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FAST observations of preferentially accelerated He^+ in association with auroral electromagnetic ion cyclotron waves

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Abstract. The TEAMS instrument on the FAST satellite has detected events in which He^+ ions are resonantly accelerated perpendicular to the magnetic field to energies of several keV. The events occur in association with electromagnetic ion cyclotron (EMIC) waves and conic distributions of up to a few hundred eV in H^+ and a few keV in O^+. Concentrations of He^+ can be significantly elevated during the events. Our interpretation is that the He^+ ions are accelerated through a cyclotron resonance with the waves. This acceleration is similar to a proposed mechanism for selective ion acceleration in impulsive solar flares.

Introduction

Ion heating and acceleration perpendicular to the magnetic field is a common feature in the auroral region. These ions acquire energies of up to several keV and then move up the field line, adiabatically exchanging perpendicular for parallel energy to produce ion conics [*Sharp et al.*, 1977]. A wide variety of waves, including electromagnetic ion cyclotron (EMIC) waves [e.g., *Chang et al.*, 1986], have been suggested as transverse acceleration mechanisms. Preferential acceleration of O^+ by auroral EMIC waves has been reported [*Erlandson et al.*, 1994], and it has recently been shown that for low concentrations of He^+ ($n_{He^+}/n_e < 0.01$), EMIC waves can heat He^+ to produce the double-conic He^+ distributions seen near the equator in the dayside outer magnetosphere [*Horne and Thorne*, 1997]. The existence of a mechanism which preferentially heats He^+ at auroral latitudes was inferred from DE-1 data by *Collin et al.* [1988], who found that number fluxes for a large fraction of upflowing He^+ events greatly exceeded the fluxes expected from a cold ionosphere.

EMIC waves have also been linked to several other physical processes in the aurora. The finite $E_{\|}$ of oblique EMIC waves can accelerate electrons to energies of several keV, producing modulations in the downgoing electron flux and thereby creating flickering aurora [*Temerin et al.*, 1986]; more recently, EMIC waves have been observed together with modulated electron fluxes [*Lund et al.*, 1995; *McFadden et al.*, 1998]. These waves have also been linked to the recently discovered short-duration solitary electric field structures, which may carry a significant fraction of the parallel potential drop [*Ergun et al.*, 1998].

The generation mechanism for these waves is unclear. The leading candidate is an instability driven by the auroral electron beam [*Temerin and Lysak*, 1984; *Oscarsson et al.* 1997]. However, unless the electron distribution used in the linear instability calculation is carefully chosen, the growth rates obtained are too low to account for the observed waves, and observations of heavy ion cyclotron waves cannot be explained by this mechanism (see *Lund and LaBelle* [1997] for discussion).

In this letter we report observations of EMIC waves in association with resonantly accelerated He^+ in the aurora. The acceleration mechanism that we infer from the data is analogous to the cyclotron resonant acceleration mechanism which has been proposed in impulsive solar flares [*Temerin and Roth*, 1992].

Description of Data

The Fast Auroral Snapshot Explorer (FAST) was launched August 21, 1996, into a 4200 × 350 km orbit with 83° inclination. FAST carries the Time-of-flight Energy Angle Mass Spectrograph (TEAMS), the first

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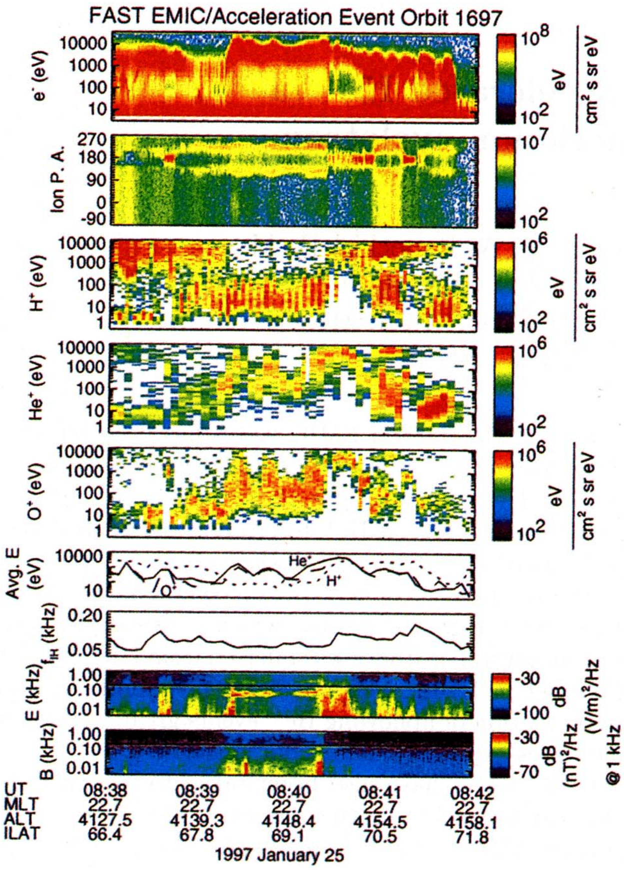

Figure 1. A four-minute overview of FAST data from orbit 1697 on January 25, 1997, showing electron energy, ion pitch angle (all species), H^+ energy, He^+ energy, O^+ energy, average energy per ion for each species, the ion hybrid frequency, ELF electric field, and ELF magnetic field. Lines on the frequency spectrograms indicate the local proton gyrofrequency. The ELF B spectra have been flattened by f^2 to reduce the dynamic range needed to show the spectrogram.

instrument which simultaneously measures 3-D distributions of H^+, He^{2+}, He^+, and O^+ at 0.001–12 keV and also provides a mass per charge spectrum over the range 1–60 amu/q [*Möbius et al.*, 1998a].

Figure 1 shows an overview of particle and ELF wave data from the inbound northern auroral pass from orbit 1697 on January 25, 1997. From top to bottom, the panels show an electron energy spectrogram; the ion pitch angle distribution (all species); H^+, He^+, and O^+ energy spectrograms; average energy per ion (upgoing energy flux divided by upgoing number flux) for each species; the H^+-He^+ ion hybrid frequency f_{IH}, which is calculated from the fractional densities of H^+, He^+, and O^+ according to the formula given by *Lund and LaBelle* [1997]; and ELF electric and magnetic field frequency spectrograms. The energy spectrograms cover all pitch angles. Lines on the wave spectrograms indicate the local proton gyrofrequency $f_{cH+} \approx 190$ Hz.

During the period 08:39–08:41 UT, FAST encountered an electron inverted V in which peak energies exceeded 20 keV, even though this orbit was geomagnetically quiet ($Kp = 1$). An ion conic was observed from just before 08:39 until 08:40:21, when an abrupt transition to a beam occurs. Three times during this interval, TEAMS detected increased fluxes and energies of He^+ and O^+. Each time, electromagnetic waves at 60–120 Hz, broadening of the ion pitch angle distribution, and increases in the energy of the inverted-V electrons are seen; however, little or no change is seen in the proton energies, which range from 3 to 200 eV. The EMIC waves dominate the electric field spectra in the ion conic; lower hybrid emissions are visible at 300–400 Hz but are about 20 dB weaker. Some of the EMIC waves lie as much as 20 Hz below f_{IH}, which is 80–100 Hz during the period the EMIC waves are observed. As can be seen in the figure, He^+ is more efficiently

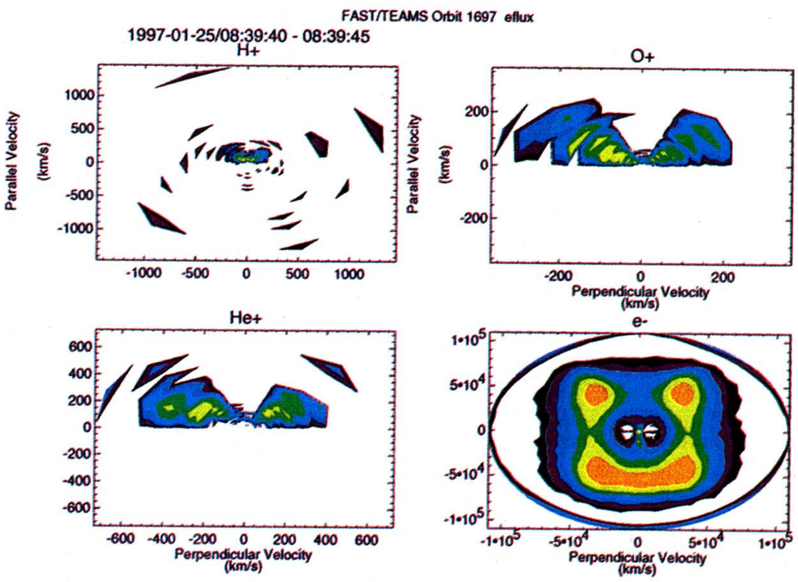

Figure 2. Velocity space distributions of H^+, He^+, O^+, and electrons at 08:39:40–45 UT on January 25, 1997.

heated than O^+ during periods of EMIC activity: He^+ typically falls in the energy range 100–5000 eV, while O^+ extends from 20 to 3000 eV. As FAST entered the ion beam, the frequency of the electromagnetic waves increased to just below f_{cH+} and broad-band electrostatic turbulence appeared below about 100 Hz; even here, the energies of He^+ and O^+ are nearly equal, whereas O^+ normally has a higher energy than He^+ in ion beams [*Möbius et al.*, 1998b].

Figure 2 shows the velocity space distribution of H^+, He^+, O^+, and electrons over one spin period at 08:39:40–45. The axes for the three ion species plots are scaled such that each plot covers the same energy range. The H^+ and O^+ distributions show classic conic signatures, with perpendicular velocities extending to about 100 km/s for H^+ and 200 km/s for O^+. The parallel temperature of O^+ is significantly higher than that of H^+. The pitch angle of the conic at the altitude of FAST (4140 km) is about 130°; unfolding the conic adiabatically implies a transverse heating region at about 2400 km. The He^+ ions lie almost entirely in the range $v_\perp$ = 100–400 km/s; they appear to have a higher minimum parallel energy and a somewhat flatter cone angle of about 110°. The latter cone angle indicates a second heating region near or above 3600 km. Two features stand out in the electron distribution: the inverted-V population, which includes the downgoing population at $v_\parallel \approx -5 \times 10^4$ km/s (an energy of about 10 keV) and some mirroring electrons, and a field-aligned component up to about 1 keV with a low perpendicular temperature.

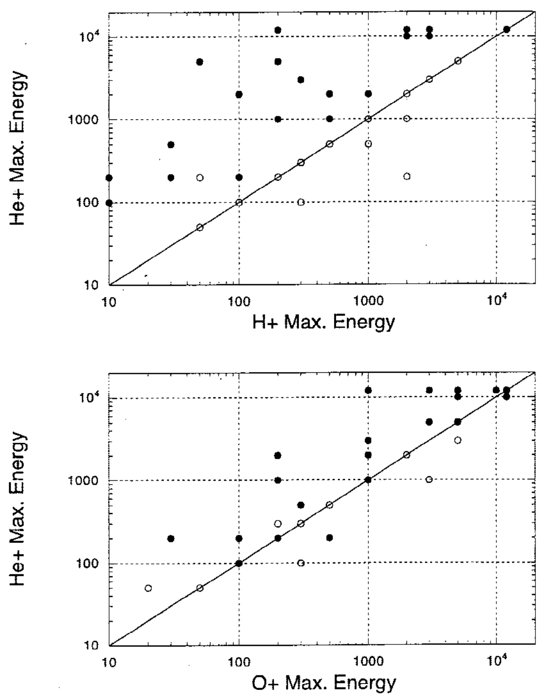

Figure 3. (a) Maximum energy of He^+ versus H^+ for 24 ion conics with EMIC waves (solid symbols) and 62 ion conics without EMIC waves (open symbols). (b) Maximum energy of He^+ versus O^+ for these events.

Several other preferential acceleration events have been identified in the data. One clear trend emerges: whenever EMIC waves are unambiguously present, preferential acceleration of He^+ occurs, while in the absence of EMIC waves energization of all ion species is comparable. This point is illustrated in Figure 3, which shows how the maximum energies of the three major species are related in 86 ion conic events, of which 24 occur simultaneously with EMIC waves. (Because the maximum energies are estimated, several points overlie one another.) All of the conics with EMIC waves (solid symbols) show He^+ preferentially heated over H^+ and most show He^+ preferentially heated over O^+; almost all of the other events (open symbols) fall along the line $y = x$ in the graphs. That ion conics fall into two or more distinct classes based on what waves are observed is consistent with a recent statistical survey of Freja data [*André et al.*, 1998]. Some of these events are accompanied by substantial increases in the He^+ density; for example, significant amounts of He^+ were detected during a preferential acceleration event observed on orbit 534 on October 9, 1996 (not shown), but He^+ was almost entirely absent elsewhere in the pass.

Discussion

The efficiency with which the He^+ ions are accelerated compared with H^+ and O^+ and the consistent association between preferential acceleration and EMIC waves suggest a cyclotron resonant acceleration mechanism. A similar mechanism has been proposed to explain the unusually high ^3He abundances seen in impulsive solar flares [*Temerin and Roth*, 1992; *Roth and Temerin*, 1997]. In impulsive solar flares, ions are accelerated to several MeV/nucleon, and the $^3He/^4He$ abundance ratio, normally $\sim 10^{-4}$, can exceed 1. A Temerin-Roth-type mechanism in the topside auroral ionosphere could easily account for the enhanced He^+ energization seen in these events. In addition, this mechanism would account for the elevated He^+ fluxes reported in the DE-1 data [*Collin et al.*, 1988].

Some previous studies of ion heating by EMIC waves [e.g., *Horne and Thorne*, 1997] have explicitly assumed that this heating occurs when the wave frequency is at or above the ion hybrid resonance frequency ω_{IH}, which plays a similar role in EMIC wave propagation to that of the lower hybrid frequency for whistler mode propagation [*Smith and Brice*, 1964]. Above this frequency a resonance cone exists and waves are guided along the field line; below this frequency perpendicular propagation is allowed and the wave can be reflected [*Rauch and Roux*, 1982]. A cutoff of EMIC waves at Ω_{He+}, which has been observed in Freja data [*Erlandson et al.*, 1994], is readily explained by this effect, since when H^+ is the majority species, $\omega_{IH} \to \Omega_{He+}$ as $n_{He+} \to 0$. However, reflection at ω_{IH} does not always occur in the auroral zone, since H^+ EMIC waves generated in the auroral acceleration region have been detected on the ground [*Sato and Hayashi*, 1985]. While the data in Figure 1 do not rule out reflection at the ion frequency, a more likely scenario is that the waves propagate beyond the ion hybrid resonance, as has been predicted in recent ray tracing calculations [*Lund and LaBelle*, 1997], and heat the He^+ near the altitude where the wave frequency matches the local helium cyclotron frequency. At 3600 km, $\Omega_{He^+} = 56$ Hz, near the lowest frequency of the observed EMIC band. As a result, He^+ can be accelerated by cyclotron resonance even when the plasma contains a substantial He^+ concentration.

It should be stressed that the resonant heating observed here is a secondary heating mechanism; some other acceleration mechanism must heat the protons to the energies observed. In this case there are two possibilities: the broad-band electrostatic waves in the beam region could heat ions which then are convected equatorward as they move upward, or the ions could be heated by electrostatic waves generated below the satellite. The relative importance of the two or more mechanisms is an open question which will be addressed in future investigations.

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References

André, M., et al., Ion energization mechanisms at 1700 kilometer in the auroral region, *J. Geophys. Res.*, in press, 1998.

Chang, T., et al., Transverse acceleration of oxygen ions by electromagnetic ion cyclotron resonance with broadband left-hand-polarized waves, *Geophys. Res. Lett.*, *8*, 636, 1986.

Collin, H. L., et al., The helium components of energetic terrestrial ion upflows: Their occurrence, morphology, and intensity, *J. Geophys. Res.*, *93*, 7558, 1988.

Ergun, R. E., et al., FAST satellite observations of large-amplitude solitary waves, *Geophys. Res. Lett.*, in press, 1998.

Erlandson, R. E., et al., Freja observations of electromagnetic ion cyclotron ELF waves and transverse oxygen ion acceleration on auroral field lines, *Geophys. Res. Lett.*, *21*, 1855, 1994.

Horne, R. B., and R. M. Thorne, Wave heating of He^+ by electromagnetic ion cyclotron waves in the magnetosphere: Heating near the H^+-He^+ bi-ion resonance frequency, *J. Geophys. Res.*, *102*, 11,457, 1997.

Lund, E. J., et al., Observation of electromagnetic oxygen cyclotron waves in a flickering aurora, *Geophys. Res. Lett.*, *22*, 2465, 1995.

Lund, E. J., and J. LaBelle, On the generation and propagation of auroral electromagnetic ion cyclotron waves, *J. Geophys. Res.*, *102*, 17,241, 1997.

McFadden, J. P., et al., Electron modulation and ion cyclotron waves observed by FAST, *Geophys. Res. Lett.*, in press, 1998.

Möbius, E., et al., The 3-D plasma distribution function analyzers with time-of-flight mass discrimination for Cluster, FAST, and Equator-S, in *Measurement Techniques in Space Plasmas*, *Geophys. Monogr. Ser.*, edited by J. Borovsky, R. F. Pfaff, and D. T. Young, in press, 1998a.

Möbius, E., et al., Species dependent energies in upward directed ion beams over auroral arcs as observed with FAST TEAMS, *Geophys. Res. Lett.*, in press, 1998b.

Oscarsson, T., et al., Towards a consistent picture of the generation of electromagnetic ion cyclotron ELF waves on auroral field lines, *J. Geophys. Res.*, *102*, 24,369, 1997.

Rauch, J. L., and A. Roux, Ray tracing of ULF waves in a multicomponent magnetospheric plasma: consequences for the generation mechanism of ion cyclotron waves, *J. Geophys. Res.*, *87*, 8191, 1982.

Roth, I., and M. Temerin, Enrichment of ^{3}He and heavy ions in impulsive solar flares, *Astrophys. J.*, *477*, 940, 1997.

Sato, N., and K. Hayashi, Band-limited ELF emission burst (auroral roar), *J. Geophys. Res.*, *90*, 3531, 1985.

Sharp, R. D., R. G. Johnson, and E. G. Shelley, Observation of an ionospheric acceleration mechanism producing energetic (keV) ions primarily normal to the geomagnetic field direction, *J. Geophys. Res.*, *82*, 3324, 1977.

Smith, R. L., and N. Brice, Propagation in multicomponent plasmas, *J. Geophys. Res.*, *69*, 5029, 1964.

Temerin, M., and R. L. Lysak, Electromagnetic ion cyclotron mode (ELF) waves generated by auroral electron precipitation, *J. Geophys. Res.*, *89*, 2849, 1984.

Temerin, M., et al., Production of flickering aurora and field-aligned electron flux by electromagnetic ion cyclotron waves, *J. Geophys. Res.*, *91*, 5769, 1986.

Temerin, M., and I. Roth, The production of ^{3}He and heavy ion enrichments in ^{3}He-rich flares by electromagnetic hydrogen cyclotron waves, *Astrophys. J.*, *391*, L105, 1992.

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