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Species dependent energies in upward directed ion beams over auroral arcs as observed with FAST TEAMS

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Abstract. Upward flowing field-aligned ion beams over auroral arcs have been observed with the 3-dimensional ion mass spectrograph TEAMS on FAST. We have performed a statistical study on a sample of 77 ion beams from the auroral campaign in early 1997. All observed beams contain substantial amounts of H^+, He^+ and O^+. A clear ordering of the total energies according to mass is found, with H^+ having the lowest and O^+ the highest energy. The composition varies significantly from beam to beam, with O^+/H^+ ratios ranging from ≈ 0.1 to 10. No variation of the energy ratio between species is observed as a function of relative abundance. These results are discussed in the light of earlier observations of higher energies for O^+ in statistical studies of beams during solar minimum and attempts to explain this behavior in terms of beam instabilities.

Introduction

Ion beams that flow upwards along the magnetic field lines above auroral arcs are known as common features in auroral physics (Shelley et al., 1976). They are usually interpreted as acceleration of ions in upward directed electric fields that are parallel to the local magnetic field. Simultaneously electrons are accelerated downward where they become responsible for the generation of the auroral glow. The energy of the beam should represent the total potential traversed by the ions, with the same energy per charge for all species. Auroral ion beams are mainly composed of H^+ and O^+ with some contribution from He^+ (Collin et al., 1988).

In previous statistical studies of the ion beam energies with mass spectrographs on DE-1 Collin et al. (1987) and Reiff et al. (1988) found that O^+ and H^+ have approximately the same energies in ion beams during the time of solar maximum, consistent with pure electrostatic potential acceleration. However, they reported substantial energy differences between the species during solar minimum, i.e. the energy of O^+ was found to be significantly higher than that of H^+. During solar maximum the ionospheric outflow of O^+ is enhanced over that of H^+ mostly due to an increase in scale height of ionospheric oxygen. To explain the observed beam energy variations between different species the influence of plasma instabilities was invoked. During solar minimum when the content of O^+ in the beams is low the excitation of an ion two-stream instability by the relative velocity between the two species at comparable total energy was thought to provide efficient energy transfer (e.g. Bergmann and Lotko, 1986; Kaufmann and Ludlow, 1986). It was argued that such an instability may accelerate the lagging O^+ towards the velocity of H^+. Simulations of beams that start with equal energy have shown that more energy can be transferred to O^+ when its relative abundance is lower (Schriver et al., 1990). Ghielmetti et al. (1987) have reported a decrease of the H^+ and O^+ beam energy with O^+ abundance and discussed the potential influence of abundances on differential energization, but they did not present a direct correlation with energy ratios.

In this paper we present new observations with the Time-of-Flight Energy Angle Mass Spectrograph (TEAMS) onboard the Fast Auroral SnapshoT Explorer (FAST). With its large geometric factor and high time resolution TEAMS allows for the first time a comprehensive study of H^+, O^+ and He^+ in auroral ion beams including beams that may be traversed in only a few seconds. It can also resolve variations across individual beams. In this first report we will concentrate on the variation of the energy ratios between the species as a function of relative abundance of O^+ and total beam energy. In particular, the persistence of similar energy ratios over two orders of magnitude in relative abundance may provide some challenges for previous attempts to explain the selective energization with the influence of two-stream instabilities. We suggest that a first stage acceleration perpendicular to the magnetic field as has been proposed to overcome the general difficulty to extract ions from the upper ionosphere (Klumpar et al., 1984; Vago et al., 1992) may play a role in the differential energization.

Instrumentation and observations

TEAMS is a plasma analyzer with mass separation capability that provides full 3-D velocity distributions for H^+, He^{2+}, He^+, and O^+ with a time resolution of up to 1/2 spacecraft spin (≈ 2.5 sec). The sensor has an instantaneous viewing of 360° by 10°, separated into 16 pixels in polar angle. It combines selection of energy per charge in a toroidal top-hat analyzer with post acceleration up to 25 kV and subsequent time-of-

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flight measurement to determine the mass per charge, energy and arrival direction of incoming ions. An energy range from 1.2 to 12000 eV/e is covered with an intrinsic resolution of $\Delta E/E \approx 0.15$ by stepping the analyzer voltage 192 steps 32 or 64 times per spacecraft spin. A more detailed description may be found elsewhere (Möbius et al., 1998). The data are put into context with complementary information from the Electron and Ion Electrostatic Analyzers (EESA and IESA, Carlson et al., 1998). FAST is in a 350 by 4200 km altitude orbit with 83° inclination and crosses both auroral ovals once every 2 hour orbit. During the auroral observation campaign from January through March 1997 the apogee was over the northern polar region with the orbit plane near the noon-midnight meridian. For this study we have selected auroral crossings during the campaign with confirmed observations of ion beams within two hours of local magnetic midnight.

A typical example of an inbound auroral crossing is shown in Fig. 1. FAST passes the auroral zone from lower latitude towards the polar cap, as can be seen from the disappearance of energetic particle populations at the end of the time interval. Shown from top to bottom are the energy-time spectrograms for electrons from 3 eV to 30 keV (a) (from the EESAs), the pitch angle distribution from 3 eV to 30 keV (b) and the energy-time spectrograms over 150° - 210° pitch angle for all ions (c) (from the IESAs), the energy-time spectrograms over 0° - 360° pitch angle for H^+ (d), the energy-time spectrograms over 150° - 210° pitch angle for H^+ (e), He^+ (f), and O^+ (g), and the pitch-angle distribution from 3 eV to 12 keV for O^+ (h) (from TEAMS). Plotted are the differential energy flux densities versus time in a color coded representation. It can be seen from the pitch-angle distributions in (b) and (h) that the spacecraft encounters regions with upflowing ion beams, starting at 10:05:00, 10:05:50, 10:06:10, and 10:06:45 UT, as is evident from the flux concentrations for all ions as well as for O^+ at 180° pitch-angle. This corresponds to upward flow (antiparallel to the magnetic field) in the northern hemisphere. The beams coincide with electron density depressions, i.e. the absence of electrons below the ion beam energy, because low energy electrons from below cannot pass the parallel potential region. Between the beams there are ion conic regions with a split of the distributions away from 180° pitch angle. Also visible in the pitch angle averaged H^+ spectrum (d) at energies > 1 keV and in the pitch-angle spectra (b and h) are precipitating ions from the plasma sheet whose flux decreases at higher latitude. However, there is no low energy component of the ions during the beam intervals, as reported by Koskinen et al. (1990) from Viking observations above 8000 km.

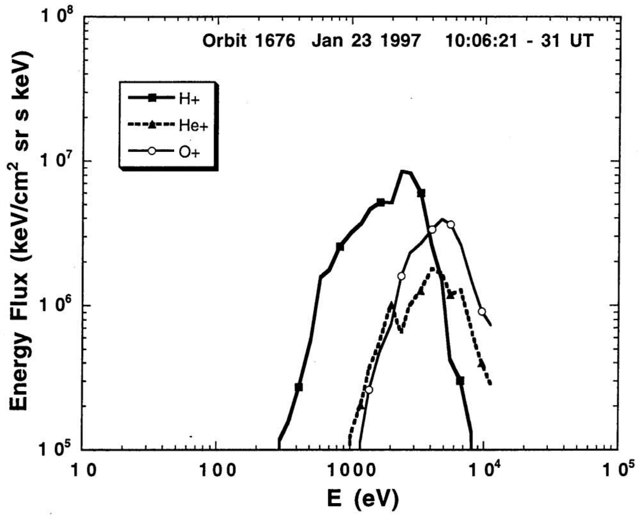

Figure 2. Energy spectra of H^+, He^+, and O^+ for 10:06:21 - 10:06:31 UT of the second ion beam in Fig. 1.

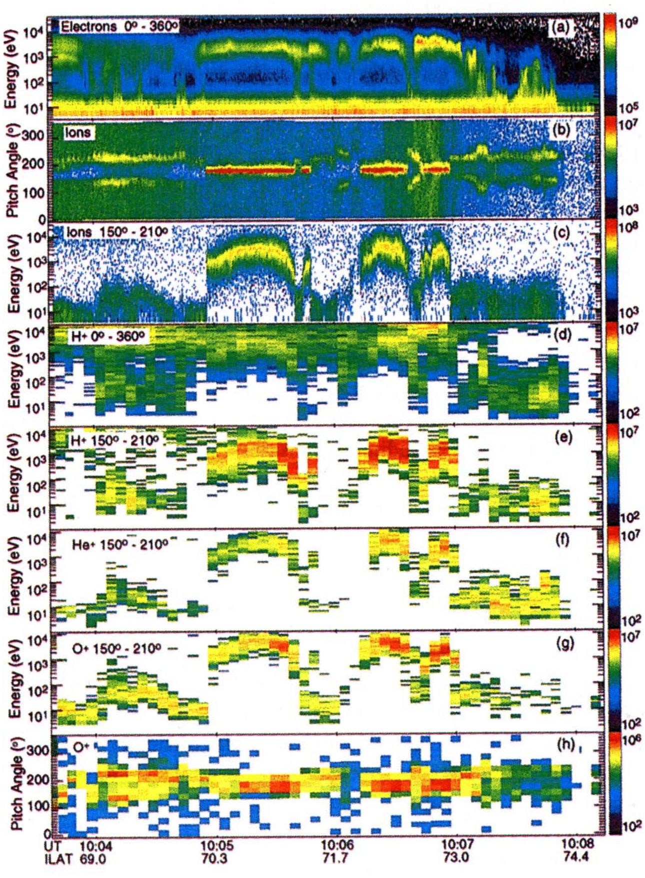

Figure 1. Colored energy flux distributions (eV/cm^2 sr s eV) for a sequence of ion beams on January 23, 1997, at an altitude of 4150 km and an MLT of 22.7 h. From top to bottom: energy-time spectrograms for electrons (a), pitch-angle distribution for all ions (b), energy-time spectrograms for all ions over 150° - 210° in pitch angle (c), for H^+ over 0° - 360° in pitch-angle (d), for H^+ (e), He^+ (f), and O^+ (g) over 150° - 210° in pitch-angle, pitch-angle distribution for O^+ (h).

Across each of the three extended beam regions during this pass the ion energy varies by more than one order of magnitude, with the lowest energies at the beam boundaries and the maximum in the center. In this example the maximum beam energy for H^+ is $\approx$ 1 keV, while the energies for He^+ and O^+ appear to be substantially higher, reaching a few keV for O^+ at 10:05:10 and 10:06:15 UT. It becomes apparent from the logarithmic scale in energy that all three species track each other approximately with the same energy ratios. It should also be noted here that the relative abundance of He^+ is significant throughout this pass and that its contribution to the beam population seems increased towards higher latitude.

The sample auroral crossing in Fig. 1 clearly suggests an ordering of the species in energy according to their mass. This is quantified by the energy spectra shown in Fig. 2 for the second beam at 10:06:30 UT. Indeed the peak energy of O^+ is substantially higher than that of H^+, with He^+ in between. To sub-

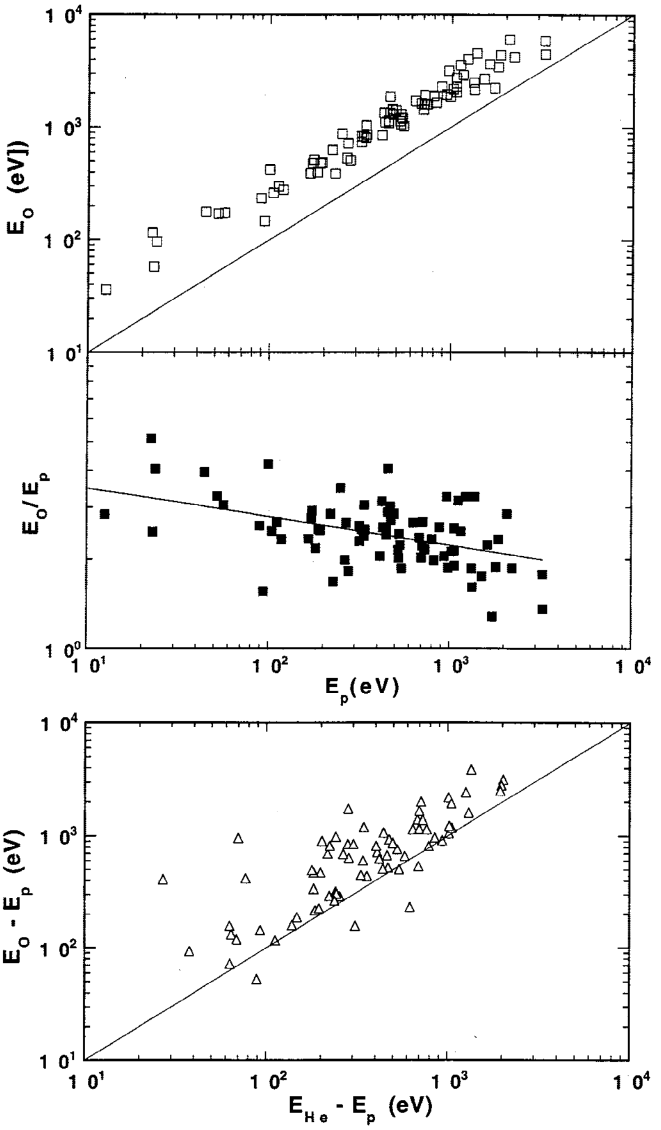

Figure 3. Peak energy of O^+ and energy ratio for O^+ and H^+ versus the H^+ energy (upper 2 panels) and differences of the O^+ and H^+ peak energies versus those of He^+ and H^+ (lower panel).

stantiate our finding and to study the dependence of this apparent differential acceleration in ion beams we have compiled data on a sample of 77 ion beams during the auroral campaign. Fig. 3 shows scatter plots of the energy of O^+ versus the energy of H^+ (top), the variation of the O^+ to H^+ energy ratio with the proton energy (center), and the energy differential of O^+ over H^+ versus that of He^+ over H^+ (bottom) in a logarithmic representation. In the top and the bottom panel the diagonal line indicates a ratio of 1. To define the energy peak of the beams quantitatively we have computed the average value of the energy distribution for pitch angles from 150° - 210°. This average can be taken over the entire energy range, because no separate low energy distribution is present. Clearly the energy of O^+ is always substantially higher than that of H^+, typically more than a factor of two, over the entire spread in beam energies of almost three orders of magnitude. It is interesting to note from the center panel that the E_{O^+}/E_{H^+} ratio is practically confined to a band between 1.5 and 4. Only one data point at very low total energy is found at ≈ 5 which is still far away from reaching the same energy per mass. Although there is significant scatter in the data points, a weak, but still clearly visible trend emerges with higher O^+ to H^+ energy ratios towards lower beam energies (a variation by approximately a factor of two over three orders of magnitude in energy with R = 0.5). As can be seen from the bottom panel the energy differential of the O^+ beam is generally higher than that of He^+, as indicated by the fact that almost all data points are found above the diagonal line. The average energy ratios are found to be $E_{O^+}/E_{H^+} \approx 2.52 \pm 0.66$ and $E_{He^+}/E_{H^+} \approx 1.92 \pm 0.52$. While the difference in the energy ratio between the individual data points for O^+ and He^+ may not be significant, the difference in the averages clearly is. A definite ordering of the beam energies with $E_{O^+} > E_{He^+} > E_{H^+}$ is demonstrated by this result. In addition, there is an inverse correlation of the beam density with energy as obtained from a power law fit with an exponent of -0.66 and R = 0.91 (not shown here), consistent with the same typical flux density for all beams of this sample.

Because we are currently in a solar minimum, the different energies of the species are in accordance with the observations by Collin et al. (1987) and Reiff et al. (1988), except that our typical E_{O^+}/E_{H^+} ratios seem to exceed the solar minimum average reported by Collin et al. (1987). It should be noted that because of the lower spectral and temporal resolution with previous instruments the sum of the beam and thermal energy had been used. This difference in the definition of the typical beam energy and the fact that longer time averages were necessary in the previous studies may be responsible for the different ratios. At this point it will be an interesting exercise to study the beam energies in direct relation to the observed abundance variations, which are already obvious for the consecutive beams shown in Fig. 1. A scatter plot of the O^+ to H^+ energy ratio as a function of the corresponding density ratio is shown in Fig. 4. Already this very restricted sample of ion beams from the near midnight aurora during solar minimum contains a relative abundance variation of almost two orders of magnitude. However, no clear trend of a variation of the energy ratio with the O^+ abundance can be found in this data set. A power law fit returns an exponent of -0.097 with a confidence level of 0.28. It also becomes obvious that for most of the beams O^+ is the dominant species in terms of ion density. If we take into account that the ion mass density determines the center of gravity between two species in their mutual interaction, O^+ dominates in all of the cases.

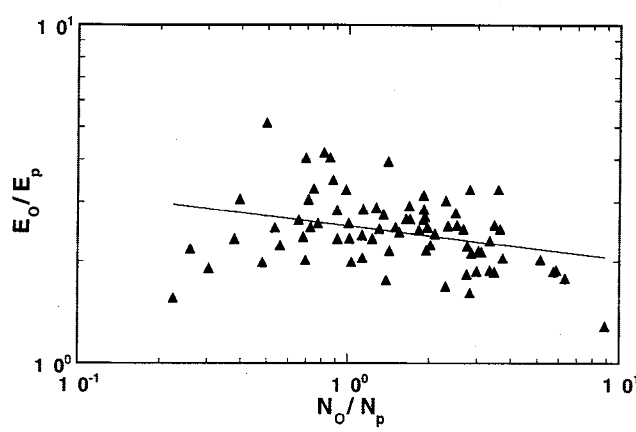

Figure 4. Variation of the O^+ to H^+ peak energy ratio with the relative abundance of O^+ in ion beams.

Discussion

In summary, the energies of O^+, He^+ and H^+ in auroral ion beams show a clear ordering according to ion mass. The respective energy ratios track each other remarkably well across individual beams and show only a relatively weak variation with the total beam energy, with the largest ratios for the lowest energy beams. The low energy beams are associated with the highest beam densities, consistent with no variation of the ion outflow over the range of beam energies. However, no variation of the energy ratios could be found over two orders of magnitude in the O^+/H^+ abundance ratio.

The observation of upward flowing field-aligned ion beams in conjunction with auroral arcs where electrons are accelerated downward suggests that the main energy source for these ion beams is acceleration in parallel electric fields beneath the observer. However, the substantially different energy per charge values observed for the three major beam constituents require additional acceleration or energy transfer processes. Ion beam instabilities have been suggested, because beams with different singly charged species at equal energy per charge form a multi-beam velocity distribution. Kaufmann and Ludlow (1986) report that a two peak distribution that arises for example from an O^+ and H^+ beam at the same energy will evolve into a distribution with a distinct high energy O^+ tail thus indicating a substantial energy transfer from H^+ to O^+. Bergmann and Lotko (1987) show that the beam interaction leads to heating of the beam constituents. This has been confirmed in particle simulations for mixed H^+, He^+, and O^+ beams by Winglee et al. (1989) who have also reported indications for this in observed ion distributions. Although these earlier results provide evidence for energy transfer between the lighter and the heavier beam component, they predict heating of the beam distributions and tail formation, rather than the distinctly different peak energies that are observed for all three species in the current investigation. Furthermore the attempt to explain the energy variations with solar activity implies, and the simulations by Schriver et al. (1990) predict, that the efficiency of multi beam interactions change significantly with the relative O^+ abundance. However, our observed energy ratios do not change notably over an abundance variation of two orders of magnitude from H^+ to O^+ domination. Either there is indeed no correlation between beam composition and the energy ratios, or the effect of the abundance variation is masked by another major influence. The distinction between these two possibilities probably requires a detailed multi-parameter study that goes beyond the scope of this paper. But it becomes apparent that the observed transition from different beam energies for O^+ and H^+ during solar minimum to equal energies at solar maximum cannot be simply explained by an activity related abundance variation in the ion beams.

In addition, it seems counterintuitive for ion beam instabilities to produce an increase in the energy ratio for low energy beams, because they are expected to become stronger with a larger velocity difference. However, this trend may be understood if the acceleration in the parallel electric field is only the second stage. Because it seems generally difficult to extract ions from the ionosphere, a two-stage process with preheating of the ions perpendicular to the magnetic field by waves has been invoked (Klumpar et al., 1984; Vago et al., 1992). In the divergent magnetic field part of the perpendicular energy is transferred into parallel energy during the outflow. More efficient wave heating of heavier ions in comparison with protons has been observed (e.g., Moore et al., 1986; Erlandson et al., 1994). An example of selective acceleration by electromagnetic ion cyclotron waves is discussed in an accompanying paper (Lund et al., 1998). Therefore, it is conceivable that part of the energy difference between H^+ and the heavier ions originally stems from energization perpendicular to the magnetic field. For lower parallel acceleration potentials this contribution could be a larger fraction of the total energy and thus lead to a larger E_{O^+}/E_{H^+} ratio. This would also be consistent with the observation that O^+ shows a significant perpendicular to parallel temperature anisotropy in ion beams (Collin et al., 1987). In order to understand the relative importance of these physical processes for the observed differential energization of ion beam species we will have to study the variation of the velocity distribution functions of all three species in detail. The TEAMS instrument provides the necessary resolution.

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