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Space Chamber Simulation of Altitude Variation on Plasma Wave Signatures

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The effects of increasing ion-neutral collisions on velocity-shear-driven ion-cyclotron waves have been studied in simulated ionospheric conditions in the Naval Research Laboratory's Space Physics Simulation Chamber. The experiments show that shear-driven ion-cyclotron waves can exist for ion-neutral collision frequencies of the order of the ion gyrofrequency. For higher collision frequencies where the ions become unmagnetized, a transition to a higher frequency mode is observed.

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CONTENTS

SPACE CHAMBER SIMULATION OF ALTITUDE VARIATION ON PLASMA WAVE SIGNATURES

1. Introduction

In the ionosphere, there are indications that structured transverse (to **B**) plasma flows can play an important role in the generation of broadband plasma turbulence [e.g., *Kelley and Carlson*, 1974; *Basu et al.*, 1988; *Earle et al.*, 1989]. Recent observations by the AMICIST sounding rocket reinforce this interpretation and also show a correlation with transverse ion energization [*Bonnell*, 1997]. Structured plasma flows can be found in the ionospheric E region as well [*Fejer and Providakes*, 1987]. At these low altitudes, where collisions between ions and neutral atoms become increasingly important, radar backscatter experiments have identified meter-scale irregularities resulting from plasma instabilities [*Fejer and Kelley*, 1980; *Schlegal and Niesen*, 1985]. Often, the waves responsible for these echoes occur in highly localized regions during periods of intense auroral activity [i.e., *Fejer et al.*, 1986] and some types of echoes have been associated with large shears in the transverse plasma flow velocity [Fejer et al., 1984]. However, the presence of inhomogeneous transverse flows can complicate the analysis of the radar backscatter spectra [*Swartz et al.*, 1988; *Knudsen et al.*, 1993; *Forme et al.*, 1998], which typically assumes spatial homogeneity across the scattering volume. Consequently, changes in the spectral signatures of waves associated with structured plasma flows in a collisional is important for understanding and interpreting data from the low-altitude ionosphere.

The stability of plasmas which include structured transverse flows has been investigated theoretically by *Ganguli et al.* [1988a, 1994] and *Gavrishchaka et al.* [1996]. These studies were verified experimentally by *Amatucci et al.*, [1994,1996,1998] and *Koepke et al.*, [1994,1995,1998a], under conditions where collisions between neutral atoms and plasma particles were inconsequential. When ions and electrons are both magnetized within a localized transverse flow layer, waves in the ion-cyclotron frequency range can result from

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the Inhomogeneous Energy Density Driven (IEDD) instability [*Ganguli et al.*, 1988a]. The IEDD plasma waves are driven by inhomogeneities in wave energy density created by the relative motion between layers of plasma. The laboratory experiments have demonstrated both the resonant [*Amatucci et al.*, 1994; *Koepke et al.*, 1994] and non-resonant [*Amatucci et al.*, 1996, 1998] manifestations of the IEDD instability. In the resonant regime, low levels of shear can modify the dispersive properties of a homogeneous plasma by modifying its resonance properties such as Landau damping or growth [*Ganguli et al.*, 1989; *Gavrishchaka et al.*, 1996]. In the non-resonant regime, a sufficiently strong shear can destroy the resonance conditions and can induce oscillations reactively by coupling neighboring regions with wave energy density of opposite sign [*Ganguli et al.*, 1988a]. This mechanism is likely to be important to the dynamics of ionospheric plasmas since recent in situ ionospheric measurements [e.g., *Bonnell*, 1997; *Louarn et al.*, 1994; *Marklund et al.*, 1994] have demonstrated that near-Earth space plasmas are often highly structured, with scale lengths as small as a few ion gyroradii. In particular, understanding the plasma response to sheared flows in collisional plasmas may be an important element in the identification of ion energization mechanisms at work in the low-altitude ionosphere.

In this paper, we present initial results from a laboratory study of the effects of ion-neutral collisions on non-resonant, shear-driven ion-cyclotron waves. The purpose of this investigation is to examine changes in the characteristic signatures of these waves with increasing neutral collisions and to determine the range of ionospheric altitudes in which they may be operative.

2. Experimental Observations

The experiments are conducted in the Naval Research Laboratory's Space Physics Simulation Chamber (SPSC), a 1.8-m-diameter by 5-m-long cylindrical vacuum vessel outfitted with a large-diameter microwave plasma source [*Walker et al.*, 1994; *Bowles et al.*, 1996]. The parameters of the steady-state argon plasma are: plasma density $n \approx 10^8$ cm^{-3}, ion and electron temperatures $T_i \approx 0.05$ eV and $T_e \approx 0.5$ eV, uniform axial magnetic field $B = 40$ G, ion gyrofrequency $f_{ci} = 1.5$ kHz ($\Omega_i = 9425$ rad/s), ion thermal speed $v_{ti} = 3.5 \times 10^4$ cm/s, ion gyroradius $\rho_i \equiv v_{ti}/\Omega_i = 3.7$ cm, electron gyrofrequency $f_{ce} = 110$ MHz ($\Omega_e = 7 \times 10^8$ rad/s), Debye length $\lambda_D \approx 0.2$ cm, plasma column diameter and effective length are 50 cm and 2 m, respectively. Wave and bulk plasma parameters are measured with heatable Langmuir probes [*Amatucci et al.*, 1993] and emissive probes.

At the base operational pressure of 3×10^{-5} torr for the experiments, the neutral density (primarily argon atoms) $n_n \approx 10^{12}$ cm^{-3}. This yields an ion-neutral collision frequency $\nu_{in} \approx 400$ s^{-1} and an electron-neutral collision frequency $\nu_{en} \approx 4 \times 10^4$ s^{-1}. Thus, the mean-free path for neutral collisions is comparable to the plasma column length, therefore collisional effects are minimal. The collision frequency between the argon ions and neutral argon atoms is calculated using a collision cross section $\sigma_{in} \approx 10^{-14}$ cm^2 [*Phelps*, 1991]. The ratios of the ion-neutral and electron-neutral collision frequencies to their respective gyrofrequencies are $\nu_{in}/\Omega_i \approx 0.04$ and $\nu_{en}/\Omega_e \approx 6 \times 10^{-5}$. Since these ratios are much less than unity, both plasma species remain well magnetized. The neutral gas pressure in the SPSC can be controlled continuously from the base pressure of $\sim 3 \times 10^{-5}$ torr to $\sim 3 \times 10^{-2}$ torr.

Figure 1 depicts the experimental setup. The IEDD instability was excited by inducing sheared azimuthal flow with a controllable, radially localized, dc electric field located within the cylindrical SPSC plasma column. This is accomplished with a grid structure made from concentric, coplanar, conducting ring electrodes [*Amatucci et al.*, 1996].

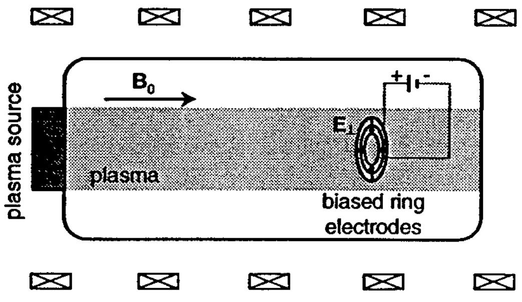

Figure 1. Schematic diagram depicting experimental setup and biasing circuit.

The ring electrodes are divided into inner and outer groups by electrically connecting each ring within a group. Application of different potentials to the inner and outer groups modifies the radial structure of the plasma potential, creating a localized, dc electric field. Particles entering the plasma column from the microwave source experience an adiabatic increase in the electric field to its peak value, leading to an azimuthal drift within a cylindrical shell (approximately two ion gyroradii wide).

Figure 2 shows the amplitude of the shear-driven ion-cyclotron waves as a function of the increasing ion-neutral collision frequency (normalized by the ion gyrofrequency). At the SPSC base operating pressure, the collisionless plasma conditions would correspond to ionospheric altitudes above $\sim$ 200 km. Mode amplitude is determined from ion saturation current fluctuations detected with a Langmuir probe. For ion-neutral collision frequencies $\nu_{in}/\Omega_i \lesssim 1.5$ the amplitude of the shear-driven ion-cyclotron waves is not strongly affected.

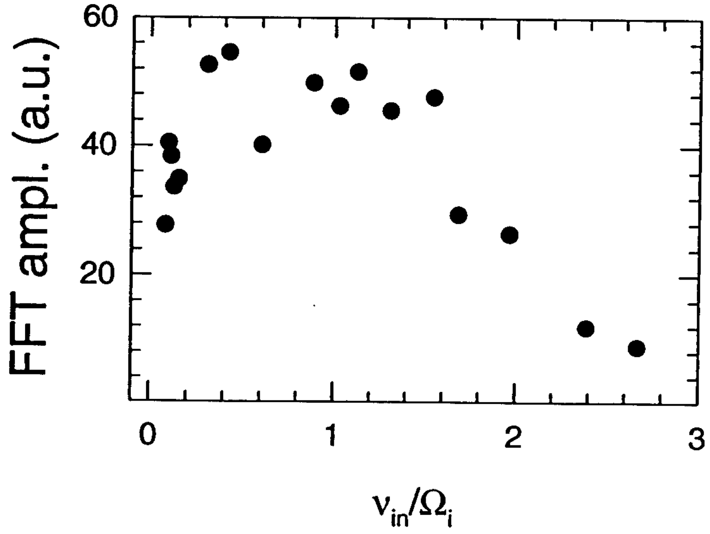

Figure 2. Collisional damping of the reactive IEDD instability.

However, when the neutral pressure is increased beyond this point, the wave amplitude is observed to steadily decrease. For collision frequencies exceeding $\nu_{in}/\Omega_i \approx 3$ (chamber pressure $\sim 2 \times 10^{-3}$ torr), the shear-driven ion-cyclotron waves are completely quenched. Collision frequencies of $\nu_{in}/\Omega_i \approx 2.7$ would correspond to ionospheric E-region altitudes. The suppression of the waves occurs because of the increased collisional damping.

By continuing to increase the ion-neutral collision frequency beyond the point where the shear-driven ion-cyclotron waves suppression begins, the onset of higher frequency oscillations is observed. Figure 3 shows a compilation of spectra observed as ν_{in}/Ω_i was increased. The fluctuations are first observed for $\nu_{in}/\Omega_i \approx 1.5$ at a frequency of $\sim$ 16.5 kHz ($\omega/\Omega_{ci} \sim 11$). As the ion-neutral collision frequency is increased, the mode is observed to upshift in frequency, to a peak of $\sim$ 21 kHz ($\omega/\Omega_{ci} \sim 14$), before being suppressed.

In this collisionality regime, the ions effectively become unmagnetized since ν_{in} becomes significantly larger than Ω_i. However, because of their much higher gyrofrequency, the electrons remain well magnetized and continue to execute $\mathbf{E} \times \mathbf{B}$ motion. This leads to the development of a cross-field current, leaving the plasma susceptible to streaming instabilities. When the magnitude of the transverse flow exceeds the ion acoustic speed, plasma waves can arise due to the Farley-Buneman instability. The linear theory of this modified two-stream instability was worked out independently by *Farley* [1963] and *Buneman* [1963], under the assumption that a uniform cross-field flow was established by a large scale transverse electric field. The predicted mode frequency for the Farley-Buneman instability for the experimental conditions is $f_{\mathrm{FB}} \sim 9\Omega_{\mathrm{i}}$. While this is in rough agreement with the experimental observations, the predicted Farley-Buneman mode frequency remains approximately constant over the range of experimental collision frequencies. However, as seen in Figure 3, the observed mode upshifts in frequency as ν_{in} is increased.

An important element of the experimental setup is the nonuniformity in the cross-field electron flow due to the localization of the transverse electric field [*Amatucci et al.*, 1996,1998]. In the case of sheared transverse flow in which electrons are magnetized, but the ions are not, modes with frequency in the lower-hybrid frequency range such as the electron-ion hybrid instability are possible as well [*Ganguli et al.*, 1988b; *Romero et al.*, 1992]. For the experimental conditions, the lower hybrid frequency $f_{\mathrm{LH}} \approx 300$ kHz. The effects of ν_{in} on the EIH modes can potentially affect the frequency spectrum. This topic is now under investigation.

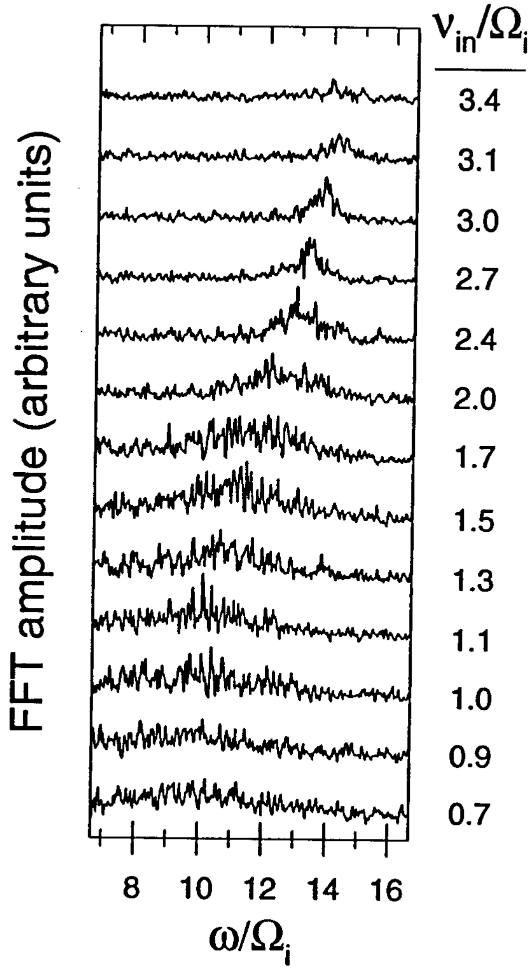

Figure 3. Composite plot of spectra as a function of increasing ν_{in}.

3. Conclusions

The results of these experiments demonstrate that velocity-shear-driven ion-cyclotron waves can be quite robust in the presence of ion-neutral collisions. In this work, waves were detected for a maximum ion-neutral collision frequency $\nu_{in} \approx 2.7\Omega_i$. This provides some indication that shear-driven processes may play important roles in the ionosphere, even in collisional plasmas such as the upper *E* region. Additional experiments performed in a different device to investigate the effects of collisions on the threshold of the resonant response of the IEDD mechanism have found a maximum collision frequency $\nu_{in} \approx 2.2\Omega_i$ [*Koepke et al.*, 1998b].

At E-region altitudes, where neutral densities are on the order of $10^{12} - 10^{13}\mathrm{cm}^{-3}$, ions become unmagnetized because their motion is dominated by collisions with neutral particles. Radar backscatter experiments and sounding rocket experiments have shown the existence of meter-scale irregularities existing within a narrow altitude range (95 - 105 km) in the E-region. Radar backscatter observations labeled Type 1 irregularities have been explained by the Farley-Buneman instability. However, strong inhomogeneities can exist within this region as well. For example, gradients in plasma density are often found in these regions. Depending upon their direction, density inhomgeneities can lead to meter-scale waves via the gradient drift instability [*Sahr and Fejer*, 1996]. These waves have been associated with Type 2 radar backscatter spectra [e.g., *Rogister and D'Angelo*, 1970]. Some types of observed irregularities (Type 3 and Type 4 radar echoes) have been associated with inhomogeneities in plasma flow. The waves responsible for these echoes often occur in highly localized regions during periods of intense auroral activity [*Fejer et al.*, 1986]. Type 3 waves have been clearly associated with large shears in the transverse plasma flow velocity, but in a collisional medium [*Fejer et al.*, 1984]. The correlation of sheared flow with Type 3 echoes was reaffirmed by interferometric radar observations of a discrete auroral arc, where bursts of Type 3 spectra were found within localized scattering regions along the poleward boundary of the arc [*Providakes et al.*, 1985]. The higher frequency mode observed for large values of ion-neutral collision frequency in this experiment may be relevant to these types of ionospheric irregularities.

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