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On the Mass Dependence of Transverse Ion Acceleration by Broad-Band Extremely Low Frequency Waves

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Abstract. Recent data from the Fast Auroral Snapshot Explorer (FAST) and other satellites indicate that broad-band extremely low frequency (BBELF) waves account for most of the transverse ion acceleration in the aurora. These waves tend to accelerate ions of different masses to approximately the same energy. We have shown previously that a downward parallel electric field is necessary in order to explain this result in terms of a cyclotron resonant acceleration process. In this paper we use triangular electric field distributions to investigate how strong and how extensive a field is necessary to equalize the energization of ions of different mass. © 2001 Elsevier Science Ltd. All rights reserved

1 Introduction

Ions are often observed to have been accelerated transversely to the background magnetic field in the auroral region (Sharp et al., 1977). As they drift upward in the diverging field, the ions exchange some of their perpendicular energy 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 a consensus has emerged that 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 (Lynch et al., 1996; André et al., 1998; Norqvist et al., 1998; Lund et al., 2000).

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, which are accelerated by a downward-directed electric field, carry the auroral return current (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 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, 2000). This result is contrary to the prediction of cyclotron resonant heating theory 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). We have previously shown that this contradiction can be resolved if a downward parallel electric field is present in the ion acceleration region (Lund et al., 1999). In this paper we examine how much of an electric field is necessary to overcome this mass-dependent heating by considering models in which the parallel electric field has a triangular profile.

2 Data

The FAST satellite, which was launched 21 August 1996 into a 4200 × 350 km orbit with 83° inclination (Carlson et al., 1998a), is ideally suited for investigating microphysical processes in the auroral region. Among its instruments is the Time-of-flight Energy Angle Mass Spectrograph (TEAMS), which provides 3-D distributions of He^{2+} and He^{+} at rates up to once per spin (5 s), and 3-D distributions of H^{+} and O^{+} twice as often (Möbius et al., 1998). TEAMS provides unprecedented resolution of mass dependencies in auroral acceleration processes.

As an example of this power, Fig. 1, which is taken from Lund et al. (1999), shows the average energies of He^{+} and O^{+} conics plotted against the average energy of H^{+} conics for 239 samples of TEAMS data taken from 20 BBELF ion conic events recorded in the prenoon (9–12 MLT) sector in January and February 1997. Most of the points plot-

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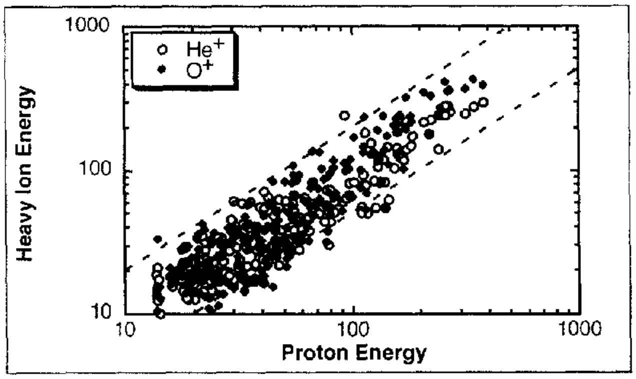

Fig. 1. Characteristic energies of O^+ (solid symbols) and He^+ (open symbols) versus H^+ for 239 samples taken from 20 BBELF ion conic events in the prenoon sector. Dashed lines indicating $y = 2x$ and $y = x/2$ have been added as a guide to the eye. From Lund et al. (1999).

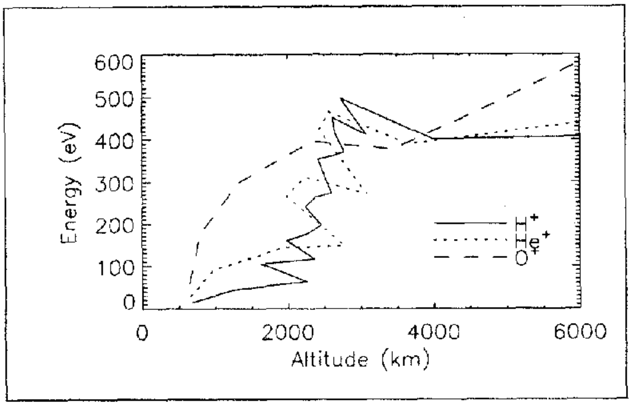

Fig. 2. Energies of H^+ (solid line), He^+ (dotted line), and O^+ (dashed line) as a function of altitude for $E_0 = -0.2$ mV/m, $z_0 = 3000$ km, $\Delta z = 1000$ km, and $\alpha = 1.5$.

ted lie between the lines $y = 2x$ and $y = x/2$. A spot check of wave spectra from these events indicates that for frequencies $f_{cO+} \le f \le f_{cH+}$ the BBELF emissions can be approximated by power law spectra with α in the range 1.0–3.0. These results are inconsistent with the predictions of cyclotron resonant heating theory (Chang et al., 1986). However, the addition of a parallel electric field can resolve this discrepancy if the electric field is sufficiently strong for a given proton heating rate and spectral index (Lund et al., 1999). In the next section we will investigate how strong a field is required.

3 Simulations

Our simulation model is based on the model used by Gorney et al. (1985) to illustrate trapping of ion conics by parallel electric fields. The equations

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

$$\frac{dv_\parallel}{dt} = \frac{q}{m}E_\parallel + \frac{3}{2}\frac{v_\perp^2}{R_E + z} \quad (2)$$

$$\frac{dz}{dt} = v_\parallel \quad (3)$$

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, are integrated for a particle launched with zero velocity $0.1R_E$ above the Earth's surface. A heating region starting at an altitude of $0.05R_E$ is assumed to give a constant, altitude-independent heating rate which is 1 eV/s for protons and scales as $m^{\alpha-1}$. The electric field is assumed to have a triangular profile:

$$E_\parallel = E_0\left(1 - \frac{|z - z_0|}{\Delta z}\right), \; z_0 - \Delta z < z < z_0 + \Delta z$$

$$E_\parallel = 0, \; |z - z_0| \ge \Delta z \quad (4)$$

where E_0 is the maximum parallel electric field at altitude z_0 and Δz is the half-width of the electric field distribution. We used the following parameter values in our simulations: $\alpha =$ 1, 1.5, 2, and 2.5; $E_0 = -0.1, -0.2, -0.5$, and -1 mV/m; $z_0 = 2000$, 3000, 4000, and 5000 km; and $\Delta z = 200$, 500, 1000, and 2000 km. We emphasize that these heating rate profiles and electric field configurations are only intended to illustrate the relevant physical processes and are not intended to represent any actual state of the aurora.

The results for a typical run are shown in Fig. 2, which traces the energy versus altitude of H^+, He^+, and O^+ for $\alpha = 1.5$, $E_0 = -0.2$ mV/m, $z_0 = 3000$ km, and $\Delta z =$ 1000 km. Below the electric field region, the ion energies are consistent with the predicted $m^{(2\alpha-1)/3}$ dependence. While O^+ has enough momentum to pass through the potential with only a small energy loss, the lighter ions bounce off the bottom side of the potential drop several times before they acquire enough energy to escape the trap. At the top of the potential drop (4000 km), the H^+ and He^+ ions have energies of 390 eV and the O^+ ion is at 408 eV. Above this altitude the energies diverge again due to the preferential heating of heavy ions.

The mere presence of an electric field is not enough to remove the mass dependence. This point is illustrated in Fig. 3, which shows the energy versus altitude for H^+, He^+, and O^+ for $\alpha = 1.5$, $E_0 = -0.1$ mV/m, $z_0 = 3000$ km, and $\Delta z = 1000$ km. Here O^+ acquires enough energy to escape the trap long before reaching the potential drop, while He^+ punches through on the first pass and H^+ bounces three times before escaping. This result is inconsistent with the data summarized in Fig. 1, which show only one of 239 samples with an O^+ to H^+ energy ratio as high as the energy ratio of 2.08 found at the 3000 km peak in the electric field and none as high as the 2.54 found at the top of the potential drop.

The results of the other runs are similar to the two shown here. A summary of the results is shown in Table 1. The dependence on the altitude of the maximum electric field is weak except for the $z_0 = \Delta z = 2000$ km case, in which the protons, and sometimes He^+ as well, are lost to the atmosphere. As the spectral index α increases, stronger potential

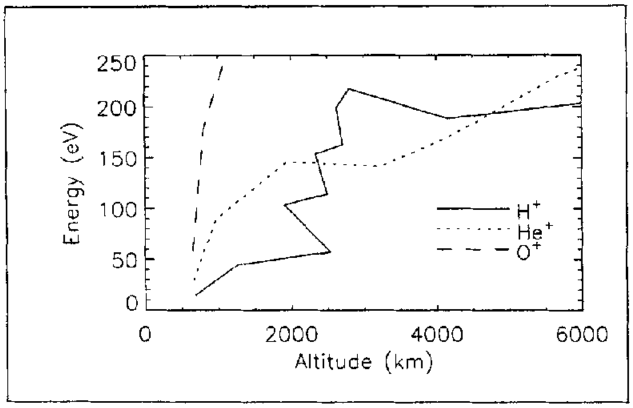

Fig. 3. Energies of H^+ (solid line), He^+ (dotted line), and O^+ (dashed line) as a function of altitude for $E_0 = -0.1$ mV/m, $z_0 = 3000$ km, $\Delta z = 1000$ km, and $\alpha = 1.5$.

drops $E_0 \Delta z$ are required to trap the O^+ ions, which receive an especially strong preferential heating for large α.

4 Discussion and Summary

In this paper we have shown that an electric field of sufficient strength is required to account for the observed lack of mass dependence in ion conic energies (Lund et al., 1999, 2000). Without the electric field, cyclotron resonant heating theory predicts that a spectrum with power proportional to $f^- \alpha$ will produce ion energies proportional to $m^{(2\alpha-1)/3}$ (Chang et al., 1986). This mass dependence is erased if the downward parallel electric field is strong enough to trap heavy ions in the "pressure cooker" proposed by Gorney et al. (1985).

Some details, many related to unrealistic features of the model, remain. Our data suggest that the parallel electric field should be related to the BBELF waves, as would be expected if the field-aligned electrons accelerated by this electric field drive the instability that produces the waves. Other features, including gravity, time dependence, and cross-field dependence, have been neglected in the model. We are continuing our investigations into these questions.

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Table 1. Estimates of Sufficient Potential Drops for Trapping

α	Potential Drop, V	$-E_0$, mV/m
1	100	≤ 0.1
1.5	200	0.5
2	500	0.5
2.5	≥ 1000	≥ 1

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