled to match the lower spatial resolution of the all-sky image. The ions only contribute significantly in the diffuse aurora south of the main arc, which is almost exclusively electron produced.

The two data sets agree well. The fit indicates that the amplitude of the main arc is somewhat larger in the optical data, but the arc is located very near the magnetic zenith and a narrow arc will appear brighter here since the line-of-sight is along the vertical extent of the arc. The southern arc, located 17 km away from the zenith and having a width of ~3 km (comparable to the resolution of the all-sky camera), shows only as a small shoulder on the intensity trace.

The luminosity within the diffuse aurora appears to be accounted for by the combined ion and electron fluxes. In displaying the total energy precipitated we assume that the efficiency of conversion to total optical emissions is the same as

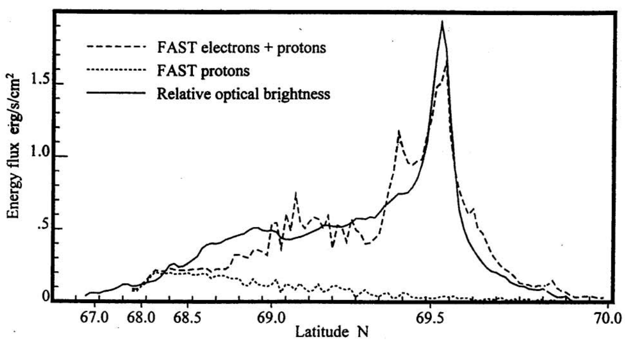

Figure 6. A comparison between the relative brightness of the arc at 8:54:35 UT and the FAST electron and ion energy fluxes. The FAST data have been scaled to approximately the same resolution as the optical image.

for both ions and electrons. There are significant ion fluxes above the instrumental cut-off between latitude 68 and 69N and it appears reasonable to assume that these ions can account for the higher brightness observed optically in this region. It is clear from the FAST observations that precipitating ions were the main source for the luminosity observed in the equatorward part of the diffuse aurora. We finally note that in contrast to the ion spectra, the electron spectra show significant fine-scale spatial structures within the diffuse aurora. To resolve these optically would have required the aircraft to have been farther south. We did observe such structures when the viewing geometry was better approximately a minute prior to the satellite pass.

The structure farther north at 08:56:10 UT in fig 5 is also present in the all sky images, but at the detection limit. The energy deposition rate is 0.6 erg/cm^{2}s. Obviously the detection limit will depend on the observing geometry and the electron energies, but it indicates that slightly less than 1 erg/cm^2/s is required for optical detection. A similar result was reached earlier by *Winningham et al.* [1977]. Using filters and longer integration may reduce this limit, but a longer integration time also means a corresponding loss of temporal resolution. Auroral structures with lower energy fluxes are observed by satellites and rockets, so the ~1 erg/cm^2/s limit is not a limit on the associated physical process, but rather a limit set by the background luminosity from airglow, starlight etc.. Also since the limit is imposed by background luminosity, it doesn't depend strongly on the detector and is roughly the same for a variety of electronic imagers, photographic film, and even the human eye.

Discussion and Summary.

A comparison between auroral arc observations made optically from an aircraft flying conjugate to the FAST satellite and energetic electron and ion data obtained by FAST has demonstrated good correlation down to smallest scale sizes (a few km) encountered. The implication is that these structures are imposed by processes at or above the altitude of FAST. There were no examples of auroral structures with scale sizes less than 1 km in our data set, and therefore, we are not able to comment on the merit of the many processes proposed for the formation of auroral fine structure [*Borovsky*, 1993; *Otto and Birk*, 1994].

The arc observed on February 5, 1997 (figures 4-6) was located in the poleward edge of the diffuse aurora. In the FAST data the diffuse aurora was characterized by the presence of energetic ions with little spatial structure and characteristic energies of a few keV at the latitude of the main arc overhead the aircraft, increasing to above the 25 keV instrumental cut-off further south. The electron spectra in the arc at the poleward edge were accelerated and the magnetometer data indicated upward current. Thus the arc would be characterized as a discrete auroral arc. The arc was located at the poleward edge of a ~200 eV upward field-aligned ion beam, and a weaker arc barely visible in the optical images was located at the equatorward edge of the beam. About 10 minutes after the passage of FAST the main arc brightened, became more structured, and an active rayed arc moved in, just poleward of the arc, from the east. The development of this clearly discrete active auroral arc originated at the poleward edge of the proton precipitation.

The auroral arc width "problem" is, largely as expected, a question of resolution and data presentation. Satellite electron energy spectra are commonly presented as plots of particle flux as function of energy and time, as for example used here in figures 2 and 5. To be able to resolve a wide range of energies and fluxes within one plot, logarithmic scales are used for both particle energy and number flux. While this provides a very efficient way of displaying the data, it tends to overemphasize the contribution by low energy electrons leading to the impression that arcs are significantly wider than observed visually. This is also the case with the FAST data. When instead the electron data are displayed as total precipitated energy on a linear scale, and incorporating the limit for detectability of 1 erg/cm^2/s, the visual auroral arc structures emerge clearly in good agreement with the optical observations even down to widths of a few km. Indeed, the FAST data at times show features even narrower than are recognizable in the associated image data.

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