Anomalous ISR echoes preceding auroral breakup: Evidence for strong Langmuir turbulence

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[1] Experimental results obtained with the 449-MHz Poker Flat Incoherent Scatter Radar (PFISR) show unusual features in both the ion line and plasma line measurements during an auroral breakup event. The features are a greatly enhanced flat ion acoustic spectrum (believed to indicate the presence of an additional peak at zero Doppler), and two peaks in the plasma line spectrum. Similar spectral morphologies are observed during active HF ionospheric modification experiments and are considered unmistakable indications of Strong Langmuir Turbulence (SLT). In SLT theory, the central peak in ion acoustic spectrum is caused by Bragg scattering from non-propagating density fluctuations (cavitons), and the two peaks in the plasma line spectrum are associated with (1) Langmuir waves trapped in the cavitons, at the cold plasma frequency, and (2) a "free mode" at the Langmuir frequency. Free modes are radiated Langmuir waves from collapsing cavitons that follow the linear dispersion relation. The observed turbulence was confined to a thin layer (∼10-km) centered at ∼230 km altitude. **Citation:** Akbari, H., J. L. Semeter, H. Dahlgren, M. Diaz, M. Zettergren, A. Strømme, M. J. Nicolls, and C. Heinselman (2012), Anomalous ISR echoes preceding auroral breakup: Evidence for strong Langmuir turbulence, *Geophys. Res. Lett.*, *39*, L03102, doi:10.1029/2011GL050288.

1. Introduction

[2] Incoherent Scatter Radar (ISR) measurements of the ion and the plasma lines from the auroral ionosphere occasionally show characteristics not accounted for in standard ISR theory [e.g., *Evans*, 1969]. In the ion line measurements sometimes one or both shoulders of the spectrum are considerably enhanced above the thermal level. These echoes are well known as Naturally Enhanced Ion Acoustic Lines (NEIALs) [*Sedgemore-Schulthess and St. Maurice*, 2001; *Michell and Samara*, 2010]. Plasma lines are usually too weak to be detected, however, in the auroral ionosphere they can be enhanced due to the presence of photoelectrons and secondary electrons and thus be detected by ISRs [*Nilsson et al.*, 1996]. This paper reports simultaneous observations of enhanced ion and plasma lines by the 449-MHz Poker Flat Incoherent Scatter Radar (PFISR) in which the ion line spectrum is flat and the plasma line spectrum contains two peaks. The altitude profile of the features suggests that they originated from a thin layer near 230 km. The position and duration of the features suggests that they were causally related to the intensification and breakup of a discrete auroral arc.

2. Observations

[3] The observations reported herein were recorded during the expansion phase of a substorm with onset at ∼11:10 UT on 23 March 2007. This was the first substorm studied using the coordinated ground-based and space-based diagnostics of the THEMIS mission and, as such, the event has received considerable attention [*Angelopoulos et al.*, 2008]. Auroral activity for this event reached the zenith of PFISR (147.48°W, 65.13°N) at ∼11:20 UT, where it was observed simultaneously by the radar and a collocated narrow-field video system. The dynamic auroral morphologies observed at this time have been discussed previously by *Semeter et al.* [2008] in the context of dispersive Alfven waves (video data is linked as dynamic content in the paper by *Semeter et al.* [2008]). Here we focus on non-thermal ISR echoes observed by PFISR during the same period.

[4] For this experiment PFISR was configured to sample a 3 × 3 grid of beam positions, plus an additional beam trained in the magnetic zenith. The transmit waveform was a 480-μs uncoded pulse, from which ion line spectra and up- and down-shifted plasma line spectra were computed for each of the 10 beams. For this report, we focus on observations in the magnetic zenith only (−154.3° az, 77.5° el), where the largest coherent echoes were observed.

[5] Figure 1a shows the total received ion line power as a function of altitude and time in the magnetic zenith beam during a 50-second period beginning at 11:20 UT. The enhanced scatter below 150 km beginning at 10 s is due to ionization of the E-region by precipitating electrons. Above this altitude, three intervals of coherent scatter can be observed, identified as 1, 2, and 3 in the figure. These events were correlated with dynamic auroral activity within the beam. Figure 2 shows representative images associated with each scattering event, along with the position of the radar beam. These images are identical to Figures 3g–3i of *Semeter et al.* [2008]. Scattering event 1 occurred near the edge of the intensifying discrete auroral arc. Event 2 occurred just after breakup as a dispersive packet of elemental arcs (100-m width) transited rapidly through the beam. Event 3 occurred as the auroral breakup filled the field of view.

[6] Figure 3 shows height-resolved ion line spectra computed from measurements for these three scattering events.

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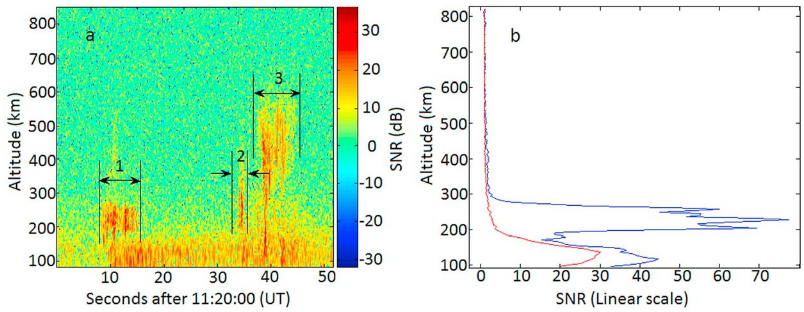

Figure 1. (a) Received radar power, in the ion line channel, for the magnetic zenith beam. Three intervals of coherent scatter are identified and numbered. (b) Vertical cuts from the power plot in Figure 1a. Blue: At a time during the scattering event 1. Red: During the thermal scattering interval between the event 1 and 2. (SNR values are not range corrected.)

Event 1 shows unusual characteristics. First, the apparent altitude extent of the scattering region is ~72 km, exhibiting a sharp cutoff at ~270 km altitude (see Figure 1b). This suggests that the scattering may be localized in altitude near 230 km but, due to the poor altitude resolution of the measurements, appears to arise from a layer with extent similar in width to the range ambiguity function, 72 km here (i.e., although the received signal is sampled at 30 μs, corresponding to a range resolution of 4.5 km, the true resolution is limited by the length of the transmitted pulse). The second unusual feature is the flat ion line spectrum. This is shown most clearly by blue line plot in Figure 4, which was produced by averaging the spectrum in Figure 3a over the scattering layer. Typical ion acoustic spectra have a double-humped shape associated with the Landau-damped ion acoustic mode matching the radar wavenumber (see red line plot in Figure 4). This type of enhanced flat ion spectrum was previously reported by *Cabrit et al.* [1996], although in an extended altitude range.

[7] Figures 5a and 5b show down- and up-shifted plasma line spectra, respectively, for scattering event 1. The critical feature is the presence of two peaks separated by ~120 kHz. This is seen more clearly in Figure 5c, which plots the plasma line power spectra through the features in Figures 5a and 5b.

[8] Scattering event 2 presents similar characteristics to those of event 1, albeit with poorer statistics since the time interval used to compute the spectra is shorter. The ion acoustic spectrum, shown in Figure 3b, also shows enhancements at zero frequency. The plasma lines were also enhanced at this time, but their morphologies were not sufficiently resolved with the limited integration period.

[9] For event 3 (Figure 3c), the ion acoustic spectrum shows features consistent with the classic Naturally Enhanced Ion Acoustic Line (NEIAL) [*Sedgemore-Schulthess and St. Maurice*, 2001; *Michell and Samara*, 2010], where one or both shoulders of the power spectrum is enhanced well above the thermal level. There was no plasma line enhancement observed for event 3.

3. Discussion

[10] Observation of the central peak in the ion acoustic spectrum [*Stubbe et al.*, 1992] and two peaks in plasma line measurements [*Isham et al.*, 1999]—one at the plasma frequency (caviton continuum line) and the other at the Langmuir frequency (“free mode” line)—are commonly observed in active high-frequency (HF) ionospheric modification experiments, and are considered as unmistakable signatures of cavitating Langmuir turbulence [*DuBois et al.*, 1990]. In active modification experiments, a powerful HF wave with frequency below the peak plasma frequency of the ionosphere is transmitted into the ionosphere. This pump wave interacts with the ionosphere near the reflection height, exciting a spectrum of plasma waves—most prominently, Langmuir waves. On long time scales after the heater is turned on, the pump wave modifies the bulk properties of the ionosphere, altering the local density and temperature and producing field-aligned irregularities. But on short time scales, after the heater is turned on and before the pump wave

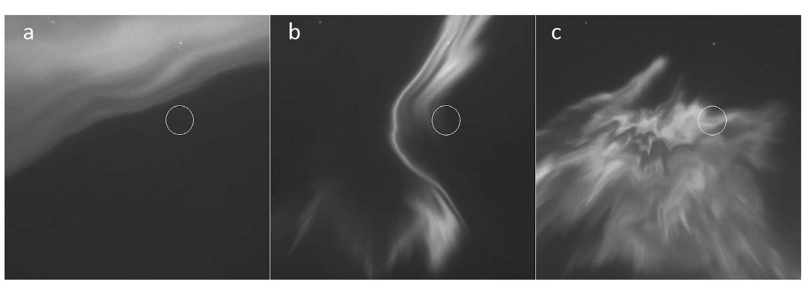

Figure 2. Representative narrow-field (11 degree diagonal field of view) images of dynamic auroral forms associated with (a) event 1, (b) event 2, and (c) event 3 in Figure 1a. White circles represent the location and approximated 3 dB beamwidth of the radar beam. Exact 3 dB beamwidth is not a circle. (Images taken from *Semeter et al.* [2008].)

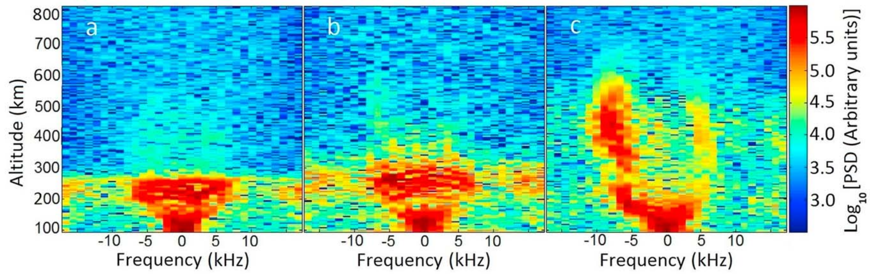

Figure 3. Ion line spectra computed from measurements within the (a) first, (b) second, and (c) third scattering events of Figure 1a. (SNR values are not range corrected.)

affects the background plasma greatly, ISR measurements from within the heated region can be used to study the induced Langmuir turbulence [*Carlson et al.*, 1972; *Fejer et al.*, 1991; *Cheung et al.*, 1992; *Isham et al.*, 1999].

[11] Langmuir turbulence theory contains two regimes, weak and strong. Weak Langmuir Turbulence (WLT) theory is based on propagating Langmuir and ion acoustic waves. The basic process is that the initial Langmuir wave is excited by some source of free energy, grows to a threshold, and undergoes a parametric decay creating a counter propagating Langmuir wave with smaller wave number and an ion acoustic wave. These three waves follow their linear dispersion relations and satisfy the matching conditions [e.g., *Diaz et al.*, 2010]. Provided there is enough free energy, the newly created Langmuir wave decays into another Langmuir wave and another ion acoustic wave. This process continues until the last created Langmuir wave does not grow enough to excite further waves [*Guio and Forme*, 2006]. This parametric decay mechanism has been commonly invoked to explain anomalous enhancements in ion acoustic spectra observed by ISR [e.g., *Sedgemore-Schulthess and St. Maurice*, 2001].

[12] If the input energy exceeds a certain threshold, the last created Langmuir wave reaches a frequency so close to the plasma frequency that further decay to a wave with lower frequency is not possible. For these conditions WLT theory is no longer applicable. This regime is referred to in Strong Langmuir Turbulence (SLT) theory as the cavitation regime [*Doolen et al.*, 1985]. In the cavitation regime propagating Langmuir and ion acoustic waves are replaced by localized Langmuir states (or "cavitons") which consist of a Langmuir field trapped in a non-propagating density depletion [*DuBois et al.*, 1990]. Under the action of the ponderomotive force, these localized states collapse forming nucleation centers for new cavitons. Thus, in the SLT regime, the turbulence is not explained by parametric decay of propagating Langmuir waves, but by nucleation and collapse of localized waves in density cavities [*Russell et al.*, 1988; *DuBois et al.*, 1988; *Cheung et al.*, 1989].

[13] In ionospheric heating experiments the central peak in the ion line is due to the Bragg scattering of the radar pulse from non-propagating ion density fluctuations created during the collapse [*DuBois et al.*, 1991]. A central ion-line peak in the natural ionosphere has been reported by B. Isham et al. (Cavitating Langmuir turbulence in the terrestrial aurora, arXiv:1101.3517v2, 2011), who interpreted this as evidence for cavitating turbulence driven by an auroral electron beam. In our measurements, the deviation from a classic double humped ion acoustic spectrum, observed in events 1 and 2, may also indicate the presence of a central peak at zero Doppler, together with some smearing in frequency. The frequency smearing may indicate a temporal modulation of the scattering layer during the integration period. Sheared plasma motion within the radar volume could produce a similar effect [*Knudsen et al.*, 1993]. Further investigation is required to fully understand the observed ion line morphology.

[14] In plasma-line measurements, the peak at the plasma frequency is due to the Langmuir waves trapped in the density wells. Collapsing cavitons also radiate Langmuir waves, known as "free mode" waves, which follow their linear dispersion relation. Plasma line measurements of SLT may thus include two distinct peaks, one at the plasma frequency and the other at the Langmuir wave frequency [*DuBois et al.*, 1993]. This interpretation of Figure 5 is supported by our calculations of plasma frequency and Langmuir frequency. By performing the standard ISR fitting procedure for the region of thermal scattering 30 seconds before Event 1, we derived the background electron density of about $n_e = 1.82 \times 10^{11}$ [m^{-3}] at 230 km (averaged over 90-km in altitude). Using the relation $f_p \approx 8.98\sqrt{n_e}$, this fixes the plasma frequency at f_p = 3.83 MHz, which agrees with the position of the first peak in our plasma line measurement. The background electron temperature is calculated to be about 1925°K, and the angle between the radar beam and the magnetic field lines at 230 km is about α = 1.148°. Substituting these into the linear Langmuir dispersion relation, $\omega^2 = \omega_p^2 + 3k^2v_{the}^2 + \Omega_e^2\sin^2(\alpha)$, gives the Langmuir frequency of 3.93 MHz which is close to the position of the second peak in our experiment (3.939 MHz). In the above

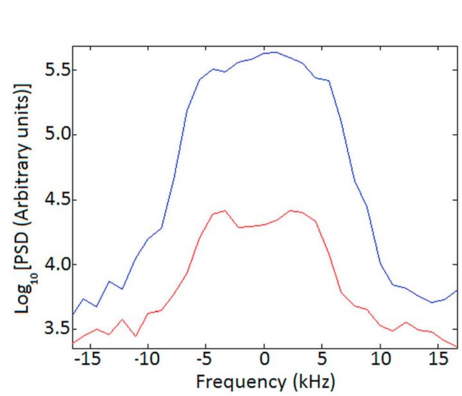

Figure 4. Blue: Ion acoustic spectrum for scattering event 1 (averaged over the scattering layer). Red: Ion acoustic spectrum for the thermal scattering interval between event 1 and 2 (averaged between 200 km and 270 km).

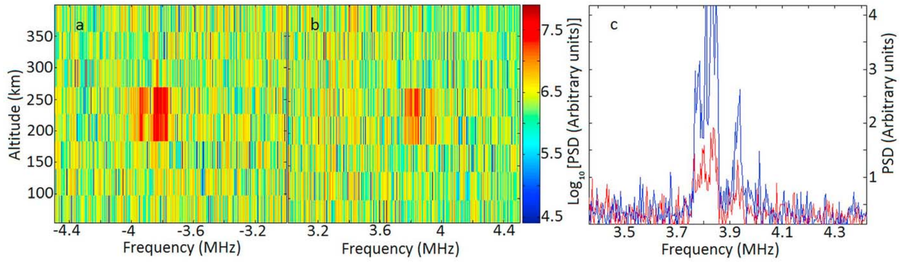

Figure 5. (a and b) Down- and up-shifted plasma line measurements, respectively, from scatter events 1. (c) Blue and red: Horizontal cuts from Figures 5a and 5b, respectively, averaged over 200-km and 250-km altitude. Showing the presence of two peaks in the plasma line spectra. (Negative frequencies are folded on top of the positive frequencies.)

equation Ω_e is electron gyrofrequency (9.6 megarad/s, computed using the IGRF model), v_{the} is mean thermal velocity of electrons, and k is the radar wave number.

[15] We propose naturally occurring SLT as a plausible interpretation of the presented data. If correct, our data lends confirmation to Isham et al. (arXiv:1101.3517v2, 2011) who proposed the occurrence of the beam driven SLT in the auroral ionosphere. However, questions remain regarding the source of the turbulence. The energy of beams responsible for the Langmuir turbulence is usually believed to be less than 200 eV, and these beams of magnetospheric origin cannot reach to the point of our observations. This suggests that the putative driver involves secondary electrons. Also an electron beam of magnetospheric origin should interact with the ionosphere over an extended altitude range, and not at a single altitude or a thin layer as in the case of our scattering event 1. Finally, it should be noted that unresolved density variability (i.e., two distinct density states within the sampling volume) could also produce a double peaked plasma line. However, the driver of the unusual ion line morphology then becomes unclear.

[16] We believe that scattering event 2, despite the fact that it does not confine to a narrow layer, is the result of the same process as event 1. However, the short duration of the event within the radar beam provided only marginal statistics for resolving spectral features, and so the double-peaked plasma line could not be unambiguously identified.

4. Summary

[17] ISR data presented in this study shows unusual characteristics both in the ion line (an enhanced flat spectrum) and the plasma line spectra (double-peaked plasma line) occurring in a thin layer near 230 km altitude preceding the breakup of an active auroral form. Although the collective features are not yet fully understood, they exhibit many similarities to SLT characteristics observed in active ionospheric modification experiments, suggesting the existence of naturally occurring SLT in the auroral ionosphere. Further clarification is required regarding the source mechanism for this turbulence.

[18] **Acknowledgments.** This work was supported by the National Science Foundation under grants AGS-1027247 and AGS-0852850.

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