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## Abstract

## Full Text

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## PHYSICS

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# WAVES AND NOISES IN THE PLASMA OF A POSITIVE COLUMN AT  
LOW PRESSURE

*(Presented by Academician M. A. Leontovich on 6 IV 1966)*

Earlier <sup>(1)</sup> it was shown experimentally that, in addition to striation oscillations, waves also propagate in a plasma column at low pressures (of the order of  $10^{-2}$  mm Hg and lower), whose properties agree with the predictions of the theory for electroacoustic plasma waves <sup>(2)</sup>. In <sup>(1)</sup> these waves were excited artificially. Subsequently, waves of this type were observed by various authors, in particular in <sup>(3-5)</sup>.

In most experiments the dc discharge was produced between an oxide cathode and a hollow anode in glass tubes with diameters of 3 and 4 cm and a length of 80 cm. Measurements were carried out in Ne, He, Ar, and in a Ne + He mixture at pressures in the range from  $5 \cdot 10^{-1}$  to  $5 \cdot 10^{-3}$  mm. Waves in the region of the positive column were studied with the aid of a photoelectronic multiplier and an oscilloscope. To record the frequency spectrum of fluctuations of the discharge glow and of the voltage on the tube electrodes, a spectrum analyzer of the S4-8 type was used. The plasma was acted upon to excite waves at frequencies from 20 to 500 kHz either by the method described in <sup>(1)</sup>, or with the aid of a short coil.

In earlier investigations <sup>(6,7)</sup> the occurrence of striations in the positive column at pressures below 0.1 mm was not found. In the experiments described, as in <sup>(1)</sup>, natural (self-excited) or artificially produced striations moving in the direction toward the cathode were observed at lower pressures, down to  $\sim 10^{-2}$  mm. The lower pressure limit for the existence of a layered positive column ( $P_{\text{lim}}$ ) in different gases corresponds to mean free paths of positive ions comparable with the tube radius ( $\lambda_+ \simeq R$ ). In Ne and Ar the natural striations persisted when the pressure was reduced to values close to the limiting value, but became weak. In He at  $p < 0.5$  mm, within the limits of the currents used, striations do not arise spontaneously (the positive column is homogeneous), but under these conditions they could be excited artificially. Table 1 gives the measured values of the length  $l_c$  and frequency  $f_c$  of natural moving striations, as well as the values of the velocity of their motion  $v_c = l_c f_c$  in neon and argon for values of the product  $Rp$  from 1 to 0.01 cm · mm Hg. The same table gives values of

the electron temperature  $U_-$  in neon plasma, obtained by the Langmuir-probe method. The values presented in this table refer to discharge currents of 0.3–0.5 A.

The table shows that the length  $l_c$  slowly increases as the pressure decreases, and its value reaches approximately 15 tube radii at the lowest pressures. Since the electron mean free path for collisions with atoms  $\lambda_-$  depends on pressure much more strongly than  $l_c$ , the value of the ratio  $l_c/\lambda_-$  changes with  $p$  over very wide limits. As the pressure decreases, this ratio falls to a value of 1.5–2 at the very lowest pressure at which striations still exist.

In a narrow pressure range near  $P_{\text{lim}}$ , striations are excited artificially. In Fig. 1 the dotted curves show the dispersion characte-

characteristics (angular frequency  $\omega$  as a function of wave number  $k$ ) for excited moving striations, obtained from measurements in helium at  $Rp = 0.03$  and in neon at  $Rp = 0.015$  with a tube of radius 1.5 cm. The data given refer to a current of 0.3 A. As can be seen,  $\omega$  decreases with increasing  $k$ , i.e., the character of the dispersion here is the same as for moving striations (anode  $\rightarrow$  cathode) at comparatively high pressures (<sup>1, 8</sup>). The values of the velocity  $v_c$  vary from  $3.3 \cdot 10^5$  to  $23 \cdot 10^5$  cm/sec in helium and from  $1.9 \cdot 10^5$  to  $20 \cdot 10^5$  cm/sec in neon when the frequency  $f_c$  is varied, for these two cases, within the ranges 40–140 and 20–80 kc/s, respectively.

(Figure: Fig. 1)

**Fig. 1.** Dispersion characteristics of moving striations (dashed curves) and electroacoustic waves (solid curves) at  $R = 1.5$  cm (a) and  $R = 2$  cm (b). Discharge current 0.2 A.

In the indicated pressure region in the positive column, space-charge waves were also excited which propagate in the direction toward the anode. Experiments showed that somewhat below this pressure ion-sound waves appear spontaneously. To investigate the dispersion of the waves mentioned, measurements of the wavelength were carried out at various fixed frequencies. To isolate individual frequencies from the broad fluctuation spectrum, the output signal of the photoelectronic multiplier was fed to an oscilloscope through a filter with variable tuning.

**Table 1**

| Gas | Quantity | $Rp,$<br>cm ·<br>mm |     |     |     |      |      |      |
|-----|----------|---------------------|-----|-----|-----|------|------|------|
|     |          | Hg                  |     |     |     |      |      |      |
|     |          | 1                   | 0.5 | 0.3 | 0.1 | 0.05 | 0.02 | 0.01 |
| Ne  | $l_c/R$  | 7.1                 | 8   | 8.3 | 10  | 11.2 | 13   | —    |

| Gas | Quantity  | $Rp,$   |      |      |     |      |      |      |
|-----|---|---------|------|------|-----|------|------|------|
|     |   | cm · mm | Hg   |      |     |      |      |      |
| Ne  | $Rf_c \cdot 10^{-4},$<br>cm · sec <sup>-1</sup> | 0.8     | 1.3  | 2    | 4   | 5.3  | 10   | —    |
| Ne  | $v_c \cdot 10^{-5},$<br>cm · sec <sup>-1</sup>  | 0.56    | 1.04 | 1.66 | 4   | 5.9  | 13   | —    |
| Ne  | $U_-,$<br>eV                                    | 2.8     | 3.2  | 3.4  | 4.4 | 5.8  | 7.3  | 10   |
| Ar  | $l_c/R$   | 9.1     | 10   | 10.5 | 12  | 12.8 | 14.2 | 14.8 |
| Ar  | $Rf_c \cdot 10^{-4},$<br>cm · sec <sup>-1</sup> | 0.19    | 0.32 | 0.5  | 1.1 | 2.2  | 5    | 8    |
| Ar  | $v_c \cdot 10^{-5},$<br>cm · sec <sup>-1</sup>  | 0.17    | 0.32 | 0.53 | 1.3 | 2.84 | 7.1  | 11.8 |

The results for the dependence of  $\omega$  on  $k$ , obtained from measurements in helium and neon plasma, are presented in Fig. 1 in the form of solid curves, for values of  $Rp$  equal to 0.015 for helium and 0.01 for neon. The curves are straight lines whose continuations pass through the origin. Thus,  $\omega$  is proportional to  $k$ , i.e., the wave velocity does not depend on frequency. This is the dispersion law corresponding to electroacoustic waves of a plasma <sup>(1)</sup>, for which the phase and group velocities are determined as

$$\frac{\omega}{k} = \frac{d\omega}{dk} = \left( \frac{\gamma_- k T_-}{m_+} \right)^{1/2}, \quad (1)$$

where  $k$  is Boltzmann's constant,  $m_+$  is the ion mass,  $T_-$  is the electron temperature, and  $\gamma_-$  is the adiabatic index for the electron gas.

For a helium plasma with electron temperature  $T_- = 170 \cdot 10^3$  °K, obtained under the conditions of the present experiment, formula (1) with  $\gamma_- = 1$  gives a velocity value of  $1.9 \cdot 10^6$  cm/sec, which is somewhat lower than the measured value, equal to  $2.3 \cdot 10^6$  cm/sec. In the case of a neon plasma with temperature  $T_- = 120 \cdot 10^3$  °K, it gives a value somewhat larger ( $6.9 \cdot 10^5$  cm/sec) than that observed experimentally ( $6.4 \cdot 10^5$  cm/sec).

The excitation of ion-acoustic waves in a nonequilibrium weakly ionized plasma, in which the electrons have an established drift velocity relative to the ions, was theoretically considered by G. Gordeev<sup>(9)</sup> and by other authors<sup>(10–12)</sup>. It was shown that, for a sufficiently large electron drift velocity  $v_{d-}$  and a sufficiently low frequency of collisions of ions with atoms  $\nu_+$ , the plasma becomes unstable with respect to excitation of ion-acoustic oscillations. The condition for wave growth has the form<sup>(9,12)</sup>

$$\frac{v_{d-}}{v_-} > \left(\frac{2}{\pi}\right)^{1/2} \frac{\nu_+}{\omega_+} \frac{[1 + k^2/k_-^2]^{3/2}}{k/k_-} \quad \text{for} \quad \frac{\omega_+}{\nu_+} > 1, \quad (2)$$

where  $v_- = (kT_-/m_-)^{1/2}$  is the mean electron velocity ( $m_-$  is the electron mass),

$$\omega_+ = (4\pi e^2 n_0 / m_+)^{1/2}$$

( $m_+$  is the ion mass,  $n_0$  is the plasma density),

$$k_-^2 = 4\pi e^2 n_0 / kT_-.$$

In expression (2), the equality sign determines the boundary between growing and damped waves for a given drift velocity  $v_{d-}$ . For oscillations with wavelength much greater than the Debye radius ( $k^2/k_-^2 \ll 1$ ), we obtain the lower limit of the wave number for propagating waves

$$k_{\text{pred}} = \left(\frac{2}{\pi}\right)^{1/2} \frac{\nu_+}{v_{d-}} \sqrt{\frac{m_+}{m_-}}. \quad (3)$$

The theory should be applicable to our experiments<sup>(13)</sup>. In the measurements the electron density  $n_0$  was only  $10^9 - 5 \cdot 10^9 \text{ cm}^{-3}$ .

Using (3), one can obtain the value  $k_{\text{pred}} = 0.49$ , if one uses the value  $v_{d-} = 10^8 \text{ cm/sec}$  at  $E/p = 140 \text{ V/cm} \cdot \text{mm}$ <sup>(14)</sup> and  $\nu_+ = 7 \cdot 10^5 \text{ sec}^{-1}$ <sup>(15)</sup> for helium at  $Rp = 0.015$  and  $p = 10^{-2} \text{ mm}$ . The experimental value is  $k_{\text{pred}} = 0.56$ . The theory also correctly reflects the character of the change in  $k_{\text{pred}}$  as a function of  $p$ . At the same value of  $Rp$ , for  $p = 7 \cdot 10^{-3} \text{ mm}$  ( $R = 2 \text{ cm}$ ), the value of  $k_{\text{pred}}$  according to formula (3) is 0.34, whereas the measured value is 0.42.

When a hot cathode is used, part of the noise may be associated with oscillations of the potential minimum near the cathode and with oscillations of the near-cathode ion sheath. In the present work, in one series of experiments the discharge was investigated between a water-cooled hollow cylindrical cathode about 10 cm long and 3 cm in diameter and a hollow movable anode in a tube of uniform cross section (diameter 3 cm). In this case the gas pressure in the

tube was varied from 1 mm to  $\sim 0.03$  mm, and the maximum current was 0.15 A. In all the gases studied, when the pressure was decreased, beginning at approximately 0.1 mm, characteristic noises appeared in the discharge with a maximum intensity in the range 0.1–0.5 MHz, depending on the kind of gas, as was noted in works (<sup>13,16</sup>), in which a hot cathode was used. In Ne and He these noises arose in the presence of moving striations in the positive column, and in helium—in the absence of striations. In a mixture of Ne and He, depending on the proportion in which the mixture was taken, the positive column could be stratified or homogeneous.

Figure 2 shows the frequency spectra of fluctuations of the discharge glow in He and in a Ne + He mixture. In Fig. 2a, b, c the first maximum ( $f = 68$  kHz) corresponds to striation oscillations. As can be seen, with increasing distance from the head of the column toward the anode the striation oscillations intensify, while the noises with maximum amplitude in the region of 0.2 MHz sharply weaken. The same weakening of the noise occurs in a helium discharge, where the column is homogeneous. The voltage fluctuations at the electrodes of the tube correspond in shape to the fluctu-

tions of the emitted light. The amplitude of the voltage fluctuations increases as the pressure is decreased from 0.1 to  $3 \cdot 10^{-2}$  mm, from tens of microvolts to hundreds of millivolts. The noises persisted when the electrodes were brought closer together until the positive column disappeared. They are not observed when only the cathode parts of the discharge are placed between the cathode and the anode. Under the experimental conditions, anode oscillations were absent (<sup>17</sup>).

**Fig. 2.** Spectrograms of the noises of a discharge with a cold cathode. Discharge current 0.2 A. *a*—He,  $p = 0.05$  mm; *b, c, d*—Ne + He (mixture ratio 1 : 1), total pressure 0.03 mm; distance from the head of the column: *a*—1.5 cm, *b*—5 cm, *c*—8 cm. Frequency marker: *a*— $f = 0.5$  MHz; *b, c, d*— $f = 0.28$  MHz.

The fact that the amplitude of the observed fluctuations is maximal in the region of the head of the positive column and rapidly decreases toward the anode is substantial evidence for the generation of noise in this region. This phenomenon is probably associated with ion-acoustic types of oscillations. It should be noted that at the beginning of the positive column there is a field accelerating the electrons, and the electron flux does not immediately acquire a stationary velocity distribution. This circumstance prevents the exact application of the theory in the present case.

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