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FAST observations of discrete electrostatic waves in association with down-going ion beams in the auroral zone

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[1] Ion beams flowing downward, into the ionosphere, along the Earth's magnetic field have frequently been observed by the FAST satellite in the auroral zone. These discrete downward moving ion beams (DFI) have been characterized by *Klumpar et al.* [1999] who interpreted the horseshoe-shaped distributions as being consistent with acceleration in a parallel potential drop above the satellite, followed by motion into a region of increased magnetic field strength. The down-flowing ion beams are associated with an intense narrowband electrostatic emission at the lower hybrid frequency, polarized perpendicular to the geomagnetic field. Hydrogen cyclotron harmonics both above and below the lower hybrid frequency are also very common. These are the first observations of down-flowing ions and associated waves outside of the cusp, and the physical mechanism producing the ions is very different from the one associated with cusp ion injections. The DFI events that had a monotonic increase in energy were associated with a clear field-aligned current signature. The DFI densities were usually ~5–10/cc, whereas the background plasma had densities up to 100/cc. The wave and DFI observations are consistent with linear dispersion relation calculations and simulations with ion ring distributions that show that the instability is due to coupling of the ion Bernstein waves to the lower hybrid wave. In addition, for a few events, electrostatic ion cyclotron waves were observed. Such waves are usually associated with up-going ion beams and have not previously been seen with DFI, which have a very different shape in the distribution. *INDEX TERMS:* 2471 Ionosphere: Plasma waves and instabilities; 2704 Magnetospheric Physics: Auroral phenomena (2407); 2772 Magnetospheric Physics: Plasma waves and instabilities; 7867 Space Plasma Physics: Wave/particle interactions; *KEYWORDS:* aurora, ion beams, lower hybrid waves, downward field-aligned current

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1. Introduction

[2] The association of various types of accelerated particle distributions, such as up-flowing O^+ and H^+ beams, inverted-V electron distributions, and up-going electron beams, with plasma waves has received much study, both experimental and theoretical. Emissions at and near harmonics of the ion cyclotron frequencies have been of particular interest in the auroral zone, due primarily to their proposed role in ion heating. The association of electrostatic ion cyclotron waves with up-flowing ion beams (UFI) was first identified by *Kintner et al.* [1979] using data from the S3-3 satellite. ISEE 1 [*Cattell et al.*, 1991], Viking [*Andre et al.*, 1987], Polar [*Mozer et al.*, 1997], and FAST [*Cattell et al.*, 1998] have also provided data on the correlation of UFI and electrostatic ion cyclotron (EIC) waves (hydrogen, oxygen, and helium cyclotron frequency waves have been observed). *Kintner* [1980] distinguished between the occurrence of EIC waves and waves at higher harmonics (>3) of the cyclotron frequency and suggested that the positive perpendicular velocity derivative of the distribution function of ion conics could drive the higher harmonics. *Gorney* [1983], using S3-3 data, and *Peterson* [1984], using DE 1 data, showed that the observed positive slope in the ion distribution was due to down-flowing ions in the cusp rather than to ion conics. Waves with similar features in Viking data at higher altitudes were also described by *Koskinen et al.* [1987], who suggested that the free energy source could be the loss cone feature in the high-energy plasma sheet

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ions. In addition, *Kintner et al.* [1991] described rocket observations of ion cyclotron harmonic structure embedded in VLF hiss which they showed was explainable by cyclotron damping. Observations of lower hybrid emissions with structure at hydrogen cyclotron harmonics in association with cusp ion injections have also been reported from FAST data [*Pfaff et al.*, 1999].

[3] Although observations of down-going ion beams in the auroral zone have been reported previously from S3-3 data, it is only recently, utilizing data from the FAST satellite ion detectors which simultaneously measure all pitch angles, that it has been recognized that down-flowing ion beams (DFI) are a common feature of the equatorward portion of the auroral zone [*Klumpar et al.*, 1999]. Klumpar et al. have presented statistical studies of the occurrence probability of DFI in local time, latitude, and altitude, and of their characteristics. They have shown that the ions are predominantly hydrogen, have a structured energy spectrum, and are usually narrowly confined in latitude. The observed shape of the distributions is frequently consistent with acceleration in a parallel electric field, followed by motion into a region of increased magnetic field strength, resulting in a horseshoe-shaped distribution. This process is the same one that produces the observed auroral electron beam distributions. Under the influence of the magnetic mirror force as they move to lower altitudes, the electron beams evolve into horseshoe-shaped distributions due to conservation of the first adiabatic invariant. The physical mechanism that initially produces the down-flowing ion beams described herein is distinctly different from that of down-flowing ions in the cusp, which are a result of magnetopause reconnection.

[4] Horseshoe-shaped ion distributions are most easily modeled by an ion ring in velocity space. *Kintner* [1980] examined the dispersion relation for flute mode waves excited by a cold ion ring in a warm magnetized plasma to explain their observation of higher cyclotron harmonics. *Cattell and Hudson* [1982] extended the study to the more realistic case of a warm ion ring using a dispersion code developed by *Lee and Birdsall* [1979] for cold rings. They found that the unstable modes were at the lower hybrid frequency, and, for more intense beams, additional emissions associated with harmonics of the ion cyclotron frequency were also observed above the lower hybrid frequency. *Roth and Hudson* [1983] performed simulations of the instability, and *Roth and Hudson* [1985] examined the effects of heavy ions to address the more complex power spectra seen in the cusp.

[5] In this paper we present results of a study of the waves associated with 19 DFI events observed by the FAST satellite. The data sets are described in section 2. Several individual events are discussed in section 3. Characteristics of the 19 events examined and comparisons with previously published theoretical calculations of the dispersion relations and simulations for ion ring distributions are given in section 4.

2. Instrumentation and Data Sets

[6] The data utilized in this study were obtained by the FAST satellite during traversals of the auroral zone, in both the Northern and Southern Hemispheres, over altitudes ranging from ~2400 to 4200 km. From the very large database of DFI events identified by *Klumpar et al.* [1999], 20 were selected for this study to provide a range of altitudes and local times. There were six events in the 2100–2400 MLT sector, six in the 0000–0300 MLT sector, five in the 0300–0600 MLT sector, and three in the 0600–0800 MLT sector. Three events were below 2000 km, and six were above 4000 km. Note that these 20 DFI events were selected without examining the wave data. Wave data were not available for one event. The onboard calculated electric and magnetic field VLF spectra (0–16 kHz) comprise the primary observations for the wave study because the DFI events usually occurred at latitudes where the satellite was in slow survey mode (see *McFadden et al.* [2001] for a discussion of modes). In this mode each spectrum is averaged over 4 s, so polarization information cannot be obtained. For events for which all or part of the DFI was in fast survey, polarization can be determined. The higher time resolution burst mode data were also examined for the several cases when bursts were triggered at the time of the DFI event. The magnitude and direction of the field-aligned currents were obtained from the fluxgate magnetometer. *Ergun et al.* [2001] describe the details of the field instrumentation. Particle measurements from the electron (EESA) and ion (IESA) electrostatic analyzers and the ion mass spectrometer (TEAMS) were utilized to determine the characteristics of the particle distributions for comparisons with the wave characteristics and to theoretical studies. Details of the electron and ion detectors are given by *Carlson et al.* [2001], and details of the ion mass spectrometer are given by *Klumpar et al.* [2001].

3. Event Examples

[7] Figure 1 presents an example of a down-flowing ion event (DFI) which occurred on 31 December 1996 (during orbit 1427) at a magnetic local time of ~1.7 MLT, an invariant latitude of ~65°, and an altitude of ~3000 km. We present the particle and fields data for ~70 s with the ion energy flux (integrated over all pitch angles) in Figure 1a; the ion pitch angle spectrogram (integrated over all energies) in Figure 1b; the electron energy flux in Figure 1c; the electron pitch angle spectrogram (integrated over all energies) in Figure 1d; the electric field spectral power density as a function of frequency and time between 0.1 and 16 kHz in Figure 1e; and the perturbation in the magnetic field, in field-aligned coordinates in Figure 1f. The down-flowing ions, observed from ~0910:10 to 0910:50, had a peak energy increasing from ~10 eV and to ~2 keV, and, although peaked at 0°, were broad in pitch angle (a horseshoe-shaped distribution with a weak beam superimposed; see Figure 1i). Although the low-energy edge of the DFI increased monotonically with latitude, the structure at the high-energy edge is more complicated. The electron energy flux was weak until just after the ion event when an intense up-flowing electron beam (UFE) occurred with an energies extending up to ~1 keV. *Klumpar et al.* [1999] have suggested that this commonly observed association of DFI with UFE indicates that the satellite has moved from an altitude below the parallel potential to one above the parallel potential. Ion conics were observed at the time of the up-flowing electron beam, as is typically seen in the FAST data set [*Carlson et al.*, 1998a, 1998b]. Plasma sheet ions can

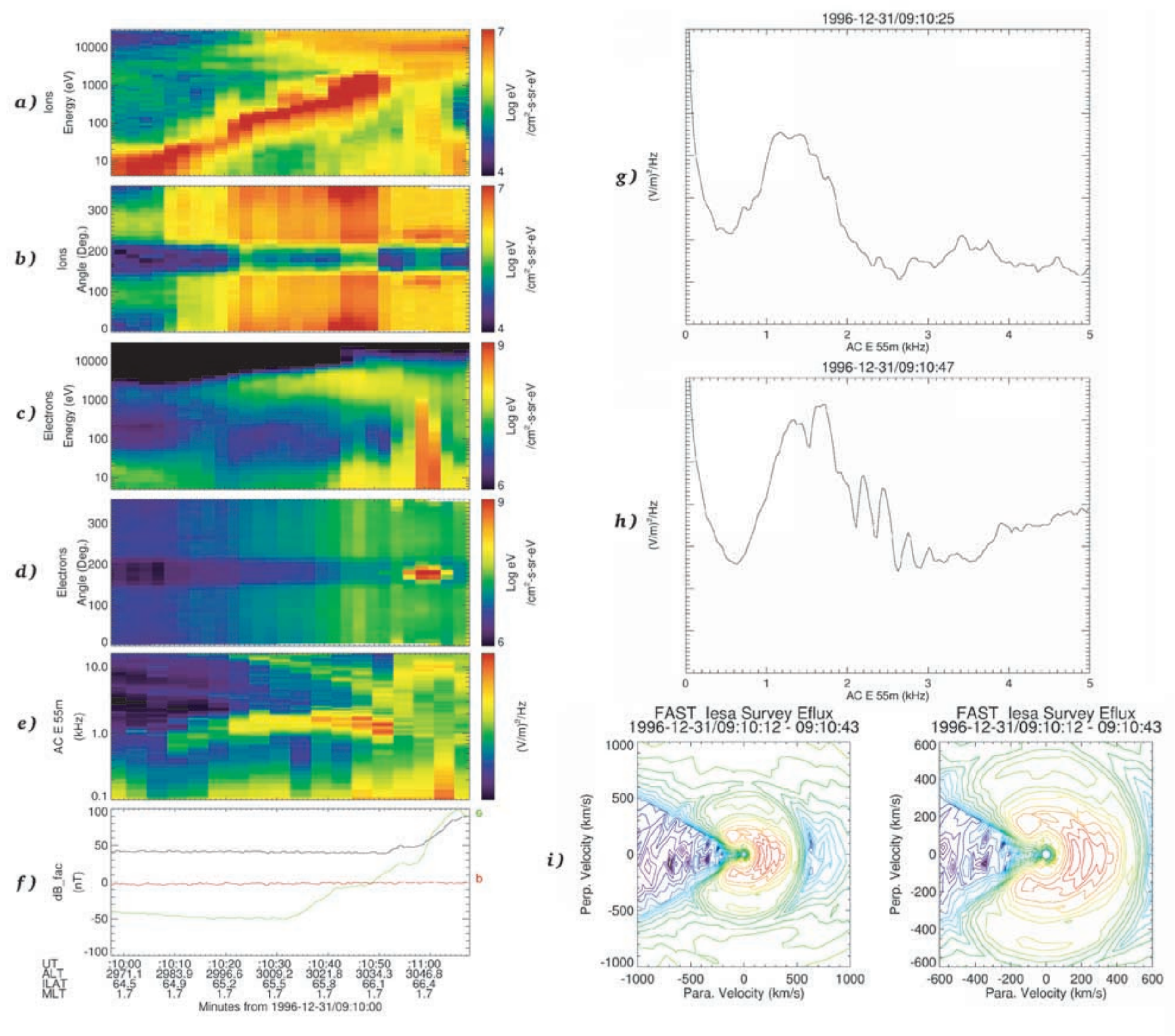

Figure 1. The particle and fields data for ~70 s on 31 December 1996 (orbit 1427). The ion energy flux (integrated over all pitch angles) is shown in Figure 1a; the ion pitch angle spectrogram (integrated over all energies) is shown in Figure 1b; the electron energy flux is shown in Figure 1c; the electron pitch angle spectrogram (integrated over all energies) is shown in Figure 1d; the electric field spectral power density as a function of frequency and time between 0.1 and 16 kHz is shown in Figure 1e; and the perturbation in the magnetic field is shown in Figure 1f, in field-aligned coordinates; green refers to eastward, black refers to outward, and red refers to field-aligned directions. Figures 1g and 1h show the wave power at two times during the event. The ion energy flux versus $v_\perp$ and $v_\parallel$ over two different velocity ranges are plotted in Figure 1i.

also be seen from ~0910:30 onward. The eastward (green) component of the magnetic field perturbation (Figure 1f) indicated a net field-aligned current flowing into the ionosphere in association with the last half of the DFI and with the up-going electron beam; however, there is no discernable signature of a current associated with the low-latitude, lower-energy portion of the DFI event.

[8] The association of the DFI with waves can be seen by comparing Figures 1a, 1b, and 1e. During the period when the DFI is observed at energies above ~20 eV, a narrow emission near 1–2 kHz, corresponding to the lower hybrid frequency (f_{lh}), can be seen in the electric field. The lack of magnetic signatures in the ac magnetic data (not shown) indicates that the waves are electrostatic. Since the hydrogen cyclotron frequency (f_{cH}) was ~0.28 kHz, the emissions occurred at ~4–7 f_{ci}. Note that the waves which descend in frequency from 16 kHz starting at ~0910:20 are due to a VLF saucer associated with the up-flowing electron beam (see R. Ergun et al. (FAST observations of VLF saucers, submitted to *Physics of Plasmas*, 2002) for a discussion of this phenomena in the FAST data set). Details of the spectrum can be seen in Figures 1g and 1h, which show the wave power at two times (indicated by arrows) during the event. In addition to the main peak, harmonic

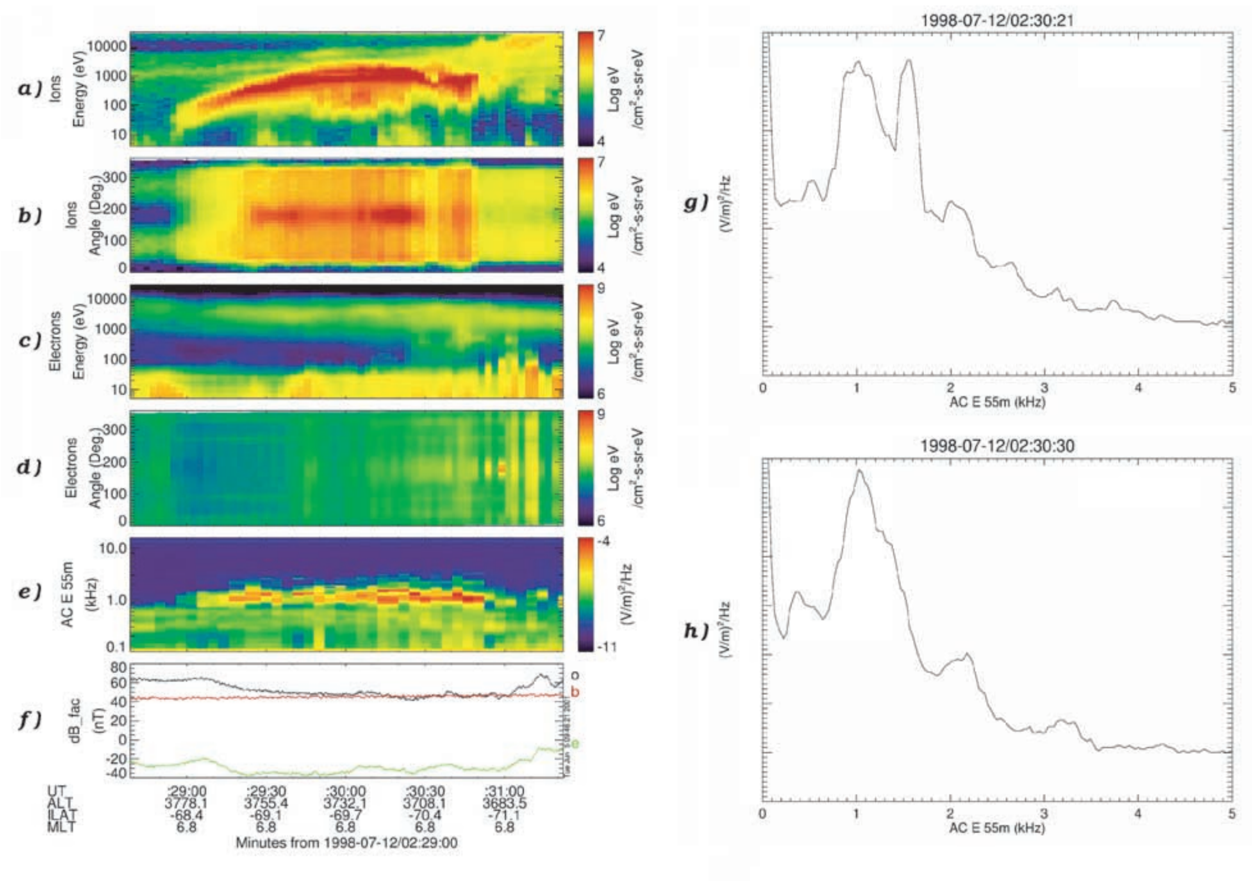

Figure 2. The ion, wave, electron, and magnetic field perturbation data on 12 July 1998 (orbit 7463) in the same format as Figure 1.

structure can be seen, most distinctly during the last part of the event when the DFI was most energetic and there was a larger heavy ion component (O^+ and He^+). The most intense waves also occurred at this time.

[9] Figure 1i plots the ion energy flux over two different velocity ranges to show the detailed shape of the ion distribution for this event. It can be seen that the ion beam has spread out to form a ring in velocity space, as would be expected due to conservation of the first adiabatic invariant as a field-aligned ion beam moved into a region of increased magnetic field strength. Estimates for the ratio of the ion beam (denoted "ring") density to the background density (n_r/n_p) vary from ~0.02 to 0.1 during the DFI. Ring densities were estimated by integrating the ion distribution over the appropriate energy range (which changed through the event), while the background density was estimated by assuming that the main peak in the waves was at the lower hybrid frequency. The measured electron density was always below that of the measured ions, implying that the background electrons were cold (either below the EESA threshold or within the energy band contaminated by photoelectrons). For low-altitude auroral parameters, this type of distribution has been shown to be unstable to electrostatic waves near the lower hybrid frequency, as discussed below in section 4.

[10] Characteristics of waves and particles for a second case (orbit 7463 on 12 July 1998, in the Southern Hemisphere at 6.8 MLT and ~69 ILAT) are shown in Figure 2. Note that because this is a Southern Hemisphere event, down-flowing ions are observed at a pitch angle of 180°. Figures 2a and 2b (ion energy and pitch angle spectrograms) show a region of intense down-going ions with peak energy increasing with latitude from ~100 eV to ~3 keV. The DFI event is embedded in higher-energy ions that are trapped at the low-latitude side of the DFI and have a loss cone distribution on the high-latitude side. The electron energy and pitch angle spectrograms (Figures 2c and 2d) indicate the presence of plasma sheet electrons throughout this interval and of low-energy (200 eV up-flowing electrons poleward of the DFI). There was either no current or a very weak current during the DFI (see magnetic field perturbation in Figure 2f). As in the previous event, at the time of the DFI, a narrow emission (Figure 2e) occurred near 1 kHz, or at ~5 f_{ci}, since at this time the hydrogen cyclotron frequency was ~0.2 kHz. Note that the waves at frequencies of ~300–600 Hz are not due to the DFI since they began well before the ion event. The two wave spectra (Figures 2g and 2h) show clearer harmonic structure than in the previous event. The ion distribution function again formed a ring, although in this case the down-going beam is stronger near 180°.

[11] A more complex event on 30 January 1997 (orbit 1751) at 22.2 MLT and ~65 ILAT in the Northern Hemisphere (i.e., down-going ions at 0°) is presented in Figure 3 (in same format as Figure 2). Although in this event the

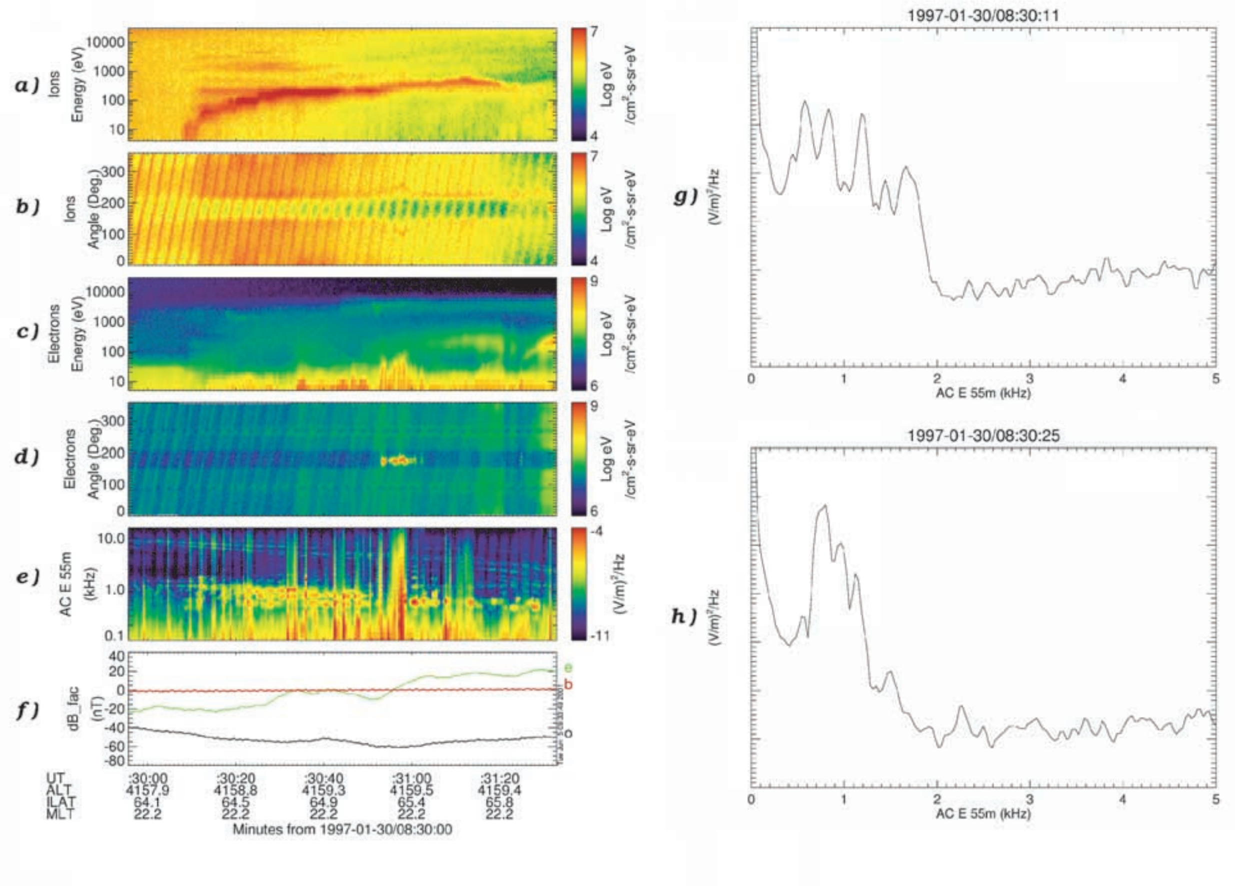

Figure 3. The data on 30 January 1997-1/30 (orbit 1751) in the same format as Figure 2.

energy of the down-flowing ion beam (Figure 3a) increased with latitude (as in the two events described above), there were much larger background ion fluxes, and more structure in the high energies at the low-latitude edge of the beam, including the existence of several discrete energy bands. There were also low energy up-going electron beams (Figures 3d and 3e) from ~0830:45 to 0831 UT. In this event, the emissions are much more structured, with clear hydrogen gyrofrequency harmonic banding (f_{cH} < 180 Hz). There is also evidence for electrostatic hydrogen cyclotron (EHC) waves (at approximately f_{cH}). EHC waves have not previously been seen in association with down-flowing ion beams and are usually observed in association with up-flowing ion beams [*Kintner et al.*, 1979; *Cattell et al.*, 1998]. In addition, there are low-frequency broadband waves, the most intense of which (at 0830:58 and before) are associated with up-flowing electron beams (see Figures 3c and 3d). It is interesting that the saucer emissions (at high frequencies) are intensified at the time of the DFI. This suggests a possible coupling between the saucer emission and the Bernstein waves, with the ion ring providing free energy to allow additional wave growth.

4. Comparisons With Theory, and Conclusions

[12] For all 19 DFI events in this study, electrostatic waves peaked at or near the lower hybrid frequency occurred in the region of the down-flowing ions. There was usually (15 events) harmonic structure associated with the hydrogen gyrofrequency, above and/or below the lower hybrid frequency. For all cases where the time resolution of the VLF spectra was fast enough to examine polarization, the waves were polarized perpendicular to the geomagnetic field. In addition, there was evidence for electrostatic ion cyclotron waves during four DFI events, including two of the three events below 2000 km. In eight events (an example is shown in Figure 2), there were weak discrete emissions at or below the lower hybrid frequency prior to the DFI which that may be driven by the $\partial f/\partial v_\perp$ of the simultaneously observed double loss cone distributions in the ions.

[13] The DFI events all had the shape of a partial ring in velocity space, some of which had enhancements in the parallel direction. Several events had multiple rings, in some cases due to heavy ions in the down-flowing beam and in other cases because there were several discrete energy bands in the DFI. The rings were usually high density, ~5/cm^3, with values up to ~15/cm^3 (determined by integrating the ion distribution over the appropriate energy range). The large DFI densities are consistent with relatively local acceleration of an ionospheric source population. With the exception of the four lowest-altitude events, the low-latitude edge of all DFI events was associated with a trapped (double loss cone) distribution in the energetic ions, and

there were up-flowing electrons, usually at the high-latitude edge. The high-energy (plasma sheet) population densities were usually a few tenths per cubic centimeter. The events which had a monotonic increase in energy with latitude were associated with a downward field-aligned current (at least in the more intense energetic portion of the DFI), whereas the events with a more complex shape in energy versus latitude were rarely associated with a single, clear field-aligned current signature. Total plasma density (estimated from the wave data by assuming that the main peak was at the lower hybrid frequency) varied from $\sim$25 to 200/cm^3, in agreement with the values reported by *Kletzing et al.* [1998] at these altitudes and latitudes. These densities were larger than the electron density (obtained by integrating the electron distributions), implying that the electrons were cold (below the lowest measured energy), consistent with the observations of *Kletzing et al.* [1998] that the electron temperature was $\sim$5 eV.

[14] The characteristics of the DFI and waves are consistent with theories of electrostatic instabilities due to warm ion rings in velocity space [*Cattell and Hudson*, 1982; *Roth and Hudson*, 1983, 1985], using the measured ring and background densities and temperatures. Studies of the linear dispersion relation for flute modes ($k_{||} = 0$) indicate that the instability is due to coupling of the plasma lower hybrid mode with the plasma ion Bernstein mode that is closest to it. The linear instability occurs at the lower hybrid frequency for weak beams, small (n_r/n_p). For higher-density beams, linear instability can, in addition, occur at harmonic bands separated by ($f_{ci}/2$) due to distortion of the Bernstein modes. The instability is driven by the positive slope in the ion distribution perpendicular to the magnetic field and saturates due flattening of the slope by quasi-linear diffusion. The growth rate increases with (n_r/n_p) and $(f_{pi}/f_{ci})^2$. The observed events have a range of $(f_{pi}/f_{ci})^2$ from $\sim$10 to $\sim$140 and (n_r/n_p) from $\sim$0.02 to $\sim$0.3. This is within the range of the parameters examined in the theoretical studies cited above, but extends to higher values of both $(f_{pi}/f_{ci})^2$ and (n_r/n_p), so the linear growth rates for these events are likely to be larger than the cases modeled previously. This may result in the additional harmonics being linearly unstable. The range of unstable wave numbers depends on the above parameters, as well as on the ratio of the DFI (ring) energy to the background ion temperature. The unstable wave numbers are those such that $d(J_n^2)/dx < 0$, where J_n is the Bessel function of $[k_\perp(v_r/2(f_{cH}))$.

[15] The order n of most importance is the harmonic number closest to the lower hybrid frequency. For a given value of $(f_{pi}/f_{ci})^2$, the larger the ring energy, the smaller the unstable $k_\perp$. When the lower hybrid frequency or $(f_{pi}/f_{ci})^2$ increases enough for the next higher harmonic to be important, the unstable modes shift to larger $k_\perp$. The resulting unstable wave numbers have $k_\perp(v_r/2(f_{cH})) < 1$. Inclusion of heavy ions (oxygen, helium) in either the ring and/or the background plasma increases the number of unstable modes because the ion Bernstein modes of each species can couple to the lower hybrid wave [*Roth and Hudson*, 1985], and the heavy ion modes are more unstable.

[16] The observations of the spectra described herein are also consistent with the simulations of *Roth and Hudson* [1983, 1985]. They showed that ion cyclotron harmonics both above and below the main (approximately lower hybrid) frequency are nonlinearly excited. Comparison of their spectra with the observations herein shows many similarities. A detailed comparison of the observed spectra to theory, however, will require an improved model of the observed ring distributions (which are usually more intense in the field-aligned direction than the simple ring model used in published studies) in the linear dispersion solver, as well as include the observed composition and ring and background densities and temperatures. Correlation of the regions of instability determined by an improved linear dispersion solver with the observed harmonic structure will allow one to infer whether or not nonlinear interactions are important for the DFI. If a harmonic observed in the data is not observed in the linear dispersion relation, it is likely to be due to a nonlinear interaction as observed by *Roth and Hudson* [1983, 1985].

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