The Fast Auroral SnapshoT (FAST) mission

C. W. Carlson
Space Science Laboratory, University of California, Berkeley

R. F. Pfaff, and J. G. Watzin
Goddard Space Flight Center, Greenbelt, MD

Abstract. The FAST satellite mission investigates plasma processes occurring in the low altitude auroral acceleration region, where magnetic field-aligned currents couple global magnetospheric current systems to the high latitude ionosphere. In the transition region between the hot tenuous magnetospheric plasma and the cold, dense ionosphere, these currents give rise to parallel electric fields, particle beams, plasma heating, and a host of wave-particle interactions. FAST instruments provide observations of plasma particles and fields in this region, with excellent temporal and spatial resolution combined with high quantitative accuracy. The spacecraft data system performs on-board evaluation of the measurements to select data "snapshots" that are stored for later transmission to the ground. New measurements from FAST show that upward and downward current regions in the auroral zone have complementary field and particle features defined by upward and downward directed parallel electric field structures and corresponding electron and ion beams. Direct measurements of wave particle interactions have led to several discoveries, including Debye-scale electric solitary waves associated with the acceleration of upgoing electron beams and ion heating, and the identification of electrons modulated by ion cyclotron waves as the source of flickering aurora. Detailed quantitative measurements of plasma density, plasma waves, and electron distributions associated with auroral kilometric radiation source regions yield a consistent explanation for AKR wave generation.

Introduction and Mission Overview

NASA's Fast Auroral SnapshoT (FAST) satellite is the second Small Explorer (SMEX) satellite selected by NASA to carry out rapid, low cost, and highly focused scientific investigations. Its primary mission is high spatial and temporal resolution measurements of charged particles and electric and magnetic fields within the low altitude auroral acceleration region. FAST was launched from the Western Test Range at Vandenberg Air Force Base on August 21, 1996 by a Pegasus-XL vehicle that placed FAST into an 83° inclination elliptical orbit of 350 km by 4175 km. As its orbital motion evolves throughout the year, the satellite crosses the auroral zones four times per orbit over a wide range of altitudes, local times, and seasons. The launch date was chosen to put FAST's initial orbit near the noon-midnight meridian with apogee over the northern auroral zone during the northern hemisphere winter of 1996-1997, when coordinated optical auroral observations from ground observatories and NASA's Polar satellite were planned.

The basic features of the mid-altitude auroral acceleration region were discovered by a succession of satellites, including ISIS, S3-3, Dynamics Explorer, Viking, and Akebono. These spacecraft identified the essential properties of inverted V electron beams, electrostatic shocks, ion beams and conics, density cavities, and numerous wave modes including auroral kilometric radiation, ion cyclotron waves and VLF auroral hiss and saucers. The time resolution of these measurements was typically limited first by the spacecraft spin period, and ultimately by telemetry capacity. In recent years, numerous sounding rocket experiments have revealed a broad range of important microphysical processes occurring in the aurora on short temporal and spatial scales [e.g., McFadden *et al.*, 1987; Vago *et al.*, 1992]. The Freja satellite, launched in 1992, carried out auroral investigations with temporal and spatial resolution similar to that of rockets, at altitudes as high as 1750 km. [Lundin, *et al.*, 1998]. The FAST mission was designed to make similar high time resolution microphysics measurements at higher altitudes, within the auroral acceleration region. These goals require wave measurements of electric fields up to the electron plasma frequency, and electron measurement resolution up to the ion cyclotron frequency. The corresponding horizontal spatial resolution for auroral structures is 10's of meters, which is shorter than typical electron inertia lengths or ion gyroradii.

FAST is dramatically different from previous auroral satellite missions. Not only do the FAST sensors acquire measurements several orders of magnitude faster than previous NASA missions, but the orientation of the instruments with respect to the magnetic field provides the first continuous measurements of particle pitch-angle distributions independent of spacecraft spin. The data collection strategy for FAST exploits the fact that auroral processes occur within limited latitudinal bands, typically 10-15 degrees wide circling the earth's magnetic poles, so high time resolution measurements need not be taken throughout the entire orbit. Instead, the instruments are programmed to take "snapshot" measurements of the auroral acceleration phenomena at rates as high as 8 Mbits/sec. The data are buffered in a mass memory until a ground station is available for reception. Furthermore, the FAST on-board computer includes multiple programmable modes so the sampling rates from each sensor may be optimized for each specific aspect of the investigation.

In accord with current NASA policy, the FAST mission has an open data policy. Survey data are made quickly available via the World Wide Web for event identification and survey studies. An important aspect of the FAST mission is its linkage to scientific studies planned by other groups in the space physics community. Observing "campaigns" have been carried out in which sounding rockets and dedicated ground-based and airborne all-sky cameras, auroral TV, and magnetometers are operated in conjunction with coincident FAST passes. In addition, FAST provides an important low-altitude complement to the International Solar-Terrestrial Physics (ISTP) program. In particular, the NASA Polar Mission images the aurora and obtains plasma measurements from its vantage point about 9 Earth radii above the polar regions.

The FAST Satellite and Instruments

The conceptual strategy behind the FAST satellite was to design a single unified scientific instrument comprising multiple

Paper number 98GL01592.
0094-8534/98/98GL-01592$05.00

particle and field sensors. A drawing of the FAST satellite showing the on-orbit configuration and major instrument locations is provided in figure 1. The spacecraft is a small, lightweight, orbit-normal spinner that provides the structure, power, thermal control, telemetry and command links, attitude control, and monitoring support for the science instruments. The satellite has a total mass of 191 kg, including 51 kg of science instruments, and carries no on-board propulsion. The diameter and height of the spacecraft body are both approximately 1m. The body-mounted solar array has 5.6 m^2 of solar cells that can supply 52 W of orbit average power to the spacecraft and instruments. The instruments draw 39 W of operating power, but consume an orbit average power of 19 W since they are only powered in the auroral regions. The spin rate and spin axis orientation are maintained by two magnetic torque coils. An S-band transponder provides uplink communications at 2 kbps and three high speed, selectable downlink rates of 900 kbps, 1.5 Mbps, or 2.25 Mbps.

The FAST science instruments include a complement of particle and fields sensors that are controlled by a single Instrument data processing unit. The following is a brief description of the main instrument systems.

Electrostatic Analyzers -ESAs. Ion and electron pitch-angle distributions are measured by a set of 16 "top hat" electrostatic analyzers. Particles enter the analyzers over a 180° field of view (FOV) where they are selected according to energy/charge, and then imaged onto a microchannel plate (MCP) detector followed by discrete anodes. The 180° FOV lies in the spacecraft spin plane, which is typically aligned within ~6° of the magnetic field when the spacecraft is in the auroral zones. The measured energy range is 4 eV to 30 keV for electrons and 3 eV to 25 keV for ions.

The analyzer heads are grouped in pairs on opposite sides of the spacecraft to obtain an unobstructed 360° field of view for each measurement. They are packaged into four ESA stacks located at 90° intervals around the spacecraft (see figure 1). Each ESA stack includes three Stepped ESA (SESA) analyzers that are operated as spectrographs to obtain the highest time resolution (1.7 ms) electron measurements in 16 pitch-angle bins. The remaining analyzer in each stack is configured as an ion or electron spectrometer (IESA or EESA), used to make high resolutions distribution measurements with 32 pitch-angle bins

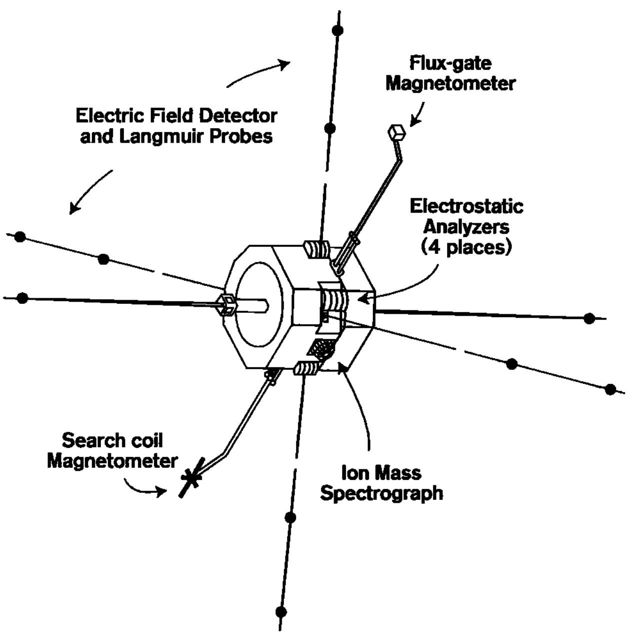

Figure 1. The FAST payload in flight configuration. The booms are shown much shorter than actual length.

every 70ms. The spectrometer analyzers include deflection plates that automatically steer their field of view to track the measured magnetic field direction.

Time-of-flight Energy Angle Mass Spectrograph - TEAMS. The TEAMS instrument is a high sensitivity, mass-resolving ion spectrometer with an instantaneous 360° x 8° field of view. It is designed to measure the full 3-dimensional distribution function of the major ion species (including H^+, He^+, He^{++}, O^+, O_2^+ and NO^+) during each half-spin period (2.5 s) of the spacecraft. Its energy range is between 1.2 and 12000 eV/charge and thus covers the core of all important plasma distributions in the auroral acceleration region. The detector consists of a "top hat" toroidal electrostatic analyzer followed by a time-of-flight analysis system and resolves 16 x 22.5° azimuthal angle bins.

Electric Field Sensors. The FAST electric fields instrument was designed to deploy ten spherical sensors, two each on four 28 m, radial wire booms and one each on two axial stacers (see figure 1). The spheres on each wire boom are located 28 m and 23 m from the spacecraft. The axial spheres are separated by 8 m tip-to-tip. Each sphere houses a preamplifier circuit. Although one of the wire booms did not deploy properly, the remaining three booms are sufficient to measure vector electric fields.

The electric field is derived from the voltage difference between two spheres. The spheres can also be operated in a Langmuir probe mode to measure plasma density. The fields signal processing spans a frequency band from DC to about 2 Mhz and has a dynamic range of 100 dB. Data products include continuous waveform capture at 2000 samples/s, burst waveforms as high as 2 x 10^6 samples/s, and spectra between 16 Hz and 2 Mhz. Dedicated on-board processing functions include; a) a high frequency resolution, tracking, spectrum analyzer, b) a wave-particle correlator, and c) a digital signal processor for fast Fourier transforms and cross-spectral analysis.

Magnetic Field Sensors. The FAST magnetic field instrument includes both a DC fluxgate magnetometer and an AC search-coil magnetometer. The fluxgate is a three-axis instrument using low noise ring core sensors that are mounted on a boom extending two meters from the spacecraft body.

The search-coil magnetometer uses a three-axis sensor system that provides AC magnetic field data over the frequency range 10 Hz to 2.5 kHz on two axes while the third axis response extends to 500 kHz.

Instrument Data Processor Unit (IDPU). The IDPU provides the sole instrument interface to the spacecraft and is the primary hub for instrument control, power conditioning, and data processing. It includes the data formatter, which interfaces to the individual sensors and performs high-speed data acquisition, compression, averaging, and packetizing the science data. The IDPU contains the high-density 1 Gbit (128 Mbyte) mass memory (solid state recorder) used to buffer all telemetry data. A single microprocessor manages all programmable aspects of the IDPU operation and evaluates on-board data quantities that trigger burst samples.

The co-investigators and their institutions are identified in Table 1. This table does not include many other scientists, students, engineers and technicians who have made essential contributions to the success of FAST.

Scientific Highlights

The FAST satellite has gathered observations which have significantly advanced our understanding of auroral acceleration physics and magnetosphere-ionosphere coupling. Many of the results presented in this issue result from auroral campaign activities that took place from January 1 through March 15, 1997 as part of the International Auroral Study. This campaign included collaboration with numerous other scientists who

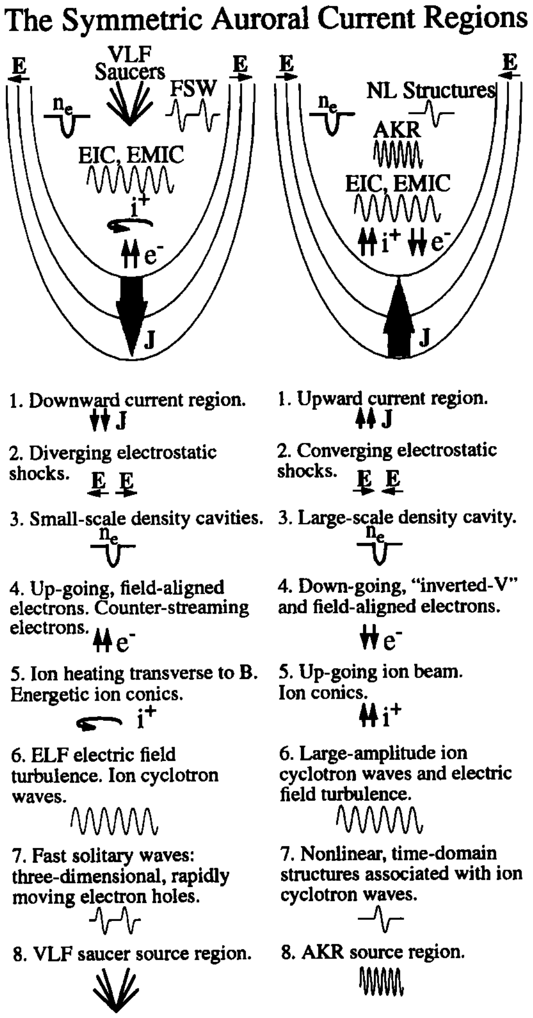

Figure 2. A schematic representation of the principle physical phenomena that characterize the upward and downward current regions in the aurora.

collected a wide range of observations from ground-based cameras, airborne instrumentation, sounding rockets, ionospheric radars, and magnetometer chains. The FAST science team activities were centered at the Poker Flat Research Range near Fairbanks, Alaska. This campaign fostered intense science discussion and was an ideal opportunity to optimize instrument operations and develop burst trigger strategies.

The Birkeland current system [e.g., Ijima and Potemra, 1978] serves to uniquely classify most auroral phenomena as characteristic of either the upward or downward auroral current regions. The visible aurora is the most obvious signature of the upward current region, and it motivated the earliest *in situ* measurements made from sounding rockets and satellites. These measurements led to the discovery of other properties of this region, such as upgoing ion beams, auroral kilometric radiation and auroral density cavities. Properties of the downward current system have been less explored. The initial results from FAST show that this region also exhibits distinctive particle and field signatures that are complementary to those found in the region of visible aurora, suggesting that this region might be considered the "inverse aurora". Figure 2 presents a summary diagram of the plasma properties that characterize the two regions. Many of the papers in this special section address the defining properties of these two regions, as summarized below.

The Upward Current Regions. The right half of Fig. 2 illustrates the region that is associated with the visible aurora, containing upward field-aligned currents, convergent electric fields (electrostatic shocks) and parallel potential drops that accelerate magnetospheric electrons downward into the atmosphere to create visible aurora. FAST data give quantitative agreement between the current carried by these auroral electron fluxes and corresponding magnetic deflections, demonstrating that hot auroral electrons account for virtually all of the field-aligned current in the arcs [Elphic *et al.*, 1998; McFadden *et al.*, 1998a,b]. The most compelling evidence for the quasi-static potential model of auroral acceleration is found when parallel potential structures extend to altitudes below the satellite. These regions are uniquely identified by the intense convergent electric fields that coincide with the edges of upgoing ion beams. FAST observations demonstrate detailed quantitative agreement between the measured electric potentials and the ion beam energies [McFadden *et al.*, 1998a; Ergun, *et al.*, 1998c], leaving no doubt that parallel potential drops are a dominant source of auroral particle acceleration. Mass composition measurements also show that additional physical processes lead to species-dependent energy differences in the acceleration of upgoing ion beams [Moebius, *et al.*, 1998].

Intense ion cyclotron waves are generated within these "inverted-V" electron regions [Cattell *et al.*, 1998], and Chaston *et al.*, [1998] show that the Poynting flux carried by these waves can be as large as 10 % of the associated electron energy flux. Direct measurements of electron modulations caused by ion cyclotron waves [McFadden *et al.*, 1998a] confirm the model suggested by Temerin *et al.*,[1986] that this process is responsible for modulating electrons that create flickering aurora. Observations of preferential heating of He^+ conics associated with ion cyclotron waves [Lund, *et al.*, 1998] provide another example of detailed verification of theoretical models by FAST measurements.

FAST results provide several important advances toward understanding auroral kilometric radiation. Analysis of the properties of VLF waves in the ion beam regions provides evidence of very low plasma density [Strangeway, *et al.*, 1998], in agreement with earlier observations [Benson and Calvert, 1979; Persoon, *et al.*, 1988]. Although these density cavities had previously been identified as source regions of auroral kilometric radiation [Benson and Calvert, 1979], the FAST observations identify several important new properties of these source regions. The observed densities of the hot auroral "inverted V" electrons show good agreement with the combined densities of the observed magnetospheric ions and upgoing beam ions [McFadden *et al.*, 1998b]. Ergun *et al.*, [1998c] find that the low frequency cutoff of AKR extends below the cold electron cyclotron frequency and show good agreement if the cyclotron frequency includes the relativistic correction corresponding to the

Table 1. Fast Co-Investigators

University of California, Berkeley
Dr. Charles W. Carlson (Principal Investigator)
Dr. Robert E. Ergun, Dr. James P. McFadden
Professor Forrest S. Mozer, Dr. Michael A. Temerin
University of Minnesota
Professor Cynthia A. Cattell
Los Alamos National Laboratory
Dr. Richard C. Elphic
Lockheed Space Science Laboratory
Dr. David M. Klumpar, Dr. William K. Peterson
Dr. Edward G. Shelley
University of New Hampshire
Professor Eberhard Möbius
University of California, Los Angeles
Dr. Robert J. Strangeway
NASA/Goddard Space Flight Center
Dr. Robert F. Pfaff (Project Scientist)

observed hot electron energies. These results demonstrate that the density cavities are devoid of cold plasma, which has an important implication for AKR wave generation and growth. Using the dispersion relation for these measured plasma conditions, Delory *et al.*, [1998] show that the positive slope over a large portion of the observed "horse-shoe" shaped electron distribution function will contribute to AKR growth.

The Downward Current Regions. The left half of Fig. 2 illustrates plasma signatures of the "inverse aurora" in the downward current region. In these regions, FAST observations frequently show intense upgoing beams of magnetic field-aligned electrons with energies up to several keV, which are the most intense electron fluxes found in the auroral region [Carlson *et al.*, 1998]. Whereas the precipitating auroral electrons are accelerated by parallel electric fields in *converging* electrostatic field structures, these upward accelerated electron beams are found in *diverging* electric field structures. As with the ion beams in converging shocks, the agreement between the measured electric potentials in the diverging field structures and the observed energies of the electron beams confirms that these electron beams are accelerated by parallel potential structures. The electron beams are also clearly associated with VLF saucers, as postulated by Gurnett *et al.*, [1972] and are also accompanied by deep density cavities and the most energetic ion conics found in the auroral region [Carlson, *et al.*, 1998]. Ergun *et al*.,. [1998c] present the discovery of large amplitude, three dimensional electric "solitary wave" structures that are occasionally found in the upgoing electron beams. These Debye-scale structures are positively charged electron "holes" that move with the beam velocity, and contain potential wells of 10's to 100's of volts. These solitary structures may play a role in supporting the parallel potentials that accelerate the beams, and appear to be a very effective source of ion heating.

The parallel electric fields that accelerate upgoing electrons also inhibit plasmasheet electron precipitation. Although the upgoing beams are seldom found at altitudes below 2000 km, the diverging field signature and occasional beams have been observed at lower altitudes by Freja. Marklund *et al.*, [1994] propose these structures as the source of the dark regions in diffuse aurora that have been identified as "black aurora".

Other regions and Correlative Studies. Observations by FAST are also gathered in other regions than the nightside auroral zone, which have led to studies of particle acceleration in the cusp [Pfaff, *et al.*, 1998] and properties of drifting ions at the inner edge of the plasmasheet [Kistler *et al.*, 1998]. FAST has also contributed to collaborative studies with other spacecraft and ground-based observations. For example, the auroral campaign operations included ground-based and aircraft-borne camera observations of auroral structures that were compared with the *in situ* electron energy fluxes [Stenbaek-Nelson *et al.*, 1998]. Other collaborative work included studies of magnetosphere-ionosphere coupling by comparing FAST and Geotail measurements [Sigsbee *et al.*, 1998], and studies of solar wind plasma entry at the cusp from simultaneous observations by the FAST and Polar satellites [Peterson *et al.*, 1998].

In summary, the FAST mission is accomplishing major advances toward our understanding of auroral physics. New technological advances were exploited to create a highly capable, light-weight scientific payload at low cost. These instruments have achieved accurate quantitative field and particle measurements with unprecedented spatial and temporal resolution that facilitate the understanding of fundamental plasma processes.

Acknowledgments The authors are indebted to the FAST science and technical team members for a successful mission. This research was conducted under NASA grant NAG5-3596.

References

Benson, R. F., and W. Calvert, ISIS 1 observations of ion energization and outflow in the high latitude magnetosphere, *Space Sci. Rev., 80*, 27-48, 1979.

Carlson , C. W., *et al*, FAST observations in the downward auroral current region: Energetic upgoing electron beams, parallel potential drops, and ion heating, *Geophys. Res. Lett.*, this issue, 1998.

Cattell, C., *et al.*, The association of electrostatic ion cyclotron waves, ion and electron beams and field-aligned current: FAST observations of an auroral zone crossing near midnight, *Geophys. Res. Lett.*, this issue, 1998.

Chaston, C. C., *et al.*, Characteristics of electromagnetic proton cyclotron waves along auroral field lines observed by FAST in regions of upward current, *Geophys. Res. Lett.*, this issue, 1998.

Delory G. T., *et al.*, FAST observations of electron distributions within AKR source regions, Geophys. Res. Lett., this issue, 1998.

Elphic, R. C., *et al.*, The auroral current circuit and field-aligned currents observed by FAST, *Geophys. Res. Lett.*, this issue, 1998.

Ergun, R. E., *et al.*, FAST satellite observations of electric field structures in the auroral zone, *Geophys. Res. Lett.*, this issue, 1998a.

Ergun, R. E., *et al.*, FAST satellite wave observations in the AKR source region, *Geophys. Res. Lett.*, this issue, 1998b.

Ergun, R. E., *et al.*, FAST satellite observations of large-amplitude solitary structures, *Geophys. Res. Lett.*, this issue, 1998c.

Gurnett, D. A., and L. A. Frank, VLF hiss and related plasma observations in the polar magnetosphere, *J Geophys. Res., 77*, 172-190, 1972.

Ijima, T., and T. A. Potemra, Large-scale characteristics of field-aligned currents associated with substorms, *J. Geophys. Res.*, 83, 599, 1978.

Kistler, L. M., et. al., FAST/TEAM observations of charge exchange signatures in ions mirroring at low altitudes, *Geophys. Res. Lett.*, this issue, 1998.

Lund, E. J., *et al.*, FAST observations of preferentially accelerated He^+ in association with auroral electromagnetic ion cyclotron waves, *Geophys. Res. Lett.*, this issue, 1998.

Marklund, G., L. Blomberg, C. G. Falthammar, and P. A. Lindqvist, On intense diverging electric fields associated with black aurora, *Geophys. Res. Lett., 21*, 1859, 1994.

McFadden, J. P., C. W. Carlson, M. H. Boehm, and T. J. Halliman, Field-aligned electron flux oscillations that produce flickering aurora, *J. Geophys. Res. 92*, 11133, 1987.

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

McFadden, J. P., *et al.*, Spatial structure and gradients of ion beams observed by FAST, *Geophys. Res. Lett.*, this issue, 1998b.

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

Persoon, A. M., *et al.*, Electron density depletions in thenightside auroral zone, *J. Geophys. Res., 93*, 1871-1895, 1988.

Peterson, W. K., *et al.*, Simultaneous observations of solar wind plasma entry from FAST and POLAR, *Geophys. Res. Lett.*, this issue, 1998.

Pfaff, P., et. al., Initial FAST satellite observations of acceleration processes in the csup, *Geophys. Res. Lett.*, this issue, 1998.

Sigsbee, K., *et. al.*, FAST-geotail correlative studies of magnetosphere-ionsphere coupling in the nightside magnetosphere., *Geophys. Res. Lett.*, this issue, 1998.

Stenbaek-Nielsen, H. C., *et al.*, Aircraft observations conjugate to FAST auroral arc thicknesses, *Geophys. Res. Lett.*, this issue, 1998.

Strangeway, R. J., *et al.*, FAST observations of VLF waves in the auroral zone: evidence of very low plasma densities, *Geophys. Res. Lett* this issue, 1998.

Temerin, M., J. P. McFadden, M. Boehm, C. W. Carlson, and W. Lotko, Production of flickering aurora and field-aligned electron fluxes by electromagnetic ion cyclotron waves, *J. Geophys. Res.91*, 5769, 1986.

Vago J. L., *et al.*, Transverse ion acceleration by lower hybrid waves in the topside auroral ionspere, *J. Geophys. Res.*, 97, 16935-16957, 1992.

C. W. Carlson, Space Sciences Laboratory, University of California, Berkeley, CA 94720. (e-mail: cwc@ssl.berkely.edu)

R. Pfaff, NASA Goddard Space Flight Center, Code 696, Greenbelt, MD 20771. (e-mail: rob.pfaff@gsfc.nasa.gov)

J. G. Watzin NASA Goddard Space Flight Center, Code 696, Greenbelt, MD 20771. (e-mail: jim.watzin@gsfc.nasa.gov)

(Received April 14, 1998; revised May 6, 1998; accepted May 7, 1998.)