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Mass-dependent effects in ion conic production: The role of parallel electric fields

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Abstract. Previous observational studies indicate that the energies of different ion species in ion conics produced by broad-band extremely low frequency (BBELF) waves are nearly equal. In contrast, theoretical studies predict a definite preferential acceleration for heavy ions over lighter ions. We show that this discrepancy can be resolved if a downward parallel electric field is present in the heating region: for a sufficiently strong electric field ions of different masses acquire approximately the same energy in escaping the trapping region.

Introduction

At auroral latitudes, ions are often accelerated transversely to the background magnetic field [*Sharp et al.*, 1977]; as they drift upward in the diverging field, some of this energy is exchanged via the mirror force for energy of motion along the field. Such distributions are called ion conics after their characteristic shape in velocity space. Many observational and theoretical studies have examined the details of the acceleration process [see *André and Yau*, 1997, for a review]. In recent years the following consensus has emerged [*Lynch et al.*, 1996; *André et al.*, 1998; *Norqvist et al.*, 1998; *Lund et al.*, 1999]: most of the transverse ion acceleration in the auroral zone is due to cyclotron-resonant interaction with broad-band extremely low frequency (BBELF) waves, although electromagnetic ion cyclotron waves and lower hybrid waves can also contribute locally to the ion outflow.

BBELF waves are associated with bursts of suprathermal field-aligned electrons [*Knudsen et al.*, 1998], which are a candidate for the free energy source of the waves. These electrons are accelerated by a downward-directed electric field [*Carlson et al.*, 1998b]. This electric field opposes the mirror force by which ion conics move up the field line; as a result of this "pressure cooker" ions can acquire substantially more energy before escaping than they could in the absence of such a field [*Gorney et al.*, 1985; *Jasperse*, 1998].

Several studies have found anecdotal evidence that the energies of different ion species in ion conics do not depend significantly on the ion mass [*Knudsen et al.*, 1994; *Norqvist et al.*, 1996; *Lund et al.*, 1999]. However, in the absence of parallel electric fields, ion cyclotron resonance heating theory predicts that a power-law wave spectrum, in which the power spectral density is proportional to $f^{-\alpha}$, where f is the frequency, should heat an ion of mass m to an energy proportional to $m^{(2\alpha-1)/3}$ [*Chang et al.*, 1986]. In this letter we show in a detailed statistical analysis of selected events that the observed energy ratios are inconsistent with this prediction, and we investigate whether parallel electric fields can counteract the predicted mass dependence of ion cyclotron resonant heating.

Observations

Figure 1 shows a FAST satellite pass through the aurora at 10.4 MLT on January 31, 1997. An overview of the FAST mission is given by *Carlson et al.* [1998a]. The electron populations (top three panels) can be divided into "inverted-V" regions, which have a positive (downward) field-aligned flux, and regions of highly field-aligned electrons which have a predominantly negative (upward) flux. The latter populations result from acceleration by a downward parallel electric field [*Carlson et al.*, 1998b] followed by thermalization by some as yet unknown process which may be related to the BBELF waves (fourth panel) seen during most of this pass. The ion pitch angle spectrogram (fifth panel) shows the classic ion conic signature over most of the interval from 09:21:20 to 09:22:40. The conics with the highest fluxes and widest cone angles, indicating heating nearest the spacecraft, are in regions where the net field-aligned number flux of electrons is negative. The narrower conics associated with the "inverted-V" electrons may have convected onto those field lines after being heated at lower altitudes [*Knudsen et al.*, 1994]. Substantial fluxes of H^+, He^+, and O^+ are observed in the mass spectrometer data (sixth through eighth pan-

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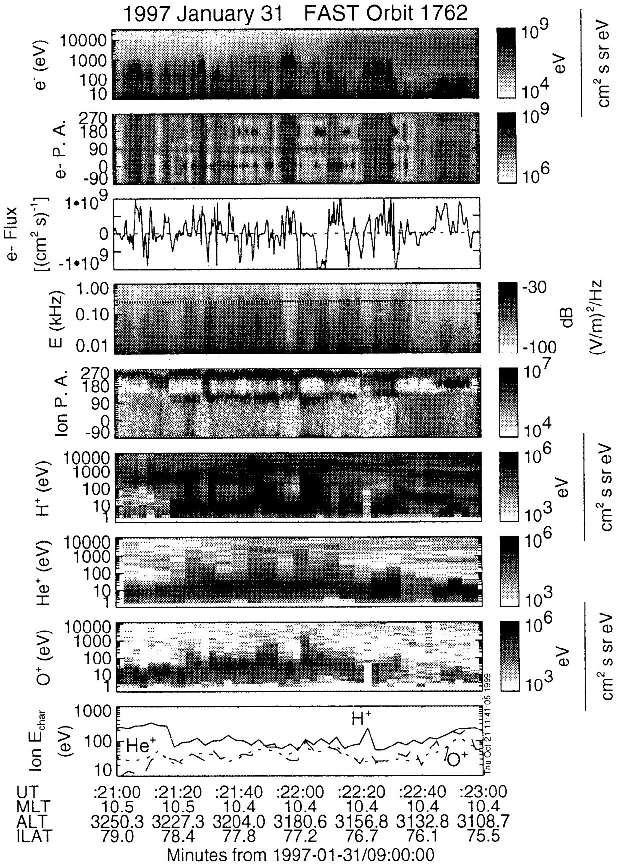

Figure 1. Overview of an ion conic event observed with FAST on January 31, 1997. From top to bottom: Electron energy spectrogram; electron pitch angle spectrogram; number flux of electrons along the magnetic field; ELF electric field spectrogram; ion pitch angle spectrogram; energy spectrograms for H^+, He^+, and O^+; and characteristic energy (energy flux divided by number flux) of the three ion species (solid for H^+, dotted for He^+, and dashed for O^+).

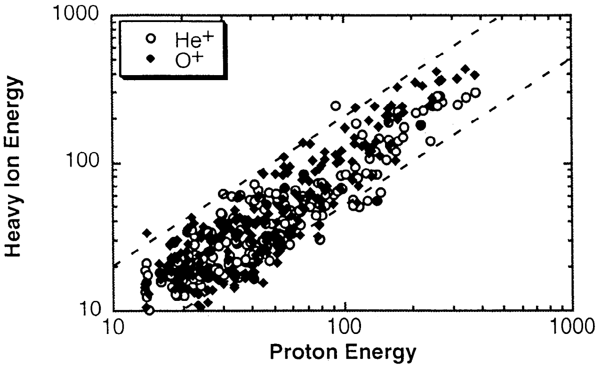

Figure 2. Characteristic energies of O^+ (solid symbols) and He^+ (open symbols) versus H^+ for 239 samples taken from 20 BBELF ion conic events in the prenoon sector. Dashed lines indicating $y = 2x$ and $y = x/2$ have been added as a guide to the eye.

els; see *Möbius et al.* [1998] for a description of this instrument). The characteristic energy (bottom panel), which is energy flux divided by number flux, of He^+ is comparable to that of O^+ throughout the ion conic, while the H^+ characteristic energy ranges from comparable to about three times higher than the other two. The H^+ characteristic energy may be overestimated at times because the plasma sheet and/or magnetosheath protons, which have lower cutoff energies that vary significantly even within a pass, have been imperfectly excluded from the calculation. We have excluded samples which we believe to be contaminated by plasma sheet or magnetosheath protons from further analysis in this study.

This pass is typical of 20 prenoon passes which have been examined in detail. An upper cutoff energy for flux integrations was determined separately by eye for each pass as a compromise between including the most energetic parts of the conic and excluding magnetosheath and plasma sheet protons; for the passes studied this cutoff energy was between 100 and 1000 eV. After we excluded points where contamination of the calculated fluxes by plasma sheet or magnetosheath protons was suspected, these 20 passes yielded 239 useable samples of mass spectrometer data, for which the He^+ and O^+ characteristic energies are plotted against the H^+ characteristic energy in Figure 2. The energies of the different species are generally within a factor of 2.

A typical electric field spectrum from this pass, taken at 09:21:47, is shown in Figure 3. The best-fit power law to this spectrum, which fits very well for $f \gtrsim f_{cO^+}$, has $\alpha = 1.32$. Other spectra we have examined have α ranging from 0.8 to 2.8 in the frequency range of interest, although not all of these spectra fit a power law as well as this example. The observed ion energies are inconsistent with the predicted $m^{(2\alpha-1)/3}$ dependence of ion energies in the absence of a parallel electric field [*Chang et al.*, 1986]. We now consider the effect of a parallel electric field on this prediction.

Model

Our model is based on the model used by *Gorney et al.* [1985] to illustrate trapping of ion conics by downward parallel electric fields. We use this model to in-

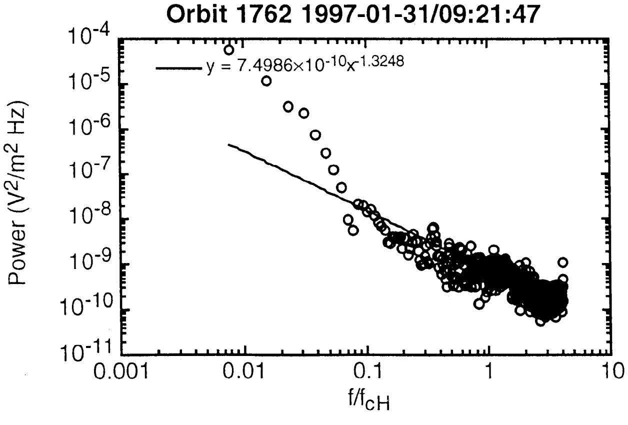

Figure 3. Sample ELF electric field spectrum at 09:21:47 from the ion conic event shown in Figure 1.

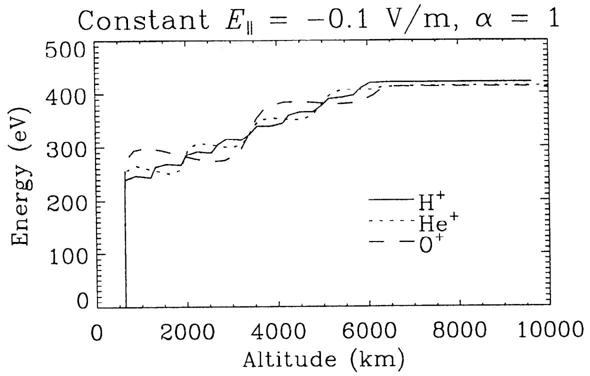

Figure 4. Energy versus altitude for H^+, He^+, and O^+ ions in the $\alpha = 1$ model described in the text.

vestigate whether the energy needed to escape the trap depends on the ion mass. This model is intended only to illustrate the relevant physical processes and is not intended to represent any electric field configuration or heating rate profile which may be present in the aurora. We integrate the equations

$$\frac{d}{dt}(v_\perp^2) = -\frac{3v_\| v_\perp^2}{R_E+z} + \frac{2}{m}\left(\frac{d\epsilon_\perp}{dt}\right)_{\mathrm{WPI}} \tag{1}$$

$$\frac{dv_\|}{dt} = \frac{q}{m}E_\| + \frac{3}{2}\frac{v_\perp^2}{R_E+z} \tag{2}$$

$$\frac{dz}{dt} = v_\| \tag{3}$$

where $(d\epsilon_\perp/dt)_{\mathrm{WPI}}$ represents the heating of the particle due to the waves, q is the ionic charge, and z is the altitude. (See *Gorney et al.* [1985] for a derivation.) In this one-dimensional model, we assume a dipole field in which field line curvature is negligible in the region of interest. Following Gorney *et al.*, we assume a constant heating rate over the region $0.1R_E < z < 1R_E$ which is 1 eV/s for protons and scales as $m^{\alpha-1}$ for heavier ions; we have used $\alpha = 1,\ 1.5,\ 2,$ and 2.5. A uniform electric field of −0.1 mV/m is imposed throughout the heating region. We release the particle (H^+, He^+, or O^+) at zero velocity at an altitude of $0.1R_E$ and trace it until it escapes the parallel electric field region.

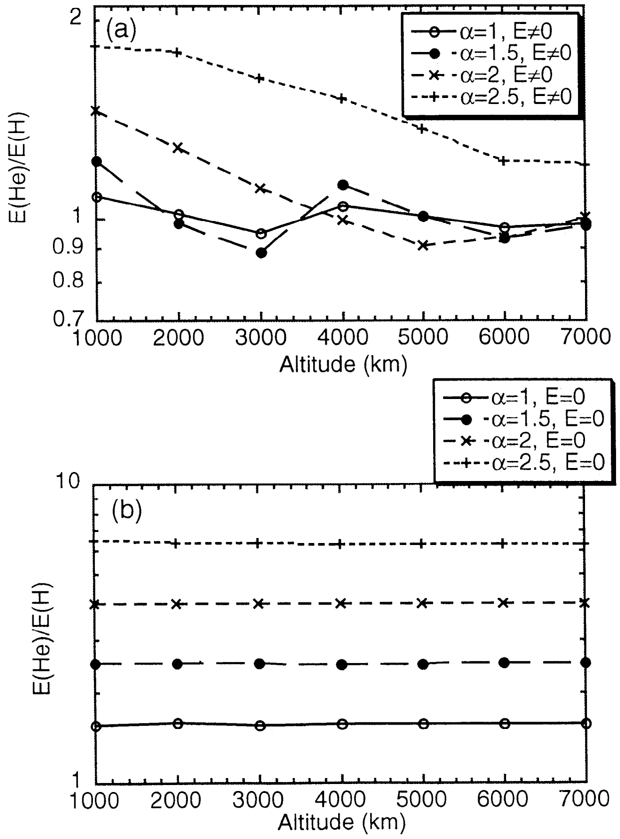

Figure 5. Ratios of He^+ energy to H^+ energy as a function of altitude for various values of α (a) with and (b) without the parallel electric field described in the text.

Simulation Results

Figure 4 shows the energy of H^+, He^+, and O^+ ions as a function of time in the $\alpha = 1$ model. The ions remain at the bottom of the trapping region until they acquire enough energy to overcome the parallel potential drop; they then move up the field line and eventually exit the trapping region with energies agreeing to within 2% for all species. There is no downward motion; the downward motion reported in Figure 4a of *Gorney et al.* [1985] is due to a numerical instability (K. A. Lynch, personal communication, 1999). Not all of the runs produce such an agreement of energies; for large values of α in particular, O^+ ions may be heated rapidly enough to escape the trap with a significantly higher energy than lighter ions.

The importance of the parallel electric field is illustrated in Figure 5, which compares the energy ratios of He^+ to H^+ for several values of α with and without the parallel electric field. In the presence of the field, only the $\alpha = 2.5$ case produces an energy ratio significantly different from 1 at the top of the trapping region, and even here the He^+ energy is only 1.21 times the H^+ energy. Higher energy ratios are seen at lower altitudes, but the trend is toward nearly equal energies. By contrast, the energy ratios in the $E_\| = 0$ case are consistent with the expected $m^{(2\alpha-1)/3}$ dependence [*Chang et al.*, 1986]. O^+ ions (not shown) behave similarly to lighter ions except for large values of α, in which case they escape the trap prematurely. In agreement with *Gorney et al.* [1985], we find that the parallel field also gives rise to higher ion energies, as shown in Table 1. Figure 5

Table 1. Ion Escape Energies (eV) in $\alpha = 1$ Model

Ion	With $E_\|$	Without $E_\|$
H^+	421	109
He^+	414	173
O^+	413	274

and Table 1 demonstrate that parallel electric fields are necessary to explain the observed mass dependence in transverse ion acceleration by BBELF waves through cyclotron resonant heating. The magnitude and shape of electric field needed to trap the ions are under investigation and will be reported in a future paper. The spread in the observed ion energy ratios could be due to time-dependent electric fields or heating rates or to convection, which are neglected in the model.

Conclusion

We have found a possible resolution of the discrepancy between the prediction of cyclotron resonant heating theory that the ion energy should depend monotonically on the ion mass [*Chang et al.*, 1986] and the observational evidence that no such dependence exists in BBELF-accelerated ion conics [*Knudsen et al.*, 1994; *Norqvist et al.*, 1996; *Lund et al.*, 1999; see also Figure 2]. We have shown that a downward parallel electric field, which can account for the field-aligned electrons that are correlated with ion conics and which can enhance ion heating by trapping, also can largely erase the mass dependence of the energization. We are investigating more realistic electric field and heating rate profiles in order to verify that the results of this study remain valid in more realistic models of the transverse ion heating region. Another open question is how the magnitude and shape of the potential drop affect the observed ion energies. We plan to investigate these questions in future papers.

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