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Explanation for the simultaneous occurrence of bipolar structures and waves near ion-cyclotron harmonics in the auroral ionosphere

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Abstract. In the downward current region of the auroral ionosphere, the FAST spacecraft has observed bipolar electrostatic structures on Debye length scales and waves at frequencies between the H^+ ion cyclotron harmonics. Such bipolar structures have been previously identified with the nonlinearly evolved state of a two-stream electron instability. In this paper, we present the results of long-duration and large-scale particle-in-cell (PIC) simulations which produce, from one set of initial conditions, both bipolar electrostatic structures and, at later times, ion Bernstein waves with peak intensities between multiples of the ion cyclotron frequency. The ion Bernstein waves are driven by a weaker beam instability caused by a residual positive slope in the nonlinearly evolved (nonthermal) electron distribution. Although there are a variety of processes which can produce ion Bernstein modes, we show that a common source (an electron beam) can produce both of these observed phenomena in the downward current region.

Introduction

High resolution observations by the FAST spacecraft [*Carlson et al.*, 1998a, and references therein] have contributed greatly to our knowledge of the wealth of phenomena associated with auroral processes. In this paper, we describe a model and numerical simulations that suggest a common source for two such phenomena observed by FAST in the downward current region: bipolar electrostatic structures and waves with peak intensities between the H^+ ion cyclotron harmonics.

Bipolar electrostatic structures have been observed with electric fields of up to 2.5 V/m and length scales of hundreds of meters [*Ergun et al.*, 1998b]. These bipolar fields have been interpreted as resulting from the saturation of a two stream instability driven by two populations of electrons drifting relative to one another [*Goldman et al.*, 1999; *Oppenheim et al.*, 1999]. Specifically, the non-linear evolution of this instability leads to the development of phase space "vortices" or "holes," which have electric fields in good agreement with the observed bipolar structures [*Muschietti et al.*, 1999]. In a 2-D magnetized plasma, these holes become "tubes" that are elongated in the dimension perpendicular to **B**. These tubes couple unstably to electrostatic whistler-mode waves [*Newman and Goldman*, 2001; *Newman et al.*, 2001] and lose perpendicular coherence within several hundred ω_{pe}^{-1} as the whistlers grow. This characteristic behavior has been verified in 3-D simulations as well [*Oppenheim et al.*, 2001].

Another class of phenomena observed by FAST—often coincident with bipolar structures—are electrostatic waves with spectral intensity peaking between the H^+ cyclotron harmonics. These wave spectra were initially identified as a signature of broadband emission with absorption at the ion cyclotron harmonics [*Ergun et al.*, 1998a]. However, the data are equally consistent with electrostatic wave generation at frequencies between the ion cyclotron harmonics (i.e., ion Bernstein waves). We will show in this letter that ion Bernstein waves can be a natural consequence of the same electron beams that are inferred to be the source of bipolar structures. There are, of course, other mechanisms that can produce spectra with structure at H^+ cyclotron harmonics independently from the formation of bipolar structures [*Gavrishchaka et al.*, 2000].

In new large-scale and long-duration simulations, we find that the initial two-stream instability that produces the bipolar structures saturates before completely removing the positive slope in the electron distribution. This residual slope drives a beam-resonant electron-ion instability, similar to the Kindel-Kennel instability [*Kindel and Kennel*, 1971]. Although its growth rate is slow compared to that of the initial electron instability, this residual instability seen in the simulations nevertheless generates strong ion Bernstein waves between the ion cyclotron harmonics after roughly 4000 ω_{pe}^{-1}. In this paper, we focus on a comparison between the results of these *new* simulations and the FAST observations. A more complete theoretical description of the model and previous simulations can be found in [*Goldman et al.*, 2000].

Particle-In-Cell Simulations

To simulate the long-term evolution of the two-stream instability, we have employed a massively-parallel 2-D electrostatic particle-in-cell (PIC) code with periodic boundary conditions [*Goldman et al.*, 1999; *Oppenheim et al.*, 1999]. The simulation runs described here use the same initial electron and ion distributions as in our previous studies. In brief, the initial electron distribution consists of two Maxwellian populations of equal density and temperature: One electron population is at rest and the other has a mean

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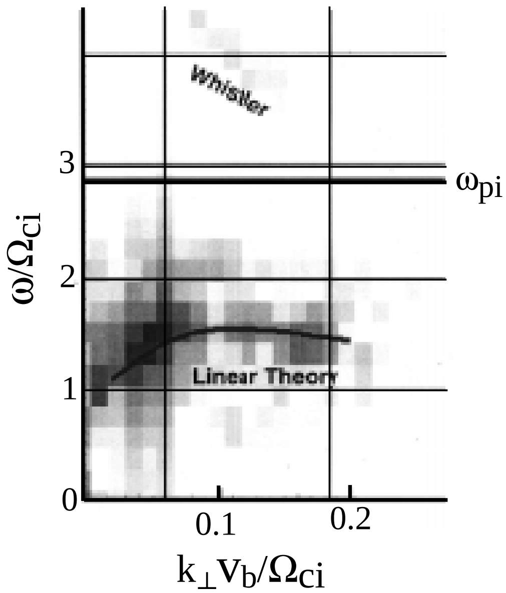

Figure 1. A power spectrum $|E(k_\perp, \omega)|^2$ showing the lowest frequency ion Bernstein mode, which was taken from the final 4096 ω_{pe}^{-1} of the $\Omega_{ce}/\omega_{pe} = 15$ simulation for $k_\parallel = 0.0077\lambda_e^{-1}$. The thin horizontal lines show the ion cyclotron harmonics, the thick horizontal line shows the lower hybrid (ion plasma) frequency, and the solid curve shows the dispersion relation predicted by linear theory. The grey-scale is logarithmic, from 10^{-3} to 10^0 times the peak intensity. (From Goldman et al. [2000])

drift velocity of v_b parallel to **B** (yielding a net drift velocity for the combined distribution of $v_b/2$ and providing a definition of an effective Debye length $\lambda_e = v_b/2\omega_{pe}$). The initial ion distribution is in the rest frame of the first electron component. We have used three magnetic field strengths in these simulations corresponding to $\Omega_{ce}/\omega_{pe} = 5$, 10, and 15.

The simulations were performed in a box of size 102.4 λ_e perpendicular to the magnetic field and 819.2 λ_e parallel to the magnetic field. Each grid cell was 0.8 λ_e in each dimension and the time step was 0.25 ω_{pe}^{-1}. The simulation was run for approximately 16,000 ω_{pe}^{-1} for each parameter set.

The initially unstable electron distribution rapidly evolves, as in previous studies [*Goldman et al.*, 1999, 2000] and phase space holes form, resulting in bipolar electrostatic structures. During this time period the electron distributions merge, producing a nonthermal distribution elongated parallel to the magnetic field. The effective parallel thermal velocity and drift relative to the ions of this evolved distribution are both approximately half the initial beam velocity. The merged electron distribution develops an asymmetry relative to the mean electron velocity due to the influence of the ions in the rest frame of one of the initial electron populations. This evolved distribution [*Goldman et al.*, 2000] retains a small positive slope indicative of residual free energy. After a few hundred ω_{pe}^{-1}, electrostatic whistler-mode waves appear and the bipolar structures have broken up in the direction perpendicular to **B** by $\sim 1000\omega_{pe}^{-1}$. [*Goldman et al.*, 1999; *Oppenheim et al.*, 1999; *Goldman et al.*, 2000; *Oppenheim et al.*, 2001].

After significantly longer times, of order 4000 ω_{pe}^{-1}, the whistler mode waves decrease in energy and nearly-perpendicular waves with peak intensity at frequencies between the ion cyclotron harmonics appear. We identify these waves as ion Bernstein waves generated by the residual positive slope in the electron distribution and the net drift between the ions and electrons (via the Kindel-Kennel instability). Figure 1 shows the spectrum of these waves at the first resolved parallel wavenumber, $k_\parallel = 0.0077\ \lambda_e^{-1}$, as a function of $k_\perp$ and ω for the case Ω_{ce}/ω_{pe}=15 (which corresponds to Ω_{ci}/ω_{pi} =0.35). Superimposed on the spectrum is a curve showing the linear dispersion relation for ion Bernstein waves, which was derived using a modified electron distribution consistent with the evolved distribution present in our simulations at $t \approx 4000\ \omega_{pe}^{-1}$ [*Goldman et al.*, 2000]. The agreement between simulation and theory confirms our identification of these waves as ion Bernstein modes. Further evidence that these waves are beam-driven modes comes from the fact that they propagate only in the direction parallel to the electron drift (rather than both parallel and antiparallel) with phase velocity $\omega/k_\parallel$ resonant with the positive slope in the electron distribution. Once these waves form, they persist for the remainder of our simulation runs (approximately 16,000 ω_{pe}^{-1}), although there is also evidence of parametric, three-wave decay at later times [*Goldman et al.*, 2000].

Given sufficient time for the slow growth rate of the instability to operate, these waves emerge in simulations with all three magnetic field strengths studied (Ω_{ce}/ω_{pe} =5, 10, and 15). Figure 2 shows spectra from the final stage of the simulations at both the first and second resolved parallel wavenumbers ($k_\parallel$ = 0.0077 and 0.00153) for all three magnetic field strengths considered here. Generally, the peak intensities occur at higher frequencies for larger $k_\parallel$, consistent with a resonant beam-driven instability with phase velocity $\omega/k_\parallel$ matching the positive slope in the beam distribution. These waves propagate with wavevectors close to perpendicular to **B** in the range $0 < k_\parallel/k_\perp \lesssim 0.125$, with the highest intensities near $k_\parallel/k_\perp \sim 0.025$. The frequency structure characterized by intensity maxima between multiples of Ω_{ci} can be seen from the lowest harmonic to slightly above the ion plasma frequency, although how prominent this structure is varies with the magnetic field strength. In general, more cyclotron harmonics are excited for weaker magnetic fields.

Comparison to FAST observations

Figure 3a shows the low-frequency part of an electric field spectrum observed by the FAST spacecraft in the auroral downward current region coincident with intense bipolar structures. In Fig. 3b we show the simulated spectrum taken from our run with Ω_{ce}/ω_{pe}=10, which closely matches the frequency ratio at the time of the FAST observation. The simulated spectrum was constructed by calculating the perpendicular electric field at a fixed point and as a function of time, computing the power spectrum from this time series using a Welch window, and then averaging over all points in our simulation volume to reduce the statistical noise.

The simulations reproduce the overall structure of the observed spectrum: Both spectra show peaks between ion-cyclotron harmonics and valleys near the harmonics. The primary differences between them are the lack of wave energy in the simulations below the ion cyclotron frequency, and the relative amplitudes of the peaks. The low-frequency

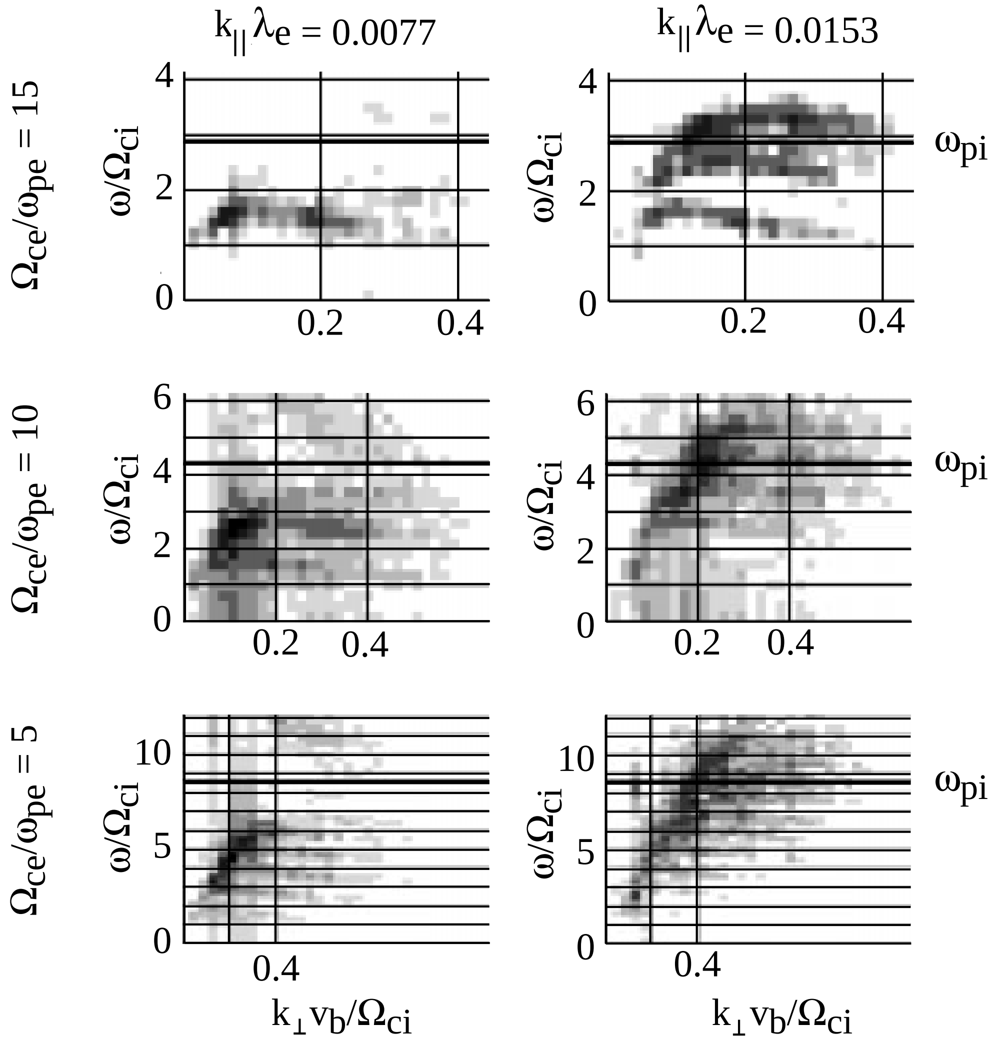

Figure 2. Power spectra, as in Figure 1, at the first (left) and second (right) resolved parallel wavenumbers in the simulations ($k_{||}$ = 0.0077 and 0.0153 λ_e^{-1}) for Ω_{ce}/ω_{pe}= 15 (top), 10 (middle) and 5 (bottom). In the Ω_{ce}/ω_{pe}=5 case, the final 8192 ω_{pe}^{-1} of the simulation were used so that the frequency resolution would be sufficient to distinguish the individual ion-cyclotron harmonics.

component in the data may be due to broadband emission from a process not included in our simulations (e.g., Doppler-shifted DC turbulence and/or Alfvén waves). The frequency and relative amplitudes of the peaks in our simulations agree quite well with the observations in the range $2\Omega_{ci} < \omega < 5\Omega_{ci}$. Nevertheless, the peak amplitudes do vary over the duration of our simulations. Each mode has a different growth rate, and at late times in the simulations there is evidence of parametric decay and three-wave interactions, which can remove energy from the Bernstein modes [*Goldman et al.*, 2000].

In addition to spectral similarities, the RMS amplitude of the simulated and observed low-frequency waves are also similar. In the simulations, we find that $\langle \epsilon_0 E_\perp^2 \rangle \sim (0.004 - 0.02) n_e k T_e$, where $T_e = m_e(v_b/2)^2$ is the "effective" parallel electron temperature of the evolved distribution. For the range of densities and temperatures in the downward current region the simulation results imply RMS amplitudes between 0.1 and 1 V/m, consistent with the FAST observations.

In our periodic simulations, the bipolar structures are observed to disappear after $\sim 3000\omega_{pe}^{-1}$, possibly due to interactions with the ion Bernstein waves. In the auroral ionosphere, the bipolar field structures would be able to propagate along magnetic field lines out of the source region, allowing them to persist for longer periods as suggested by recent FAST observations. In either case, one would expect to observe ion Bernstein waves in the absence of bipolar structures, even when both share a common origin. In fact, the FAST spacecraft does often observe ion Bernstein modes in the downward current region without accompanying bipolar fields, with the latter being seen only 5-10% of the time [*Ergun et al.*, 1998b]. Because our simulations are initial-value runs rather than runs driven by the continuous

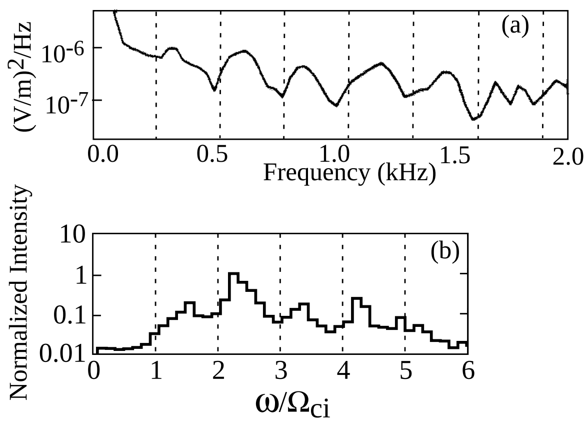

Figure 3. Power spectra of ion cyclotron waves, from (a) the FAST satellite on 1997-02-18 at time 14:26:11.385 UT, and (b) from our Ω_{ce}/ω_{pe}= 10 simulation. The simulated spectrum has been normalized by its peak intensity. The dotted lines in both frames show the ion cyclotron harmonics.

injection or acceleration of electrons at a boundary, we cannot make rigorous statements about the spatial distribution of bipolar structures or the regions in which ion Bernstein modes would be present.

The saturated electron distributions in our simulations are consistent with ones observed in the downward current region by FAST [*Carlson et al.*, 1998b; *Ergun et al.*, 1998b]. These observed distributions are highly elongated along the direction of the magnetic field (i.e., $T_{\parallel} \gg T_{\perp}$, as in the simulations), and typically exhibit a significant anti-Earthward drift relative to the ions, which contributes to the downward current in the region.

In summary, the PIC simulations agree with the FAST observations and show many of the same phenomena. In addition to the bipolar structures, our simulations also reproduce the waves observed between ion cyclotron harmonics and identify them as beam-driven ion cyclotron harmonic (Bernstein) modes. The amplitudes we obtain in the simulations and the long-lasting character of these waves are also consistent with the FAST data. These waves are a result of the same electron beam which produces the bipolar structures, and no additional causes or processes are required to account for this aspect of the FAST observations.

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