



## How important are dispersive Alfvén waves for auroral particle acceleration?

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[1] The means by which charged particles are accelerated in space to form the aurora is still not fully understood. This acceleration produces earthward streaming electrons driving auroral luminosity and outward streaming ionospheric ions which populate space with terrestrial matter. With the advent of high resolution space borne field and particle instruments, dispersive Alfvén waves (DAWs) have been identified as drivers of auroral particle acceleration and it has been shown that the Alfvén wave energy observed is sufficient to power a significant fraction of auroral luminosity. Since previously it has been considered that auroral particle acceleration occurs in quasi-steady field-aligned currents, quantifying the amount of particle acceleration occurring in DAWs relative to the traditionally invoked processes is fundamental to our understanding of how the aurora works. We combine coincident satellite measurements of fields and particles to demonstrate that as functions of increasing auroral activity 25–39% of the total electron energy deposited in the ionosphere and 15–34% of total energetic ion outflow may be attributed to the action of DAWs. In fact in the vicinity of the polar cusps and pre-midnight auroral oval, DAWs may provide the dominant means for powering electron and ion acceleration during active times. **Citation:** Chaston, C. C., C. W. Carlson, J. P. McFadden, R. E. Ergun, and R. J. Strangeway (2007), How important are dispersive Alfvén waves for auroral particle acceleration?, *Geophys. Res. Lett.*, *34*, L07101, doi:10.1029/2006GL029144.

### 1. Introduction

[2] The terrestrial aurora is perhaps the most striking demonstration of the electrodynamic connection between the Earth and the Sun. Enhancements in solar activity are well represented by enhanced auroral displays. In the simplest case these displays may be powered by the precipitation of electrons and ions into the upper atmosphere from pre-existing reservoirs of energetic plasmas trapped in the Earth's magnetic field. However, such processes provide diffuse bands of luminosity and not the discrete features generally associated with aurora observed from the ground. The means by which electrons are accelerated into the ionosphere with sufficient energy and flux to

stimulate such features is an area of ongoing research [Paschmann *et al.*, 2003]. Observations and modelling indicate that this acceleration occurs in electric fields parallel to the geomagnetic field [Mozer *et al.*, 1977] contained within a region extending above the Earth's surface from a few 1000 kilometers up to a few 10's of thousands of kilometers. Traditionally, these electric fields and the discrete auroral displays they drive have been interpreted in terms of current-voltage relationships [Knight, 1973]. These are assumed invariant or quasi-steady over the time taken by an electron to travel through the field-aligned potential drop that the integrated product of the 'resistivity' of the plasma and geomagnetic field aligned current define. This model provides a distinct 'mono-energetic' peak in electron spectrograms which has been traditionally labeled an 'inverted-V' [Evans, 1974; Newell *et al.*, 1996].

[3] However, more recent observations have identified downgoing accelerated electrons above the aurora with no 'mono-energetic peak' inconsistent with the quasi-steady model. These features are often described as supra-thermal electron bursts [Johnstone and Winningham, 1982; Newell, 2000] and it has been demonstrated that these bursts are commonly observed in association with electromagnetic fluctuations identified as dispersive Alfvén waves (DAWs) [Andersson *et al.*, 2002]. Shear Alfvén waves are described as DAWs when they have scales transverse to the geomagnetic field of the order the electron skin depth ( $\lambda_e = c/\omega_{pe}$  where  $c$  is the speed of light and  $\omega_{pe}$  is the electron plasma frequency; inertial Alfvén waves), ion gyro-radii or ion acoustic gyro-radii (kinetic Alfvén waves) or less [Lysak and Lotko, 1996]. Above the auroral oval  $\lambda_e$  is generally larger than the gyro-radii scales and provides the most important correction to shear Alfvén wave dispersion [Goertz and Boswell, 1979]. Detailed case-study comparisons between simulation predictions, observed waveforms and electron velocity distributions have shown how the parallel electric fields in DAWs are responsible for supra-thermal electron bursts found in electron spectrograms above the auroral oval [Chaston *et al.*, 2000; Kletzing and Hu, 2001]. Furthermore, wave Poynting fluxes in Alfvén waves at high altitudes have been shown sufficient to account for 30–35% of auroral luminosity [Wygant *et al.*, 2002; Keiling *et al.*, 2003]. However, to conclusively determine the importance of DAWs for electron acceleration and formation of aurora, simultaneous, in-situ measurements of the waves and the electrons they accelerate at the base of the acceleration region are necessary.

[4] While the visible aurora is largely due to earthward electron acceleration a striking feature gleaned from observations of the aurora from space is the coincident upward or outward flow of ions from the ionosphere [Yau *et al.*, 1985]. These accelerated ion outflows are extremely important in

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magnetospheric dynamics since the  $O^+$  ions they contain ‘mass load’ the magnetosphere. For the case of the quasi-steady current-voltage interpretation given above, these outflows are expected since the same parallel electric fields that accelerates electrons downwards will accelerate ions outwards. However, ions are observed to flow outwards even when the direction of the current is reversed and also when no clear current direction is observed at all. This outflow is thought to be driven largely by plasma waves [Hultqvist *et al.*, 1999]. Comparisons between simulations and observations have demonstrated the efficacy of DAWs in driving ion acceleration either directly or by decay to higher frequency modes [André *et al.*, 1998; Stasiewicz *et al.*, 2000; Chaston *et al.*, 2004; Singh and Khazanov, 2004]. However, the relative importance of these waves for accelerating ions to provide the outflow observed at high latitudes is unknown.

## 2. Observations

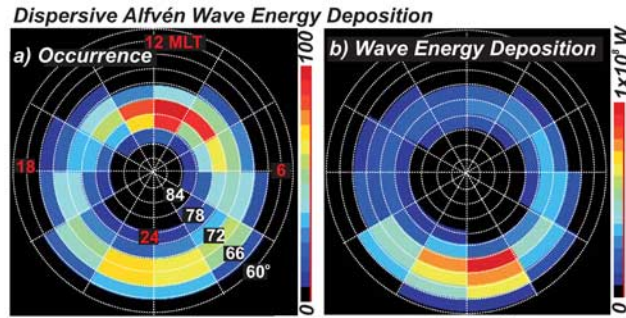
[5] In this letter we use observations from NASA’s small explorer spacecraft FAST [Pffaf, 2001] collected from 21st November 1996 until 2nd March 1999 including more than 5000 traversals of the polar region to quantify statistically the occurrence of field-aligned currents, DAWs, downgoing electron energy fluxes and outgoing ion fluxes. This satellite orbits between the topside ionosphere and the lowest reaches of the auroral acceleration region and is ideally located for performing this study. Intervals where quasi-steady or Alfvénic acceleration mechanisms may dominate are separated by using the ratio of the observed electric ( $\Delta E_x$ ) and magnetic field ( $\Delta B_y$ ). These are measured transverse to the geomagnetic field. For quasi-steady field-aligned currents this ratio is  $\Delta E_x/\Delta B_y \approx 1/(\mu_o \Sigma_p)$  [Sugiura, 1984] where  $\Sigma_p$  is the height integrated Pedersen conductivity. DAWs with a finite perpendicular scale or wave number ( $k_x$ ) provide a ratio over the altitude range traversed by FAST given by  $\Delta E_x/\Delta B_y \approx V_A(1 + k_x^2 \lambda_e^2)^{1/2}$  [Goertz and Boswell, 1979]. Here  $V_A = B_o/(\mu_o \rho)^{1/2}$  is the Alfvén speed,  $B_o$  is the geomagnetic field strength,  $\mu_o$  is the permeability constant and  $\rho$  is the mass density. For observed plasma parameters above the auroral oval it is generally found that  $V_A \gg 1/(\mu_o \Sigma_p)$  and  $2\pi \lambda_e < 10$  km. With this result we can use the criteria  $0.1 V_A < \Delta E_x/\Delta B_y < 10 V_A$  and width transverse to  $B_o$  of less than 10 km to identify field fluctuations consistent with DAWs. These criteria account for deviations in  $\Delta E_x/\Delta B_y$  in Alfvén waves from  $V_A$  due to finite  $k_x \lambda_e$  and due to ionospheric reflection [Lysak, 1998] while still providing sufficient separation from quasi-steady currents. Imbedded within these criteria is a dependency on the parallel wave scale ( $\lambda_{||}$ ) and hence wave frequency. For  $\lambda_{||}$  much greater than the distance from FAST satellite to the ionosphere it can be expected that  $\Delta E_x/\Delta B_y$  will increasingly appear like that of a quasi-steady field-aligned current and because of this field-line resonances on small transverse scales, while still DAWs, may not pass the selection criteria. These criteria may also fail if FAST happens to traverse nodes and anti-nodes in interfering incident and reflected waves. We have however developed and tested these criteria by application to numerous individual FAST orbits and have applied it to simulations [Chaston *et al.*, 2004] for both travelling DAWs and DAWs bouncing or

resonating within the ionospheric Alfvén resonator. From these efforts we find that these criteria generally provide a reliable means for identifying DAWs (if not field-line resonances) over the FAST altitude range and provide a more rigorous test on the Alfvénic nature of the observed fields than has been attempted in previous statistical studies.

[6] Once the intervals of Alfvénic activity have been identified we integrate the particle fluxes and downward Poynting fluxes along the spacecraft trajectory and separate these results into those found within DAWs wavefields and those not. These results are then further subdivided into a spatial grid in magnetic local time and invariant latitude. We then perform a 2nd integration over the longitudinal width of each grid cell at the altitude of observation to yield results in Watts for electron energy deposition and ions per second for ion outflow in each grid cell. The total value from all the intervals in each grid cell, and all the specifically DAW intervals in each cell is then divided by the number of FAST traversals through each grid cell (with some corrections based on the FAST trajectory) to provide average values.

[7] The energy range of the particle measurements is defined at the low energy end by the lowest of either the spacecraft potential ( $\phi_{sp}$ ) or lowest energy bin of the detector (4 eV). Typically at FAST  $\phi_{sp}$  is negative, attracting ions and repelling electrons and has a magnitude mostly less than 20 V. The highest energies considered for electrons is set by the upper limit of the detector (30 keV) and within DAW wavefields by the upper limit of the supra-thermal fluxes as we shall describe momentarily. For electrons we only include pitch angles within the range of angles which will reach the ionosphere without mirroring. For ions the upper energy limit is not critical since we are looking at number flux rather than energy flux and the low energies generally contribute significantly more than the plasma sheet/magnetosheath (the contribution of the unaccelerated upward fluxes is further limited by the loss cone). However, we include only that portion of the observed distribution facing opposite to the satellite trajectory (including both upward and downward going ions) and multiply by 2 to get the total net flux under the assumption the distribution is gyrotropic. This pitch angle range is selected because of the spurious contribution of spacecraft ‘ram’ (i.e.,  $E \propto (\text{spacecraft velocity})^2$ ). This however does mean that we generally miss the very lowest energy ions and the polar wind. The frequency range over which the Poynting fluxes are calculated is set at the low frequency end by the width of the current filament over which the  $\Delta E_x/\Delta B_y$  calculation is performed, and at the high frequency end by the resolution of the magnetic field or by the oxygen gyrofrequency—which ever is lowest. Application of this methodology allows us to quantitatively determine the average electron energy deposition into the ionosphere, ion outflow into the magnetosphere and downgoing DAW wave energy at high latitudes over the FAST altitude range.

[8] To specifically identify those electron fluxes within DAW wavefields that are accelerated by these waves, we apply to each measurement a requirement that the spectral shape in differential energy flux in the field-aligned direction be relatively monotonic with energy (i.e., no major peaks). From case study observations, and simulations this form allows us to discriminate DAW accelerated electrons from inverted-V and un-accelerated plasma sheet/magneto-



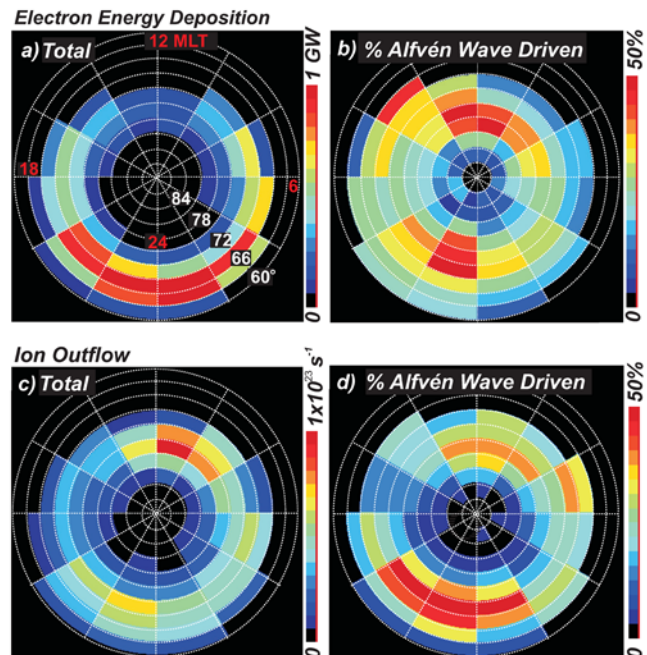
**Figure 1.** (a) View looking down onto the polar regions of the occurrence distribution of dispersive Alfvén wave current filaments normalized by the number of satellite traversals through each grid segment. (b) Distribution of the average dispersive Alfvén wave energy deposition from integrated Poynting flux measurements over the area of each grid segment and for transverse scales less than 10 km mapped to the ionosphere.

sheath contributions which may simultaneously be present and effectively sets the upper energy limit of the measurement. In the case of ions, since there are no specifically identifiable features in the distributions indicative of acceleration in Alfvén waves, our case for claiming the acceleration is driven by Alfvén waves is from the coincidence of transverse ion fluxes and DAW wavefields alone. This does not mean necessarily that the DAW wavefields directly accelerate the ions but instead that they locally provide the energy for this process to occur either directly or through the generation of secondary wave modes. Simulations [Chaston *et al.*, 2004; Singh and Khazanov, 2004] and observations from FAST and Freja [André *et al.*, 1998] traversals of the auroral oval generally show sharp enhancements in out flowing ion fluxes in the presence of these waves suggestive of a causal relationship as we propose in this work.

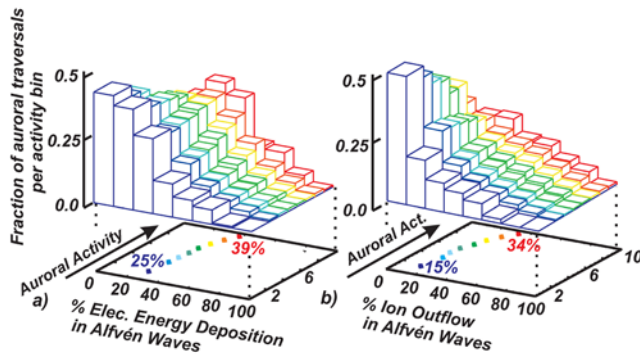
[9] Figure 1a shows the statistical map for the average occurrence of DAWs from FAST. These observations are presented as functions of magnetic latitude and magnetic local time and may be understood as a view looking down onto the Earth's Polar Regions from above with the dayside and nightside at the top and bottom respectively. This plot indicates that DAWs are observed throughout the auroral oval but that they are most commonly found close to noon and somewhat less frequently near midnight. In the magnetosphere these regions correspond to the cusps, and immediate vicinity, and the high-latitude magnetotail. Integrating the Poynting fluxes observed in these waves over the polar regions ( $>60^\circ$  magnetic latitude) we find that the total power in DAWs directed toward the ionosphere observed from FAST is on average  $\sim 2$  GW however this figure is strongly dependent on geomagnetic activity and is as large as 10 GW during active times. The distribution of this wave power is shown in Figure 1b and indicates that DAWs observed near midnight are several times more energetic than on the dayside - a pattern which is in fact repeated in energetic electron fluxes which we will now consider.

[10] The distribution of power delivered to the Polar Regions due to electron energy deposition is peaked near midnight as shown in Figure 2a. Summing each element shown in this plot yields a total average power of  $\sim 18$  GW. During geomagnetically active periods this value may exceed 100 GW. The fraction of this power which is provided by electron fluxes with distributions consistent with acceleration in DAWs and which are observed within DAW wavefields, is shown in Figure 2b. Near noon and pre-midnight on average this fraction is  $\sim 50\%$  and more generally, over the entire high latitude region has a value of 31%. These results are however geomagnetic activity dependent. As shown by the bar plots in the upper plane of Figure 3a the fraction of the total electron energy deposition attributable to DAWs per FAST orbit increases with auroral activity. While in the lower plane of Figure 3a, the results averaged over the whole high latitude region, show that the fraction of the total energetic electron flux incident on the high latitude upper atmosphere that is most likely driven by DAWs increases from 25% up to 39% with increasing auroral activity. In fact, near noon and pre-midnight on the poleward edge of the auroral oval during active times, we find that electron fluxes in DAWs having distributions consistent with acceleration by these waves, provide the dominant contribution to electron energy deposition into the upper atmosphere and hence formation of aurora.

[11] In contrast to the electron results, the measured accelerated ion outflow shown in Figure 2c is instead strongly peaked near noon, corresponding to the magnetospheric



**Figure 2.** (a) View looking down onto the polar regions of the distribution of the average total electron energy deposition. (b) Distribution of the percentage of the total electron energy flux observed in dispersive Alfvén waves. (c) Distribution of the average total ion outflow. (d) Distribution of the percentage of the total ion outflow observed in dispersive Alfvén waves.



**Figure 3.** (a) Shows the dependency of the percentage of the total electron energy deposition in dispersive Alfvén waves on auroral activity. The level of activity is derived from electron observations from the NOAA POES satellites (available at <http://www.sec.noaa.gov/pmap>). The upper plane presents a bar plot of the fraction of electron energy deposition per orbit found in DAWs. The lower plane shows the average percentage of the total electron energy deposition in dispersive Alfvén waves integrated over the whole polar region at each activity level. (b) Shows the dependency of the percentage of the total ion outflow in dispersive Alfvén waves on auroral activity. The description of Figure 3b is the same as Figure 3a but for ions.

cusps, with a second, albeit smaller peak, pre-midnight. A similar pattern has previously been identified from FAST measurements by *Andersson et al.* [2004]. As shown in Figure 2d 40–50% of the energetic ion outflow in these regions is on average contained in the ion fluxes observed in DAW wavefields with 22% being the average over the entire polar region sampled. Integrating over the entire polar region the total ion outflow over the altitude range traversed by the FAST satellite is  $\sim 2.5 \times 10^{24} \text{ s}^{-1}$ . We note that this value is significantly smaller than those presented by *Yau and Andre* [1997] from the DE-1 spacecraft (16000–24000 km altitude) and *Lennartsson et al.* [2004] from Polar spacecraft close to apogee ( $\sim 18000$ – $48000$  km altitude) over similar energy ranges. Yet, our total flux is similar to the perigee ( $\sim 6000$  km) observations from Polar reported by *Lennartsson et al.* [2004]. These variations are presumably due to ion acceleration above the altitude of FAST and solar cycle effects (the FAST measurements were performed around solar minimum). As shown in Figure 3b the fraction of this total that may be driven by DAWs is auroral activity dependent. The lower plane of Figure 3b shows that from the quietest to the most active times 15–34% of the energetic ion outflow from the high latitude regions is found in the ion fluxes contained within DAW wavefields. In fact near noon and pre-midnight on the poleward edge of the auroral oval during active times, we find that energetic ion outflow in DAWs provides the dominant contribution to energetic outflow from these regions.

### 3. Conclusions

[12] These results demonstrate that DAWs provide a significant, though generally not dominant means for accelerating electrons to form the aurora and for driving ion

outflow from the ionosphere into the magnetosphere. The contribution of DAWs to auroral particle acceleration is however highly variable and provides during geomagnetically quiet periods, a small contribution, yet during active times the dominant fraction near noon and midnight. An outstanding question that this raises is how the large scale variability of the magnetosphere is transported to the small dispersive wave scales where these acceleration processes occur. Indeed, a consideration of the energetics indicates that a continual supply of energy to DAWs along high latitude field-lines is required to account for observations. Answering this question remains a challenging task for theorists and present and future multi-satellite missions.

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