Observations of Plasma Line Splitting in the Ionospheric Incoherent Scatter Spectrum

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Wide-bandwidth ionospheric incoherent scatter (IS) spectra obtained using the Arecibo IS radar show the occurrence of a split in the plasma line (i.e., two plasma lines) when the plasma frequency is close to the second harmonic of the electron gyrofrequency. This split is predicted in the IS theory for a magnetized plasma, but observations have never been reported. Here we present the experimental results and theoretical calculations supporting the observations. These results may assist in understanding the behavior of Langmuir waves in the magnetized plasma and are a validation of what historically was a somewhat controversial aspect of the IS theory.

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Introduction.—The theory of incoherent scatter (IS) from plasma was developed in the 1960s by several independent authors (e.g., [1–3]), and was soon refined to include a magnetic field (e.g., [4–8]), collisions (e.g., [9]), and other effects. Recently, the theory has been modified for radar probing angles very close to perpendicular to the magnetic field [10–12]; however, our present understanding on the incoherent scattering process is essentially unaltered from that of the 1960s. The validation of this theory was the first experimental verification of Landau damping [13].

The IS spectrum is divided into two components: an ion component (ion line) that is the result of scattering from the ion-acoustic waves in the ionospheric plasma, and an electron component that consists of two symmetric pairs of resonance lines called the plasma line and the gyro line. The plasma line can be interpreted as scatter from Langmuir (electron plasma) waves in the ionosphere, which are enhanced above their thermal level by the presence of the energetic photoelectrons during the daytime [13]. The plasma line frequency can be used to precisely measure the plasma frequency and consequently the electron density (e.g., [14,15]), and also to obtain electron temperature using slight asymmetries in the up- and down-shifted lines (e.g., [16]). The gyro line is associated with the electrostatic component of Whistler mode waves, which in turn are influenced by the electron gyro motion around the Earth's magnetic field lines [17]. The gyro line is associated with thermal velocities in the Maxwellian velocity distribution and does not get enhanced by the energetic particles.

The goal of the experiments described here was to investigate the role of low electron density and temperature conditions on the IS spectrum, after recently reported surprising observations of the gyro line [18,19], which has historically been very difficult to measure, with only one previously reported observation at Arecibo [20]. The experiments were conducted during the morning and the evening periods during the winter months at Arecibo, to investigate the effects of conjugate photoelectrons on this portion of the IS spectrum. The observations show a split in the plasma line when the plasma frequency passes through the second electron gyroharmonic. This effect was predicted in the early days of incoherent scatter theory [8], when it was noted that the dispersion relation for electron plasma waves exhibits "frequency gaps" (no roots) at some multiples of the electron gyrofrequency [21,22]. Instead, two roots appear, one on either side of the frequency gap [23]. The existence of these so-called frequency gaps in theory was met with doubt initially [24], despite theoretical confirmations using a different approach by Salpeter [8]. The practical implication of these predictions is that when the plasma frequency is near a gyroharmonic, the plasma line can split into two lines. First ever observations of this "split" are presented here with the supporting theory.

Observations.—The experiments described in this paper were carried out using the Arecibo 430 MHz IS radar (18°20' N, 66°45' W) in Puerto Rico. In December 2005, evening experiments were conducted in the period 1700–2000 LT (UT = LT + 4). A 500 μs uncoded long pulse (=75 km in range) with an interpulse period of 10 ms was transmitted to ensure a high signal-to-noise ratio (SNR) for the returned signal in order to study the weak features. The receiver bandwidth was 5 MHz (sampling rate = 0.2 μs). The radar was pointed 349° in azimuth, aligned with the magnetic meridian, and 15° offset from the zenith towards north. The dip angle at Arecibo is close to 45° at E- and F-region altitudes; hence, the angle between the radar pointing and the magnetic field (α) was close to 60°. All the spectra shown in this Letter have been integrated for 20 s (2000 pulses).

The evening results reported here were taken on December 23 and are representative of the observations on other days. The spectra were computed at four independent altitude bins, centered at—145, 217, 289, and

362 km. At 1700 LT, the electron density was low ($\leq 8 \times 10^{10}$ m^{-3}, corresponding to a plasma frequency of ~2.5 MHz). The F-peak was around 250 km. The plasma lines were observed at the two lower altitudes. Figure 1 is a frequency-time-intensity (FTI) plot at 217 km, showing the ion line centered at zero frequency offset, the gyro line starting at an offset of 500 kHz, and the plasma line starting at an offset of 2.5 MHz that decreases with time. The electron density decreases with time (plasma line moves towards the center). The plasma line trace is seen from 2.5 MHz ending at ~2.3 MHz, reappearing at ~1.8 MHz and ending at ~1.25 MHz. The gap between the disappearance and the reappearance of the trace is ~450 kHz. The center frequency of this gap (where the split occurs) is ~2 MHz, which is close to the second electron gyroharmonic at this altitude, the magnetic field intensity being 35 000 nT ($f_{ce} = 0.9$ MHz). The local sunset at this altitude was at 1901 LT. The plasma line trace disappears ~30 minutes before sunset. The box inserted in Fig. 1 shows sample individual spectra at 1 min intervals between 1726 to 1742 LT (time progressing upward). The split occurs close to 2 MHz.

Figure 2 shows a frequency-time-intensity plot for a morning experiment on November 22, 2006 with considerably more spectral structure. This experiment had the same parameters described above, except that the total receiver bandwidth was 10 MHz. The plasma line can be seen to increase in frequency from ~1.2 MHz beginning at 0430 LT. When it reaches ~2 MHz, the split occurs and the plasma line 'jumps' to an offset ~450 kHz higher. This plasma line indicates the presence of an intermediate layer of electron density, which typically occurs between the F and the sporadic E layers at night and is a result of the tidal oscillations in the neutral atmosphere [25]. Since we transmitted a long pulse, we were also able to see what we believe to be a second density layer occurring within the 75-km pulse, which starts to form around 0700 LT at an offset of 1.5 MHz. This can be seen more clearly in the subplot. The plasma line for this layer splits at 0730 LT, again at 2 MHz and it "jumps" to an offset of 2.3 MHz at 0737 LT. Note the wavy activity characteristic of intermediate layers, which are sharp density layers consisting mainly of metallic and molecular ions confined to a narrow region in altitude. These observations, showing two independent plasma layers jumping in frequency at the second electron gyroharmonic at different times, provide evidence that this frequency is indeed a crucial parameter.

Note that the gyro line does not seem to have any noticeable correlation with the split in the plasma line. The gyro line can be seen in both Figs. 1 and 2 and remains relatively constant in frequency close to the electron gyrofrequency multiplied by $\cos\alpha$, near ± 0.5 MHz. This is also consistent with the IS theory.

Discussion.—At high frequencies (i.e., frequencies corresponding to velocities much larger than the ion-acoustic speed), the electron density fluctuation spectrum observed with an IS radar is controlled mainly by the electrons, which can be thought of as the induced electron density fluctuations caused by a "test electron" as well as the intrinsic fluctuations of a noninteracting electron plasma [6]. Following the notation of Farley *et al.* [4], the density fluctuation spectrum including only electron effects for a Maxwellian velocity distribution may be written as

$$\frac{\langle |n_e(\mathbf{k}, \omega)|^2 \rangle}{N_e} = \frac{\lambda_e^4 k^4}{\omega} \frac{\mathrm{Re}(y_e)}{|y_e + i\lambda_e^2 k^2|^2}, \qquad (1)$$

or

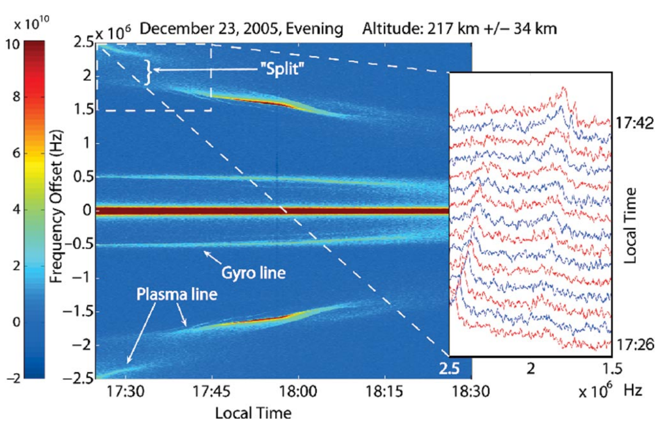

FIG. 1 (color). FTI plot showing the plasma line from 2.5 MHz to ~2.25 MHz, jumping to ~1.9 MHz and disappearing at ~1.4 MHz. The box inserted in the figure shows individual spectra for the period of 1726 to 1742 LT at an interval of approximately 1 min, and the frequency offset from 1.5 to 2.5 MHz. The color bar indicates relative intensity of the spectra.

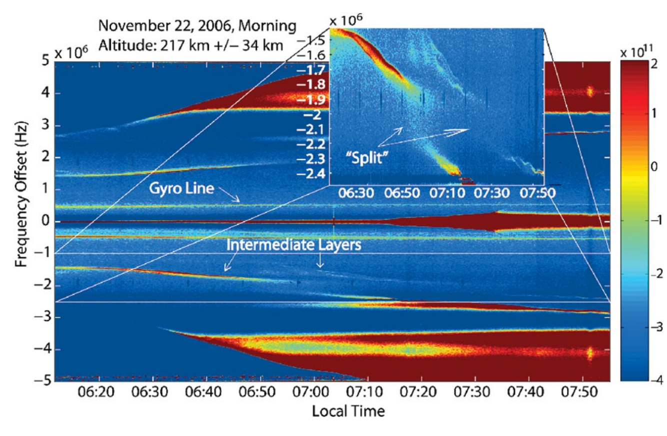

FIG. 2 (color). FTI plot from data obtained during the morning of November 22, 2006 for an altitude of 217 km. The sunrise at this altitude was at 0602 LT. The plasma line starts at 1.5 MHz at 0600 LT, splits at ~2 MHz and reappears at ~2.2 MHz at 0700 LT. Another density layer appears just before 0700 LT at ~1.6 MHz, splits at ~2 MHz and reappears at ~2.3 MHz at 0737 LT, which is clearer in the inserted subplot. The color bar indicates relative intensity of the spectra.

$$\frac{\langle|n_e(\mathbf{k},\omega)|^2\rangle}{N_e} = \frac{\lambda_e^4 k^4}{\omega}\frac{\mathrm{Re}(y_e)}{\mathrm{Re}(y_e)^2 + [\mathrm{Im}(y_e) + \lambda_e^2 k^2]^2}, \quad (2)$$

where we have neglected the effect of bulk electron motion. In this equation, λ_e is the electron Debye length; $k = 4\pi/\lambda$ is the Bragg scattering wave number where λ is the probing wavelength; and y_e is the electron admittance function. The admittance function neglecting collisions can be written as

$$y_e = i + \theta_e J(\theta_e), \quad (3)$$

where $\theta_e = \omega/kv_{\mathrm{the}}$ is a normalized radian frequency and $v_{\mathrm{the}} = \sqrt{2k_B T_e/m_e}$ is the electron thermal velocity (T_e = electron temperature, m_e = mass of the electron, k_B = Boltzmann's constant). The function $J(\theta_e)$ refers to a Gordeyev integral, which, when including the magnetic field effects but excluding collisions of all types, can be written as [4]

$$J(\theta_e) = \int_0^\infty e^{-i\theta_e t - \phi_e^{-2}\sin^2\alpha \sin^2(1/2)\phi_e t - (1/4)t^2\cos^2\alpha} dt, \quad (4)$$

where $\phi_e = \Omega_e/kv_{\mathrm{the}}$ is a normalized gyrofrequency. The Gordeyev integral may be interpreted as the one-sided Fourier transform of the single particle autocorrelation function (e.g., [10,11]).

We note that equating the denominator of (1) to zero corresponds to the dispersion relation for free oscillations (normal modes) in the plasma [4]. Since $\mathrm{Re}(y_e)$ is very small, it can be shown that resonances occur when the following expression is satisfied:

$$\mathrm{Im}(y_e) + \lambda_e^2 k^2 = \lambda_e^2 k^2 + \frac{\sin^2\alpha}{2(\phi_e^2 - \theta_e^2)} + \frac{(\sin^2\alpha - 2\phi_e^2)\cos^2\alpha}{4\phi_e^2\theta_e^2} = 0. \quad (5)$$

There are two roots to this equation, one corresponding to the gyro lines and the other corresponding to the plasma lines. The plasma line dispersion relation after some simplification is

$$\omega^2 = \omega_{\mathrm{pe}}^2 + \frac{3}{2}k^2 v_{\mathrm{th}}^2 + \Omega_e^2 \sin^2\alpha. \quad (6)$$

All the calculations in our analysis have been carried out with Arecibo radar parameters. In Fig. 3, the electron density spectrum in the region of parameter space where the interesting behavior discussed above occurs is plotted. The density is varied and the spectrum is plotted for two different values of electron temperature, with constant $\alpha = 60°$. It is apparent that as the plasma line passes through the second harmonic of the gyrofrequency (denoted by the dashed line), it is split into two resonances, which is the feature apparent in Figs. 1 and 2. Other noticeable effects are (a) the gyro line, which is stronger at lower densities, in agreement with the theoretical expressions of Salpeter [8] and the observations of Janches and Nicolls [19] and

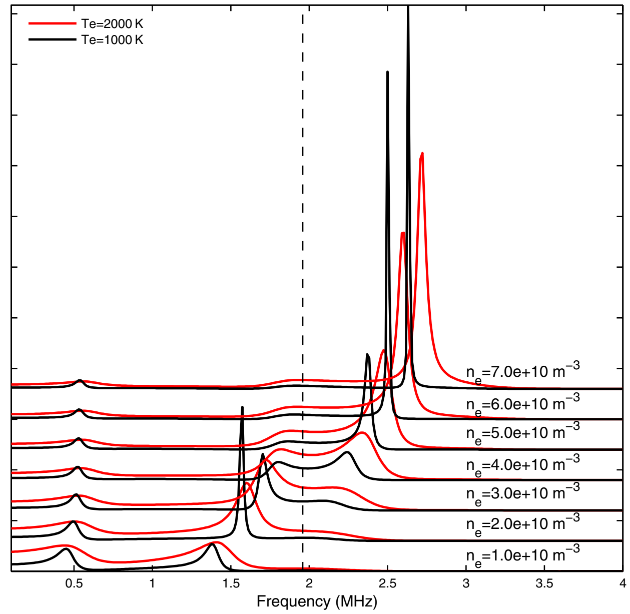

FIG. 3 (color online). Theoretical spectra calculated for two different values of electron temperature, varying electron density, and $\alpha = 60°$. The electron density increases from bottom to top. The split is shown by the dashed line.

(b) the broadening effects of the temperature. Both of these properties may have useful applications for ionospheric measurements.

However, plasma line splitting depends on the value of α. Splitting does not occur below a threshold for α, which was discussed by Perkins [23]. To estimate that critical angle, a simple method is to note that an additional resonance indicates an additional region where the slope of $\mathrm{Im}(y_e)$ is zero (resulting in an additional spike in the spectrum). Evaluating the derivative of $\mathrm{Im}(y_e)$ at $\theta_e = 2\phi_e$ using a power series expansion of the plasma dispersion relation about 0, the appropriate condition to be satisfied is

$$\frac{9(\sin^2\alpha_2 - 2\phi_e^2)\cos^4\alpha_2}{2\phi_e^2(16 - 25\sin^2\alpha_2)\sin^2\alpha_2} = 1, \quad (7)$$

which depends on T_e and α. Taking the case of T_e = 1000 K ($\phi_e = 2$), we find $\alpha_2 = 56°$, in agreement with the calculations of Perkins [23]. Including $\mathrm{Re}(y_e)$ in this estimate results in a small correction, and we find $\alpha_2 = 57.3°$ in that case. At probing angles above this critical angle, a double hump will appear near the plasma frequency. The two peaks will be given by the broadening of the hump, which is determined by the temperature and is about $kv_{\mathrm{the}}/2\pi$. A calculation for the third gyroharmonic indicates that the resonance will occur above a critical angle of $\alpha_3 \approx 75°$, and for the fourth gyroharmonic, $\alpha_c \approx 86°$. In the limit of probing angle approaching perpendicularity, harmonics should be observed at all gyroharmonics. We note that the limit of Arecibo scanning is

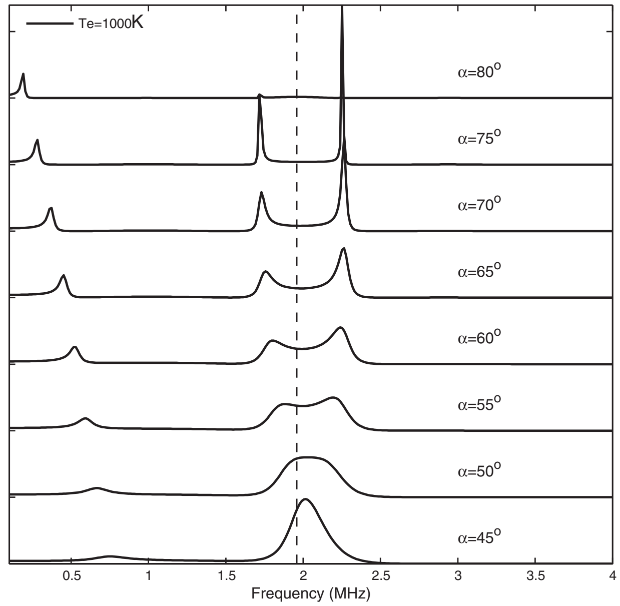

FIG. 4. Theoretical spectra calculated for different values of α. These spectra are calculated for $T_e = 1000$ K and $N_e = 4.0 \times 10^{10}$ m^{-3}. For Arecibo parameters, the split occurs only in the range of $55° \leq \alpha \leq 75°$.

$\alpha \sim 60°$; however, other systems could look for other harmonics (although detecting the plasma line at low densities can be difficult with most IS systems).

In Fig. 4, we plot the theoretical spectra for several values of α at a constant electron density 4×10^{10} m^{-3} and $T_e = 1000$ K. At about 55° we see the presence of the double hump, as expected. The lines get narrow with increasing α. The separation of the humps is about $kv_{\mathrm{the}}/2\pi$, but does vary slightly with α. Also evident in this plot is the increasing power of the gyro line as the probing geometry approaches perpendicular to the magnetic field.

Conclusion.—We have presented here results obtained from evening and morning time experiments at the Arecibo Observatory, where we were able to make observations of the entire IS spectra at low electron densities. As predicted by the IS theory, when the plasma frequency is near the second gyroharmonic, the plasma line splits into two resonances, and is greatly enhanced when it comes out of the split. Our observations also indicate that the split occurs regardless of the energy in (intensity of) the plasma line. We have observed split plasma line in weak intermediate layers during morning experiments, when the layer passes through second gyroharmonic.

In recent years, high latitude ionospheric modification experiments done at the second gyroharmonic have produced some interesting results using optical diagnostics [26,27]. An enhancement in the artificial airglow has been observed while heating the ionosphere at second gyroharmonic. It has been suggested that the Langmuir waves participate in the electron cyclotron acceleration when the local plasma and electron gyrofrequencies match [28]. We plan to make further observations to investigate this effect using an ISR as a diagnostic tool for an ionospheric modification experiment.

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