GEOPHYSICAL RESEARCH LETTERS, VOL. 25, NO.12, PAGES 2085-2088, JUNE 15, 1998

FAST/TEAMS observations of charge exchange signatures in ions mirroring at low altitudes

L. M. Kistler,[1,2] E. Möbius,[1,2] D. M. Klumpar,[3] M. A. Popecki,[1] L. Tang,[1,2] V. Jordanova,[1] B. Klecker,[4] W. K. Peterson,[3] E. G. Shelley,[3] D. Hovestadt,[4] M. Temerin,[5] R. E. Ergun,[5] J. P. McFadden,[5] C. W. Carlson,[5] F. S. Mozer,[5] R. C. Elphic,[6] R. J. Strangeway,[7] C. A. Cattell,[8] and R. F. Pfaff[9]

Abstract. Using the TEAMS instrument on FAST, we have observed a case in which signatures of the inner edge of the plasma sheet are clearly observed in the energy spectra of ions mirroring at the FAST altitude. That inner edge is dominated by He^+. We show that this is the natural composition expected from charge exchange as the ions drift in from the plasma sheet.

Introduction

It is well known that the signatures of ion drift trajectories are evident in the measurements of particle energy spectra in the inner magnetosphere. Most of the work on these features has involved spacecraft observations near the equatorial plane (e.g. *McIlwain, 1972, Smith and Hoffman, 1974, Ejiri, 1980, Kistler et al., 1989*) but some studies have also used measurements from polar-orbiting spacecraft (e.g. *Strangeway and Johnson, 1984, Shirai et al., 1997*). The adiabatic theory for these particle drift trajectories also has a long history. *Chen, 1970* did the first formulation of ion drift trajectories in a dipole magnetic field and dawn-dusk electric field, and many additions and improvements were added by *Kivelson and Southwood, 1975.*, *Cowley and Ashour-Abdalla, 1976.*, *Ejiri, 1978.*, *Kaye and Kivelson, 1979.* and others. More recent work has concentrated on adding time dependence and realistic losses to the calculations (*Fok et al, 1993*, *Chen et al., 1994*, *Jordanova et al, 1994*).

In steady state, four basic classes of drift trajectories are found: low energy ions on closed drift paths drifting eastward (TE), ions on closed drift paths drifting westward (TW), an intermediate band of orbits which execute closed, banana-shaped orbits across the dusk meridian (B), and open drift paths which come in from the plasma sheet and leave out the front-side magnetopause. The exact energy and spatial range of each of the trajectory types depends on the exact electric and magnetic field models being used, but the overall structure is the same. Figure 1 shows the locations of the boundaries of equatorially mirroring ions a function of invariant latitude at a particular local time, 2100 MLT, assuming a dipole magnetic field model and a Volland–Stern (*Volland, 1973*, *Stern, 1975*) electric field. The open drift trajectories extend far into the inner magnetosphere in a narrow energy band around 20 keV. The actual boundaries observed in the particles do not generally agree with the theoretical steady state boundaries for two reasons. First, the magnetosphere is rarely in a "steady state", so the time of the ion injection or acceleration in the tail combined with the finite drift time of the ions affects where the inner boundary of the open drift paths is observed. Second, there are losses along the drift paths. The predominant loss mechanism for energetic ions (> 1 keV) is charge exchange with the neutral hydrogen geocorona. This loss has not been considered very important for the ions on open drift paths on the nightside because most of the studies of this phenomenon have concentrated on ions observed near the equatorial plane where the charge-exchange lifetime is relatively long. However, for ions mirroring at low altitudes, charge exchange can be significant. In this paper we show an example where the inner edge of the ion boundary shows a significant species dependence. We show that the observed composition is a result of the species dependence of the charge exchange lifetimes.

[1]Space Science Center, University of New Hampshire, Durham

[2]Also at Physics Department, University of New Hampshire, Durham

[3]Lockheed Martin Palo Alto Research Laboratory, Palo Alto, California

[4]Max-Planck-Institut für extraterrestrische Physik, Garching, Germany

[5]Space Sciences Laboratory, University of California, Berkeley

[6]Los Alamos National Laboratory, Los Alamos, New Mexico

[7]Institute for Geophysics and Planetary Physics, University of California, Los Angeles

[8]School of Physics and Astronomy, University of Minnesota, Minneapolis

[9]NASA Goddard Space Flight Center, Greenbelt, Maryland

Paper number 98GL00331.
0094-8534/98/98GL-00331$05.00

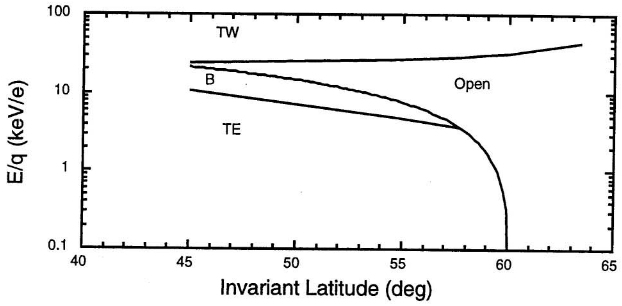

Figure 1. The drift regions expected for equatorially mirroring ions in the magnetosphere at 21:00 MLT. A dipole magnetic field and Volland-Stern electric field have been assumed.

Instrumentation

The Fast Auroral SnapshoT (FAST) satellite was launched into a 4200 × 350 km, 83° inclination orbit on August 21, 1996. FAST carries a full complement of particle and fields instruments designed to make high time resolution measurements in the aurora. The data in this paper are mainly from the Time Energy Angle Mass Spectrometer (TEAMS). This instrument uses a combination of an energy per charge measurement in a top cap electrostatic analyzer, post-acceleration, and a time-of-flight measurement to determine the energy, mass per charge, and incoming direction of ions over the energy range 1–12000 eV. The 360 × 10 degree viewing angle, combined with the spacecraft spin gives a full 3D measurement of the velocity distribution function of all species in 1/2 spin (2.5 s). The actual time resolution depends on the instrument mode. The instrument is described in more detail in *Möbius et al. 1997.*

Observations

Figure 2 shows data from Feb 7, 1997, 02:50-03:10 UT when the spacecraft is moving northbound approaching the auroral oval at about 21:36 MLT. The pass extends from 57.4° invariant latitude to about 80°. The top three panels show the differential energy flux averaged over all pitch angles as a function of energy and time for the species H^+, He^+, and O^+. The 4th and 5th panels show the pitch angle spectra for H^+ for energy ranges 1000–12000 eV, and 10–1000 eV. The bottom panel shows the He^+ pitch angle spectrum over the energy range 10–12000 eV. This pass occurs during a relatively quiet time. The Kp was 0, and had been below 3 for the three previous days. The estimated AE was also very low. There was some activity on the previous day, with a small excursion up to 200 nT during hour 22:00, and a larger excursion just above 500 nT around noon.

From 2:50 to 2:58, as the spacecraft moves north in latitude, the drift path transitions are evident in the top three panels. Comparisons with Figure 1 can be used to help distinguish the different populations. Initially, only the low energy trapped population (TE) is observed. Then the ions on open drift paths appear, first at the highest energies (12 keV) and then at lower energies. A species dependence in the open/closed drift path boundary is clearly evident. At the TEAMS high energy end, the He^+ flux is observed first, at about 02:51. The H^+ is not observed until 02:54. O^+ is observed beginning at an intermediate time between these two values. At about 2:58, all the drift paths observed are open. There is also an instrument mode change at this time, so the data are accumulated over shorter time intervals. The particle populations observed after this point are a combination of the plasma sheet ions mirroring or precipitating at the spacecraft location and the auroral ions accelerated up along the field line. This is clear from the pitch angle distributions. Prior to 3:02, both the low and high energy pitch angle spectra have peaks at 90° and 270° (mirroring ions) with a minimum in the upflowing ions (180°), but in some cases a full loss cone (0°). The He^+ in the last panel shows the same pitch angle distribution, indicating that this is also a mirroring population, not a population with a local ionospheric source. After 3:02, auroral conics and beams flowing up along the field lines are observed, in addition to the precipitating population.

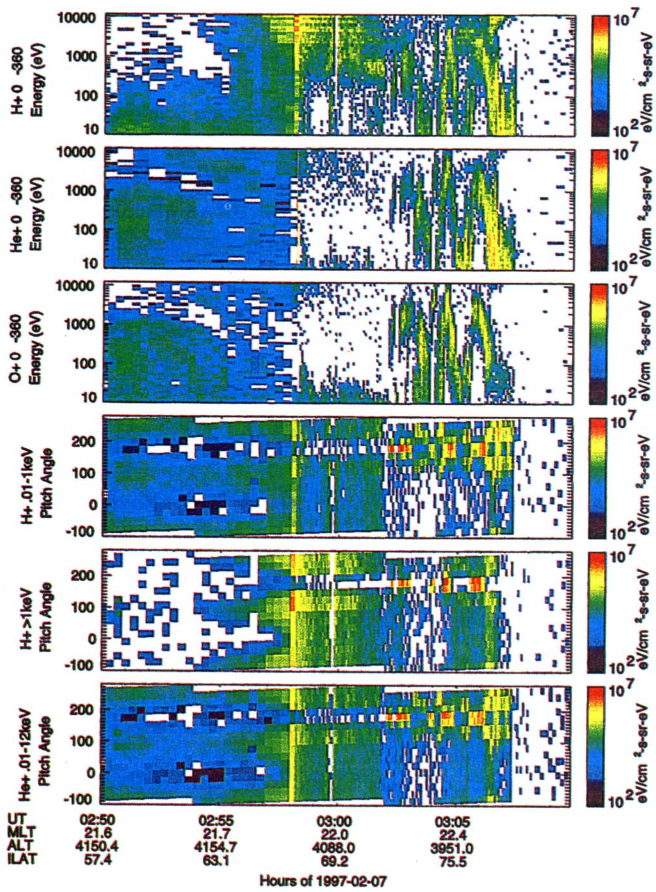

Figure 2. Ion flux observed by the TEAMS instrument on a pass approaching the north auroral oval at about 22:00 MLT on Feb 7, 1997. Details are given in the text.

Simulation

Figure 3 shows drift paths in the equatorial plane of ions that reach 21.6 MLT , L= 4.5 ($\approx 62°$ invariant latitude), for 3 energies 7, 9, and 11 keV, and L=4.0 for 1 energy, 11 keV. Also shown is the trajectory of the spacecraft for the time period from Figure 2, mapped to the equatorial plane. The drift paths were calculated for the ions which would mirror at the FAST altitude - about 10° equatorial pitch angle, in a dipole magnetic field and a Volland-Stern electric field for Kp = 1. The paths are calculated backwards in time. The arrows indicate the forward direction of the drift and spacecraft trajectories. The transition from open to closed drift paths at L=4.5 occurs between 7 and 9 keV. At 7 keV the ion has drifted around the dusk side on a closed orbit. The ions observed at 9 and 11 keV have drifted in from the plasma sheet. Note that the drift velocity of these ions is also very low. Symbols are plotted every 2 hours on this plot, so it takes about 18 hours for a 10 keV ion to drift from L=10 to L=4.5. Because these ions are mirroring at 4000 km altitude, they spend much of their time at an altitude where the neutral hydrogen density is large. Therefore, they are strongly subject to the effects of charge exchange. The charge exchange lifetimes are species and energy dependent. At 10 keV the lifetime for H^+ is $1 \times 10^7 s/cm^3$, for O^+ is $5 \times 10^7 s/cm^3$ and for He^+ is $2.5 \times 10^8 s/cm^3$ (*Smith and Bewtra, 1978*). Therefore, we would expect that H^+ would be lost at a much faster rate than the other species.

To test this quantitatively, we have calculated the charge exchange loss of ions drifting from L=6.5 to L= 3.6 (the innermost point of the ion trajectory). We used the trajectories of ions which cross L = 4.0 (60° ILAT) and 21.6 degrees MLT at 11 keV. This is the fourth trajectory shown in Figure 3. We have used an approximation for the bounce averaged neutral hydrogen density determined by *Schultz and Blake, 1990.* In drifting from L = 6.5 to L = 3.6 the ion energy increases from 3.7 keV to 13.34 keV. The changes in energy and pitch angle as the ion drifts have been taken into account in the charge exchange calculation. We have used the charge exchange cross sections given by *Smith and Bewtra, 1978.* and the neutral hydrogen density model of *Rairden, 1986.* The population at L=6.5 was matched to the flux ratios measured in the mirroring plasma sheet ions from 2:58 to 3:00 UT on this orbit.

The results of the calculation are shown in Figure 4. Shown is the fraction of the total flux contributed by each species as a function of invariant latitude for the calculated trajectory. We start with a population that

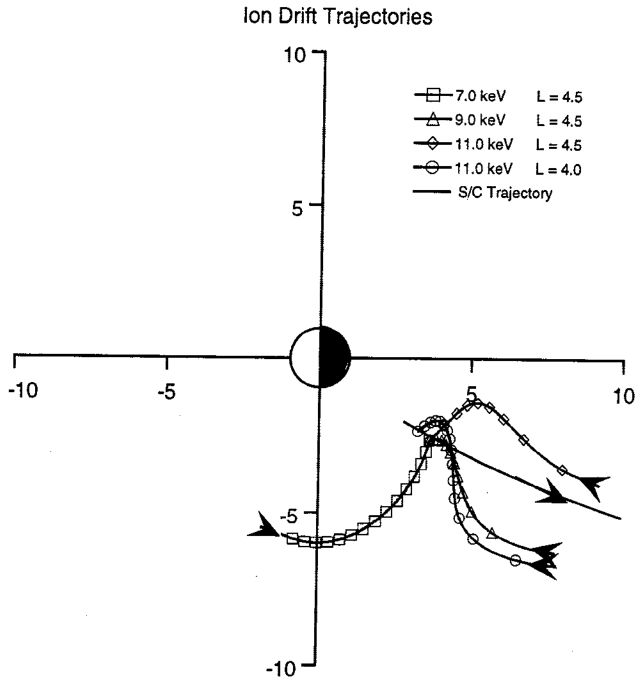

Figure 3. Ion drift paths and the spacecraft trajectory mapped to the equatorial plane.

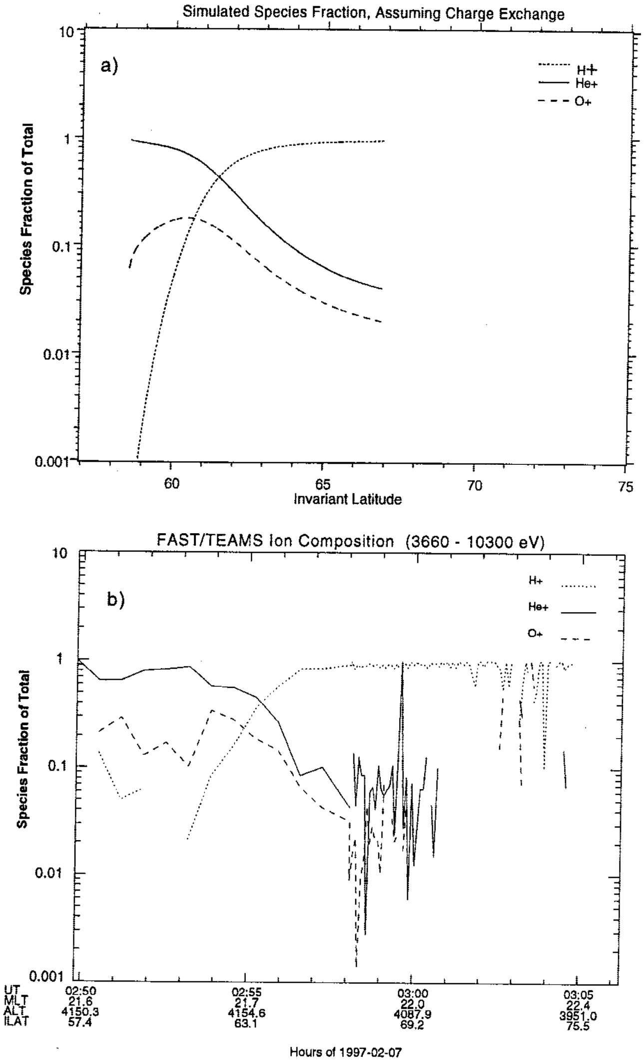

Figure 4. a) The modeled species fraction as a function of invariant latitude. b) The measured species fraction for the energy range 3660 – 10300 eV for the same time period as Figure 2.

is 94% H^+, 4% He^+, and 2% O^+. At lower latitudes the H^+ fraction declines, and He^+ becomes the dominant population, in agreement with our observations.

For a more quantitative comparison with observations, we show in the bottom panel the species fraction measure by FAST/TEAMS for an energy band of 3660 – 10300 eV, over approximately the same invariant latitude range. From Figure 2 we can see that this energy band is dominated by the ions on open drift paths. The data also show the decline in H^+ and the increase in the fraction contributed by He^+ with decreasing invariant latitude. The H^+/ He^+ crossover point differs by about 2° in invariant latitude between the observations and the model, but considering the simplicity of the model, the agreement between the calculated and observed composition is remarkably good.

Note that the theoretical quantity calculated is not exactly the same as the observational quantity measured. For the model, we are calculating the loss along the ion drift path for a particular starting energy. The ion energy increases as the ion drifts inward. For the data, we are calculating the ratio along the satellite trajectory, not the ion drift path, for a constant energy band that approximately covers the range of the calculated particle trajectory. A more accurate calculation would involve taking each point along the satellite trajectory and determining the charge exchange losses for the ions that drift to each point. However, despite the simplifying assumptions made, the main point is clear: the dominance of He^+ at the inner edge of the drift boundary is due to charge exchange.

Acknowledgments. The authors are indebted to the many unnamed individuals at UNH, MPE, LPARL, and UCB who contributed to the successful implementation of the TEAMS instrument and the FAST mission. The work at the University of New Hampshire was supported by the National Aeronautics and Space Administration under grant NAS5-31283.

References

Chen, A. J., Penetration of low-energy protons deep into the magnetosphere, J. Geophys. Res., *75*, 2458, 1970.

Chen, M. W., L. R. Lyons, and M. Schulz, Simulations of phase space distributions of storm time proton ring current, J. Geophys. Res., *99*, 5745, 1994.

Cowley, S. W. H., and M. Ashour-Abdalla, Adiabatic plasma convection in a dipole field: proton forbidden–zone effects for a simple electric field model, *Planet. Space. Sci.*, *24*, 821, 1976.

Ejiri, M., Trajectory traces of charged particles in the magnetosphere, J. Geophys. Res., *83*, 4798, 1978.

Ejiri, M., R. A. Hoffman, and P. H. Smith, Energetic particle penetrations into the inner magnetosphere, J. Geophys. Res., *85*, 653, 1980.

Fok, M. C., J. U. Kozyra, A. F. Nagy, C. E. Rasmussen, and G. V. Khazanov, Decay of equatorial ring current ions and associated aeronomical consequences, J. Geophys. Res., *98*, 19381, 1993.

Jordanova, V. K., J. U. Kozyra, G. V. Khazanov, A. F. Nagy, C. E. Rasmussen, and M. -C. Fok, A bounce-averaged kinectic model of the ring current ion population, Geophys. Res. Lett., *21*, 2785, 1994.

Kaye, S. M., M. G. Kivelson, Time dependent convection electric fields and plasma injection, J. Geophys. Res., *84*, 4183, 1979.

Kistler, L. M., F. M. Ipavich, D. C. Hamilton, G. Gloeckler, B. Wilken, G. Kremser, and W. Stüdemann, Energy spectra of the major ion species in the ring current during geomagnetic storms, J. Geophys. Res., *94*, 3579, 1989.

Kivelson, M. G. and D. J. Southwood, Local time variations of particle flux produced by an electrostatic field in the magnetosphere, J. Geophys. Res., *80*, 3528, 1975.

McIlwain, C. E., Plasma convection in the vicinity of the geosynchronous orbit, *Earth's Magnetospheric Processes*, ed. B. M. McCormac), D. Reidel, Dordrecht-Holland, 268, 1972.

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, 1998.

Rairden, R. L., L. A. Frank, and J. D. Craven, Geocoronal imaging with Dynamics Explorer, J. Geophys. Res., *91*, 13613, 1986.

Schultz, M. and J. B. Blake, Analytical estimates for gyration-, bounce-, and drift-averaged atmospheric densities experienced by geomagnetically trapped particles (abstract), *EOS Trans. AGU*, *71*, 1556, 1990.

Shirai, H., K. Maezawa, M. Fugimoto, T. Mukai, Y. Saito, and N. Kaya, Mono-energetic ion drop-off in the inner magnetosphere, J. Geophys. Res., *102*, 19873, 1997.

Smith, P. H., and N. K. Bewtra, Charge exchange lifetimes for ring current ions, . *Space. Sci. Rev*, *22*, 301, 1978.

Smith, P. H., and R. A. Hoffman, Direct observations in the dusk hours of the characteristics of the storm time ring current particles during the beginning of magnetic storms, J. Geophys. Res., it 79, 966, 1974.

Stern, D. P., The motion of a proton in the equatorial magnetosphere, J. Geophys. Res., it 80, 595, 1975.

Strangeway, R. J., and R. G. Johnson, Energetic ion mass composition as observed at near-geosynchronous and low altitudes during the storm period of February 21 and 22, 1979, J. Geophys. Res., it 89, 8919, 1984.

Volland, H., A Semiempirical model of large-scale magnetopsheric electric fields, J. Geophys. Res., it 78, 171, 1973.

C. W. Carlson, R. E. Ergun, J. P. McFadden, F. S. Mozer, and M. Temerin, Space Sciences Laboratory, University of California, Berkeley, CA 94720

C. A. Cattell, School of Physics and Astronomy, University of Minnesota, 116 Church St. SE, Minneapolis, MN 55455

R. C. Elphic, Los Alamos National Laboratory, MS D466, Los Alamos, NM 87545

D. Hovestadt and B. Klecker, Max-Planck-Institut für extraterrestrische Physik, D-85740 Garching, Germany

L. M. Kistler, E. J. Lund, E. Möbius, M. A. Popecki, and L. Tang, Space Science Center, Morse Hall, University of New Hampshire, Durham, NH 03824; Eric.Lund@unh.edu

D. M. Klumpar, W. K. Peterson, and E. G. Shelley, Lockheed Martin Palo Alto Research Laboratory, 3251 Hanover St., Palo Alto, CA 94304

R. F. Pfaff, NASA Goddard Space Flight Center, Code 696, Greenbelt, MD 20771

R. J. Strangeway, Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90024

(Received September 5, 1997; accepted December 22, 1997.)