OBSERVATIONS OF IONIC SOUND WAVES IN PLASMAS

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The object of this Letter is to report the observation of ionic sound waves in a typical discharge-tube kind of plasma, and also in a plasma restricted by the presence of a magnetic field. Earlier, partial reports of these experiments have been given local distribution.[1-3] The earliest work in this field is thought to be the prediction of ionic sound waves in plasmas by Tonks and Langmuir in 1929.[4] The fundamental frequency and first and second overtones were found in a mercury vapor discharge confined in a spherical tube by Revans in 1933.[5] He also showed evidence for radial standing waves in a cylindrical tube. Data from the recent discharge-tube experiments of Crawford[6] have been analyzed by this laboratory[1] and by Moore[7] and shown apparently to exhibit ionic sound waves. Additional work by Crawford[8] confirms this analysis.

The theory of propagation of ionic sound waves is much like that of ordinary sound waves. The velocity v of an ionic sound wave is related to the electron temperature T_e and the ion mass m_i by the expression

$$v = (\gamma k T_e / m_i)^{1/2}.$$

Here k is Boltzmann's constant and γ is the adiabatic compression coefficient which is $\frac{5}{3}$ for ordinary sound waves and may be as high as 3 in rare plasmas.[9]

If the plasma is restricted to a long cylindrical column by a magnetic field and the sound wave is reflected similarly at each end, standing ionic sound waves may result as ordinary sound waves do in an open organ pipe. Then the fundamental frequency should be $v/2L$, where L is the length of the column, and the harmonics should be integral multiples of the fundamental.

If the plasma is confined by a spherical discharge tube without a magnetic field, the frequency of the fundamental is v/CD, where D is the sphere diameter, and C is a constant that can be 1.51 or 1.0 depending on the plasma boundary conditions. Higher frequency modes of oscillation should occur, but their frequency also depends on the boundary conditions. For a pressure antinode at the wall ($C = 1.51$), the frequency ratios for the first six overtones to the fundamental are 1.61, 2.16, 2.17, 2.71, 2.85, 3.25.

A schematic diagram of the apparatus which produced the cylindrical plasma column is shown in Fig. 1 (inset). The plasma column was produced by a $\frac{1}{4}$-inch diameter electron stream (up to one ampere) from a negatively biased (up to -120 volts) hot filament. The magnetic field could be varied from 1000 to 7000 oersteds. The frequency as observed on a wire probing the column was found to be grossly independent of the magnetic field and the filament bias. It did not depend on background gas pressure which was uniform over the length of the column and in the range 10^{-4} to 10^{-3} mm Hg. The filament temperature had the most effect on the frequency which could be "pulled" slightly but which would change discontinuously to a higher mode if "pulled" too far. The amplitude of the probe signal varied considerably (more than 20 volts) with change in the above parameters. Sinusoidal frequencies were observed up to the fifth harmonic. At times the wave shape gave evidence of higher harmonics present with the fundamental.

The observed variation of frequency with ion mass for two lengths of plasma column is shown in Fig. 1. The solid lines are the theoretical curves for a γ of 3, and an electron temperature of 17 ev, the average of the first excitation potential of the inert gases. Electron temperature measurements made with a Langmuir probe were within a factor of two of this value. Obtaining reliable probe characteristic curves proved to be very difficult under the conditions of operation. In general, gases whose first excitation potential was greater than 17 ev supported standing waves with frequencies higher than predicted, and lower excitation potentials resulted in correspondingly lower frequencies.

For a convincing proof of the existence of these waves it was felt that they should be exhibited in a different system, one not using a magnetic field. After preliminary experiments, a spherical glass discharge tube was chosen instead of the usual cylindrical type. It was thought that the lowest mode of oscillation in a sphere might be less damped, as this mode involves no transport of matter parallel to the wall. The diagram of the sphere is shown schematically in Fig. 2 (inset). The sphere is glass with a hot cathode of tungsten wire and a metal disk as an anode. Both are flush

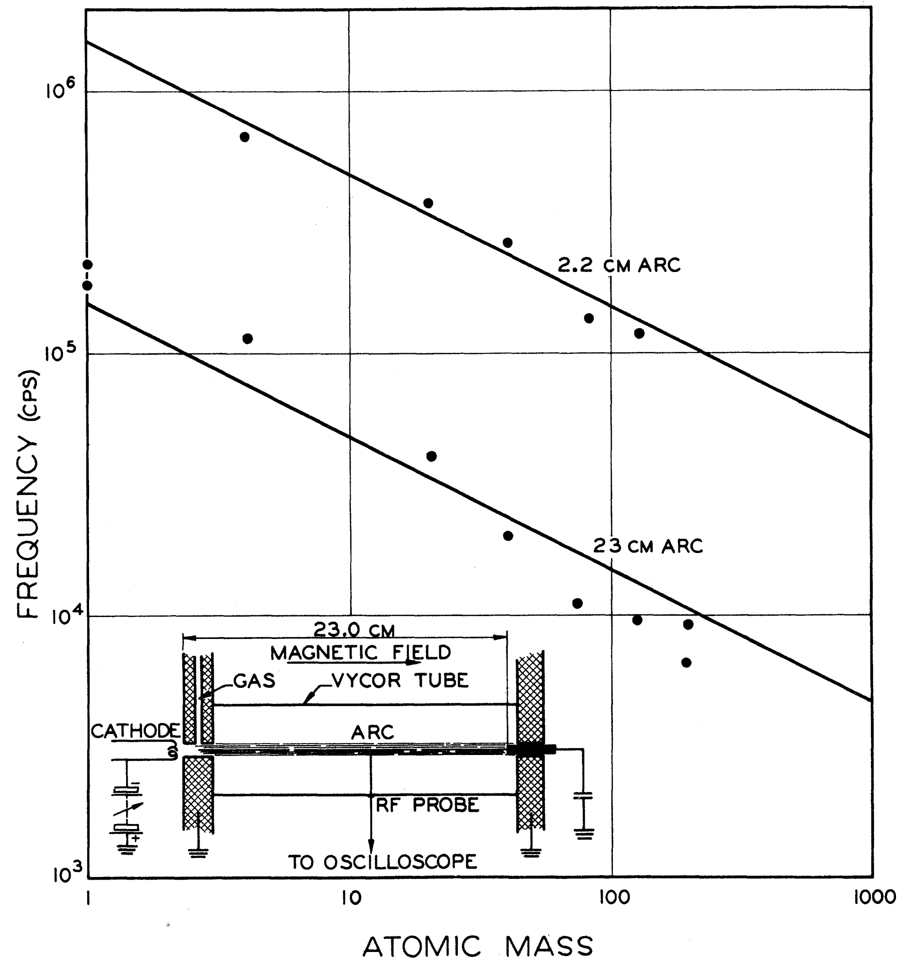

FIG. 1. Frequency vs atomic mass for two lengths of plasma column. The inset is a schematic diagram of the 23-cm arc. The 2.2-cm arc was excited in the same manner.

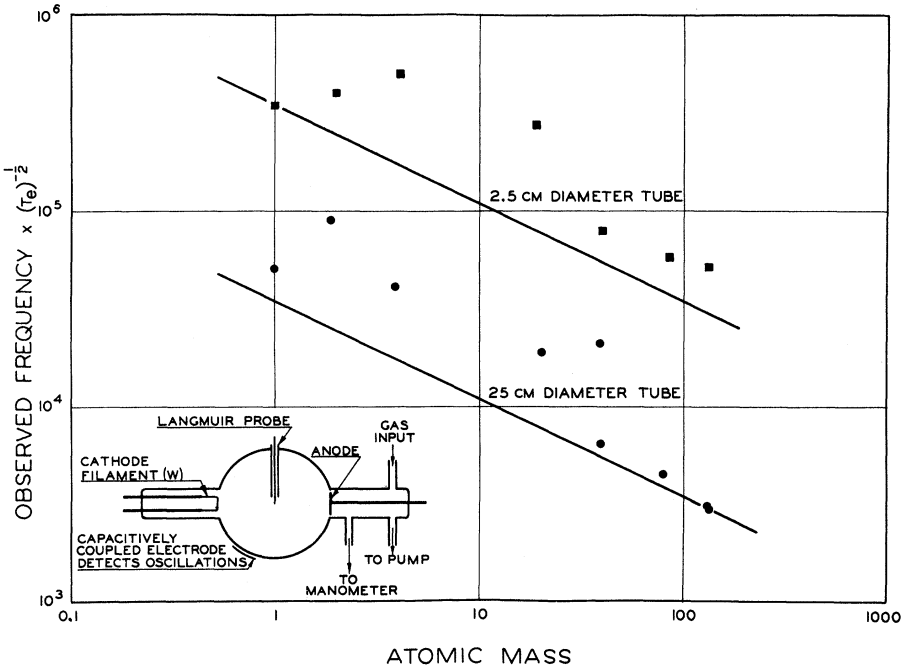

FIG. 2. Frequency vs atomic mass for two diameters of spheres. The inset is a schematic diagram of the sphere geometry. Electrode sizes were proportional to sphere diameter in each size sphere.

Table I. Ratios of frequencies observed to the fundamental for the different gases used. The calculated ratios are given in the left-hand column. The lowest frequency observed for helium, neon, and argon was thought to be the first overtone since this provided a better fit of the data.

$C=1.51$	Hydrogen	Helium	Neon	Argon	Krypton	Xenon
1	1				1	1
1.61	1.46	1.61	1.61	1.61	1.75	1.57
2.16			1.93		2.00	2.16
2.17		2.30	2.22	2.20		
2.71		2.72			2.59	2.63
2.85						
3.25			3.43			

with the wall and on opposite ends of a diameter. A Langmuir probe in the center was used to measure the electron temperature. Oscillations were detected by means of a capacitively coupled electrode outside of the sphere. Pressures of about 10^{-2} mm Hg and currents of 100 ma resulted in oscillation amplitudes of about one volt in the detection circuit. Varying the discharge parameters caused the oscillation frequency to change discontinuously to the higher frequency modes. The lowest frequency mode that was thought to correspond to the fundamental of the sphere was very difficult and sometimes impossible to excite. Probably some asymmetry in the sphere preferentially excited higher frequencies, and the high gas pressure needed to maintain the discharge in the sphere preferentially damped the lower frequencies.

In analogy with the plasma column work the lowest frequency observed in plasmas of different atomic mass and for spheres of 2.5 and 25 cm in diameter are plotted in Fig. 2. As the measured electron temperature now varied widely, all frequencies were normalized to an electron temperature of 1 ev. The solid lines represent the lines of slope $(-\frac{1}{2})$ which pass through the lowest observed frequency for both sphere diameters. Assuming that the lines pass through the fundamental frequencies, $\gamma=\frac{5}{3}$ and $C=1.51$. The value $\gamma=\frac{5}{3}$ is reasonable for the spheres in view of the high gas pressure in the discharge. In general the frequency is seen to be proportional to $(D)^{-1}$ and $(m_i)^{-1/2}$. Apparently the fundamental was not excited in some of the gases.

As many as four different frequencies have been observed for one gas. Classification is difficult because the fundamental might not have been excited and the frequency on an overtone may be altered by possible changes in the boundary conditions. An attempt at classification appears in Table I.

Another complication in working with ionic sound waves in discharge tubes appears if the pressure is too high. At about 1 mm Hg strong oscillations appear which are lower in frequency than the fundamental of the ionic sound waves. These frequencies apparently correspond to ordinary sound waves in the residual gas.

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