Magnetic fluctuations associated with field-aligned striations

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Abstract. In a laboratory experiment modeling conditions in the auroral ionosphere, magnetic and density fluctuations are observed to grow spontaneously within a field aligned density depletion. The plasma has both cross-field pressure gradients and magnetically field-aligned currents. The magnetic fluctuations, identified as shear Alfvén waves, are coupled with the density fluctuations depending upon the plasma beta, β. The fluctuations exhibit a coherent eigenmode structure at higher β and evolve towards broadband Alfvén turbulence as β is lowered. We identify the cross field pressure gradient as the dominant driving source for the fluctuations.

In studies of the Earth's auroral ionosphere there is considerable interest about the properties of low frequency wave activity associated with field aligned density depletions (striations) [Chmyrev et al., 1988; Boehm et al., 1990; Louarn et al., 1994; Lundin et al., 1994]. Wave activity generated at striations could result in local ion heating [Erlandson et al., 1994] and also in non-local electron acceleration as waves propagate over long distances, as may be appropriate for shear Alfvén waves [Hasegawa, 1976]. Although attention has recently been focused on the behavior of lower-hybrid waves associated with striations [Kinney et al., 1992; Eriksson et al., 1994], the properties and consequences of magnetic and electric noise in the frequency band below the Hydrogen ion gyrofrequency are the subject of renewed interest [Gustafsson et al., 1990; Stasiewicz et al., 1994]. It appears that waves in this part of the frequency spectrum may play a major role in the actual heating and acceleration of ions and electrons in the auroral ionosphere. The study of these waves from rapidly moving spacecraft is a difficult undertaking, but the laboratory offers an environment in which their temporal and spatial behavior can be studied in detail.

Motivated by the need to understand the behavior of spontaneous wave generation in striations, we have designed a laboratory experiment in which a controlled, magnetic field-aligned density depletion is produced in a large laboratory plasma device (the LAPD at UCLA [Gekelman et al., 1991]) by selective coating or masking of an emissive oxide coated cathode. The transverse dimension of the striation is comparable to the electron skin-depth while its length along the magnetic field is about 10⁶ Debye-lengths. The striation is located at the center of a plasma column whose radius is over ten times larger than the striation radius, so that, in the radial direction, the plasma conditions are essentially those of an unbounded plasma. It is observed that when a weak current system (\(j/j_T < 0.1\), where \(j_T\) is the thermal current) flows around the striation, both density and magnetic fluctuations spontaneously develop in the frequency band 0.1-1.0 \(f_T\), i.e., below the ion cyclotron frequency. We have chosen to express all experimental results in terms of scaled quantities in order to emphasize their universality. Readers interested in obtaining numerical values of the operational plasma parameters should consult Gekelman et al., [1991].

We describe the basic properties of these fluctuations with the purpose of relating them to observations made by spacecraft in the auroral ionosphere and stimulating an intellectual link between laboratory and space studies. For simplicity the present experiment uses a single ion species (Helium) whose ion gyroradius is about five times smaller than the striation radius. The ratio of cyclotron to plasma frequency for electrons is \(f_c/f_p = 0.1-1.0\).

Figure 1 displays the spatial dependence of the ambient plasma density, \(n_0\), and the amplitude of the Fourier transform of the density fluctuations, \(\delta n(\omega)\), (at a specific frequency corresponding to the largest amplitude) in the direction perpendicular to the magnetic field. For this plasma the contrast between the density in the center of the hole and the surrounding plasma is about a factor of three. The fluctuations in density are obtained by measuring the local ion saturation current, proportional to \(n_0(T_e/m_i)^{1/2}\), collected by a small Langmuir probe (\(m_i\) is the ion mass and \(T_e\) is the electron temperature). The local electron temperature is determined from the current-voltage trace obtained by the Langmuir probe, but this measurement is not fast enough to be used for correcting the ion saturation current for rapid fluctuations in \(T_e\). Thus the signal we refer to as \(\delta n(\omega)\) also contains contributions arising from fluctuations in the local electron temperature. The radial profile of the density fluctuations shown in Figure 1 is for a fre-

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Figure 1. Radial profile of the Fourier amplitude of fluctuations in the ion saturation current, \(\delta n(\omega)\), at \(\omega/\omega_c - .09\). and zero order density profile, \(n_0\), in the vicinity of the striation. The fluctuation Fourier amplitude is plotted using arbitrary units.
frequency of $\omega/\omega_{ci} = 0.09$ and plasma electron beta, $\beta_e = 10^{-3} \approx 4 \ \text{m}_e/\text{m}_i$. It is apparent in Figure 1 that the density fluctuations are trapped within the striation as would be expected for the radial profile of an eigenmode. The characteristic radial structure exhibits a rough reflection symmetry about the center of the striation and the fluctuation amplitude peaks close to the point where the pressure gradient is maximum.

Simultaneously with the density fluctuations the time-derivative of the vector magnetic field is measured with a small, tri axial, inductive-loop probe. In addition, the electrical current along the ambient magnetic field is measured using a double-sided Langmuir probe. The radial profile of the amplitude of the Fourier transform of the magnetic field, $|\delta B(\omega)|$, at frequency $\omega/\omega_{ci} = 0.09$ and the RMS (Root Mean Square) value of the axial current, $\delta I_{ax}$, are shown in Figure 2. Of course, the RMS value of the current fluctuations encompasses all frequencies since the Fourier transform of the axial current is not taken. The $\delta B(\omega)$ measurements are shown only up to the center of the striation because the shielding and support structure of the magnetic probe is large enough to disturb the structure of the density profile if the probe is inserted through the striation. However, the $\delta I_{ax}$ profile is shown across the entire striation because the Langmuir probe structure is small and does not disturb the striation. It is found that the peak amplitude of the fluctuations occurs near the point of the largest density gradient. The magnetic fluctuations exhibit a radial structure similar to that of the density fluctuations shown in Figure 1 and are seen to be correlated with field aligned oscillations in the electrical current.

The polarization of the magnetic fluctuations is determined by comparing the signals received by each of the mutually orthogonal coils in the tri-axial arrangement of the induction-loop probe. In Figure 3 the amplitude of the temporal Fourier transform of the component of the fluctuating magnetic field perpendicular to the ambient magnetic field, $|\delta B_\perp(\omega)|$, compared to the component along the field, $|\delta B_\parallel(\omega)|$.

It is evident that the magnetic fluctuations are shear waves, as opposed to compressional waves, since the parallel component is 100 times smaller than the perpendicular component. In fact, much of the small parallel component recorded probably results from slight misalignment of the magnetic probe which results in a portion of the perpendicular component appearing in the loop purportedly measuring the parallel component. Since these shear-like magnetic oscillations are accompanied by fluctuations in the density and in the parallel electron current, this mode can be identified as a kinetic, drift-Alfvén wave trapped within the striation.

It is found that the coupling between density and magnetic fluctuations is determined by the value of the electron plasma beta, $\beta_e = 4\pi n_0 v_T^2/\epsilon B^2$, as is illustrated by the frequency spectra displayed in Figure 4. The different values of beta are obtained by varying the strength of the background magnetic field. For the higher beta values (Figure 4a, $\beta_e \approx 10^{-3}$) it is seen that a sharply peaked density eigenmode at $\omega/\omega_{ci} = 0.09$ is accompanied by a corresponding magnetic fluctuation. However, at lower beta (Figure 4b, $\beta_e = 3 \times 10^{-4}$) the highest amplitude eigenmode still occurs at a frequency near $\omega/\omega_{ci} = 0.09$ but does not have a corresponding density fluctuation. Thus while the eigenmode structure appears to scale linearly with background magnetic field strength, the change in beta causes the nature of the mode to change. The decoupling between the density and magnetic fluctuations implies a separation between electrostatic and electromagnetic behavior. Pure electrostatic behavior corresponds to drift waves, while pure electromagnetic behavior corresponds to the shear Alfvén wave. The two phenomena are separate at low beta but merge at higher beta values and become the drift-Alfvén wave. The measured values of the eigen frequencies are in good agreement with analytical calculations too lengthy to report here [Peñaño, et al., 1995]. Those readers interested in theoretical studies of the effect of sharp gradients in space plasmas should note that several papers on this topic have been published by Ganguly (see e.g., [Ganguly, et al., 1994]). Fluctuations associated with striations do not necessarily have a sharply peaked eigenmode frequency spectrum. Depending upon the plasma parameters (mostly $\beta_e$) broadband spectra can prevail. An example of a broadband magnetic fluctuation spectra obtained early in the discharge when the plasma beta is low is shown in Figure 5.
is flowing at a speed of about 0.1 $v_T$, where $v_T$ is the electron thermal speed.

The fast electrons emitted from the cathode also serve to heat the plasma. Thus inside the striation the electron temperature drops because there are no fast electrons to deposit heat. The temperature drops from about 12 eV outside the striation to around 6 eV at its center. This decrease in temperature together with the decrease in density give rise to a substantial cross field pressure gradient (about 10 dynes/cm$^2$).

It is of interest to determine the driving source for the fluctuations. The shear Alfvén phase speed is about $(m_e/\beta n_e)^{1/2} v_T$, so that it is well within the bulk distribution and much slower than the fast electrons emitted from the cathode. Thus if an axial current drives the waves we expect it should be the bulk current. We have observed that the fluctuations rapidly disappear when the primary electron current is shut off which provides us with an opportunity to determine the driving source. Two hundred microseconds after termination of the primary current the fluctuations are gone, but a substantial axial current persists in the plasma carried by the bulk drift at about 0.1 $v_T$ and the plasma density profile shows no significant change. However, the most dramatic change is a substantial decrease in the electron temperature to about 3 eV everywhere in the plasma. The pressure difference across the striation drops by an order of magnitude mostly due to electron cooling. Since the fluctuations vanish when the primary current is terminated but the bulk axial current persists while the cross field pressure gradient collapses, we attribute the driving source of the fluctuations to the cross-field pressure gradient.

In summary, we have reported the observation of substantial density and magnetic fluctuations ($\delta n/n_0 = 0.2$ : $\delta B/B_0 = 2 \times 10^{-3}$) arising spontaneously along a density striation in a laboratory plasma having many features in common with the auroral ionosphere. The fluctuations are trapped within the density striation and the radial structure of the fluctuations have scale sizes on the order of the cross-field gradient scale length. Density fluctuations can be strongly coupled to shear-like magnetic fluctuations depending upon the plasma beta. The observed fluctuations are of interest because they may in

**Figure 4.** Frequency spectra of the magnetic, $\delta B(\omega)$, and density, $\delta n(\omega)$, fluctuations for two different values of plasma beta: a). $\beta_e = 10^{-3}$; b). $\beta_e = 3 \times 10^{-4}$.

The cutoff of the fluctuation spectra at the ion cyclotron frequency also illustrates the shear wave nature of the fluctuations.

Our laboratory plasma has many features in common with the auroral ionosphere including parallel currents and cross field pressure gradients. Axial electrical currents are carried by two distinct populations of electrons. Electrons emitted from the cathode form a fast, tail population along the entire length of the device and carry a current towards the cathode. However, along the length of the machine between the anode and end of the device, the current carried by fast electrons is canceled by a current due to a drift in the bulk plasma. This happens because the semi-transparent wire mesh anode is located near the cathode at $z = 60$ cm, and is the only return current path available to electrons because the plasma column is terminated by an electrically floating copper plate. Thus there is on average no net axial current along most of the length of the device (9.4 meters), but a current flowing away from the cathode is carried by bulk electrons while an equal and opposite current is carried by fast electrons. It should be noted, however, that the current is zero when averaged over the entire cross section of the plasma, so that, at any fixed axial position, the axial current along a particular field line in the plasma may be non zero. Thus there are locations in the plasma where an axial current is flowing away or toward the cathode depending upon whether the primary or bulk flux of electrons dominates. In particular, within the striation there are no primaries so that there is also, for the most part, no bulk flow and thus no axial current. In the region of the plasma outside the striation the bulk plasma

**Figure 5.** Spectral power density of the magnetic fluctuations at a time early in the discharge when the plasma beta is low.
teract with the ambient plasma and lead to heating and particle acceleration. One of the noteworthy results of our experiment is that the growth of the density and magnetic fluctuations does not destroy the striation over a length of more than one million Debye lengths. Thus, if a similar process is occurring in the auroral ionosphere, one might expect to find a density striation filled with relatively time-steady magnetic and density fluctuations with frequencies lower than the gyrofrequency of the majority ion species. Of particular interest are the shear Alfvén magnetic fluctuations which have an electric field along the magnetic field and may cause parallel electron acceleration. In this regard it is interesting to note that Alfvén waves have been associated with regions of auroral electron precipitation [Boehm, et al., 1990] and the Alfvén speed at altitudes of 1 R\(_e\) corresponds to the velocity of keV electrons. Furthermore, the parallel electric field associated with the shear Alfvén wave depends upon the ratio of the perpendicular wave length, \(2\pi k_L\), to the electron skin-depth, \(c/\omega_{pe}\), and is largest for \(k_L c/\omega_{pe} = 1\) [Morales, et al., 1994]. Thus the largest parallel electric fields should be associated with scale lengths on the size of the electron skin-depth which scales very well with the thickness of discrete auroral arcs [Horovsky, 1993].

The observations reported here provide a global spatial picture of the environment around a density striation that may prove useful in interpreting and analyzing spacecraft data. Hopefully these results will stimulate theoretical work that will clarify the relationship between the experiment and auroral acceleration processes. In this regard an experimental study in which a controlled current is drawn through the striation is worth pursuing.

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References


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