Particle Acceleration in Alfven Waves Above the Aurora: Observations and Simulations

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ABSTRACT

We demonstrate how Alfven wave energy is dissipated in near-Earth space through electron and ion acceleration due to non-MHD corrections to Alfven wave dispersion and the ponderomotive force. It shown from observations from the FAST spacecraft and simulations how Alfven waves accelerate electrons and ions to produce aurora and intense ion outflow from the high latitude ionosphere. Statistical measurements are employed to examine the dissipation of wave energy in Alfven waves as a function of altitude and compared directly with those obtained through simulations.

INTRODUCTION

Alfven waves are ubiquitous above the auroral oval. They are responsible for the transport of energy from the boundaries of the Earth’s magnetosphere (Wygant et al., 2002) to the inner magnetosphere and ionosphere. The FAST spacecraft at altitudes from 350 to 4180 km observes Alfven waves throughout the auroral oval. Invariably these waves are observed to be accompanied by accelerated ion and electron distributions. The processes by which these particles are accelerated in the Alfven wave are quite different for each species. Electrons are responsive to the parallel to the geomagnetic field ($B_0$) electric field carried by Alfven waves in the inertial limit (Lysak and Lotko, 1996). These particles may interact in a resonant manner with up or downgoing Alfven waves and in the process are accelerated to energies approaching 10 keV. Observations show that the electron energy fluxes generated in this process are some of the largest seen in the aurora (Chaston et al., 2002a) and may exceed 100 ergs cm\textsuperscript{-2}s\textsuperscript{-1}. Ions on the other hand are generally not appreciably accelerated by the parallel field carried by the wave. This is because this field is generally insufficient to accelerate the ions up to the wave phase speed in less than 1/2 of a wave period. Consequently these particles see a fluctuating parallel electric field in which they oscillate up and down as the wave passes over them. However, the ions are responsive to a ponderomotive force associated with the field-aligned gradient in the $E_\perp \times B_0/B_0^2$ drift due to the increasing Alfven speed ($V_A$) with altitude below 6000 km (Li and Temerin, 1986) where $E_\perp$ is the perpendicular to $B_0$ electric wavefield. In addition the gyro-radii of some of the ions may be in the vicinity of the perpendicular wavelength of the Alfven wave. This disrupts the usual cyclotron motion of the ions and may lead to strong heating (Stasiewicz et al., 2000). However, due to space limitations in this brief report we will only discuss the simulation results for electrons.

OBSERVATIONS

Figure 1 shows an example of an Alfven wave event in the pre-midnight polar cap boundary. Panel a) shows the magnetic field ($B_{\perp 2}$) measured perpendicular to the spacecraft trajectory and the geomagnetic field, or roughly in a direction tangential to the auroral oval boundary. This field quantity is composed of fluctuations over a range of
frequencies from 50 mHz to greater than 1 Hz. Panel b) shows the electric field ($E_{\perp 1}$) measured along the spacecraft trajectory and also perpendicular to the geomagnetic field. This direction is roughly perpendicular to the polar cap boundary. The interval of turbulence in this component is well correlated with that of the magnetometer and the sharpest deviations in $B_{\perp 2}$ are correlated with the largest fluctuations in $E_{\perp 1}$. Panels c) and d) of Figure 1 show the electron energy and pitch angle spectra. These panels reveal bursts of field-aligned (0°) electrons coincident with the wave activity with energies extending up to 10 keV or roughly up to the energy of the plasma sheet electrons. The plasma sheet component can be seen as the faint band at several keV that begins at the far left of panel c) and provides the isotropic background fluxes shown in the pitch angle spectra. Brief bursts of counter field-aligned (180°) electrons are occasionally observed (at 20:22:47 UT for example) throughout the displayed interval with energies less than 100 eV. These are distinct from the backscattered field-aligned electrons present throughout the display interval (which span the full width of the loss cone) since their fluxes are considerably larger than that of the back scatter and are even more field-aligned than the downgoing electrons. The Panel e) contains the integrated electron energy flux in the source cone populated by the field-aligned electron bursts and shows that these electrons
supply up to 30 ergs cm\(^{-2}\) s\(^{-1}\) of electron energy flux into the ionosphere. These fluxes are sufficient to cause bright aurora (Chaston et al., 2002a). The grey line in this panel is the field-aligned wave Poynting flux multiplied by 3 for comparison with the electron energy flux. While this quantity has values lower than the electron energy flux at this altitude, the largest peaks are correlated with those of the electron energy flux. Panels f) and g) show the ion measurements over this time interval. The period of wave activity is coincident with enhanced fluxes of upstreaming ions with energies generally less than 1 keV distributed as conics at angles very close to 90/270° suggestive of near local heating. Integrated fluxes at this time are up to \(10^9\) cm\(^{-2}\) s\(^{-1}\).

SIMULATIONS

To simulate this data we rely on the model equations of Thompson and Lysak (1996), an active ionosphere, and a density and composition profile based on observations from FAST (Chaston et al., 2002a). Details about the implementation of this simulation can be found in Chaston et al., (2002a,b). We apply a Gaussian variation in the potential at the magnetospheric end of the simulation sufficient to supply wave amplitudes at FAST altitudes consistent with observations (up to a few hundred mV/m and 10’s of nT) and allow the system to evolve in time. The perpendicular wavenumber varies with the square-root of the geomagnetic field and is 5000 m in the ionosphere at 100 km altitude.

Figure 2 shows the variation in field-aligned wave Poynting flux (a) and electron energy flux (b) due to electron acceleration in the wave field from the simulation. The color scale corresponds to downgoing fluxes while where contours are superimposed the fluxes are upgoing. The initial Alfvenic pulse can be seen entering the simulation at t~0.5s and 30000 km altitude. It travels down the field-line losing about 50% of its energy flux through partial reflection on the Alfven speed gradients occurring above 4000km. After penetrating through this altitude it travels largely without losses due to reflection until it reaches the ionosphere. The electron precipitation that results from acceleration in the parallel electric field of the wave, as shown in figure 2 b, causes enhanced ionospheric conductivity resulting in over reflection of the wave from the ionosphere. In the presence of ionospheric convection the enhanced conductivity allows the reflected wave to have a larger amplitude than the incident wave. The reflected wave then moves back up the field line (t~2.5s) until it experiences the strong gradients in \(V_A\) that exist at altitudes above 3000 km where a portion of the wave energy flux is reflected back down towards the ionosphere. The wave then becomes effectively trapped between the ionosphere and the Alfven speed gradients above it. This region of trapped wave energy flux is known as the ionospheric Alfven resonator (Trakhtengertz, 1987). In this simulated case the enhanced reflection from the ionosphere is sufficient than the system can become unstable to the feedback instability (Lysak, 1991) and we can observe increasing wave energy fluxes in this region over time. Comparing Figure 2 a and b it can be seen that the energy that the electrons receive in this process represents a significant portion of the total incident wave energy applied from 30000 km. In fact at FAST altitude we generally observe the field-aligned wave Poynting flux to be less than the electron energy flux as found in this simulation.

Figure 3 shows results taken from a slice through the simulated system at 1700 km altitude. The panels are as in the observed results of Figure 1. The first two panels show that field amplitudes increase in time under the influence of the ionospheric feedback interaction, while the third and fourth panels show the effects of these wave field on the electrons. The first dispersive electron burst is associated with electron acceleration from one Earth radii and above or at altitudes greater than that of the upper boundary of the resonator. The parallel electric wave field in the wave at resonator altitudes is very small compared with that above and once the wave enters the resonator region electron acceleration virtually ceases and we obtain electron dispersion. The lack of electron acceleration in the resonator region is clear from Figure 2b which shows relatively small enhanced electron fluxes after the initial burst. Eventually the wave field in the resonator grows to sufficient amplitudes that the portion of the wave leaking through the top of the resonator can provide downward electron acceleration to account for the field-aligned bursts at 9 and 11 seconds.
CONCLUSIONS

It has been shown from FAST observations that Alfven waves occur in association with accelerated field-aligned electrons and heated ion distributions. It has been demonstrated that Alfven waves can efficiently accelerate electrons to provide spectral results similar to those observed. In this process the majority of the incident wave Poynting flux may be transferred to electrons. Finally, it has been indicated that the majority of electron acceleration in Alfven waves above the aurora occurs at altitudes above the resonator region, or above ~4000 km in altitude.

REFERENCES