The Transmission of Waves Through an Ionized Gas

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A discharge in mercury vapor at approximately 0.001 mm pressure maintained in a 9 cm spherical bulb between a hot filament and a nearby disk anode was found to become oscillatory at a value of the filament current which depended on the anode potential and was quite definite for a given voltage. By means of a movable probe, the energy of the electrons was determined at various points in the nonoscillating and in the oscillating discharge. When oscillations set in, the electron temperature increased markedly. The frequencies present seemed to consist of a fundamental and a long series of harmonics ranging from about 2×10^4 to 10^6 cycles per sec. The fundamental was constant over a wide range of anode currents and voltages and its frequency was in good agreement with that calculated on the basis of Sir. J. J. Thomson's theory. The overtone that was most intense changed discontinuously with the anode current as though the discharge favored one mode of oscillation at one time as does an organ pipe. It was concluded that the glow was vibrating as a whole in a manner similar to the air in a Helmholtz resonator. A movable probe maintained about ten volts positive with respect to the filament collected currents that showed variations with position and had two or three marked maxima and minima along a diameter of the spherical bulb. In a long cylindrical tube, the currents collected by a probe moved along the tube axis showed no maxima or minima, but those collected by a probe moved along a diameter varied in a manner similar to those in the spherical bulb.

INTRODUCTION

THE existence of electrical oscillations through electrical discharges in gases at low pressures has been known for many years. Such oscillations may be grouped into two broad classes, of essentially different character. The first kind are those whose frequency is a function of the constants of the external circuit used to maintain the discharge, such as capacity-resistance oscillations for the generation of which the discharge tube acts mainly as a valve for controlling the fluctuations of potential in the external circuit. The inductance-capacity oscillations of the Duddell singing arc are of the same character. The second kind are due to the properties of the ionized gas itself, and have been called "ionic oscillations." They have been investigated by a number of observers,[2] including Tonks and Langmuir,[3] and, theoretically, by Sir J. J. Thomson,[4] by whom a complete supporting theory has been developed. It is the object of this paper to describe experiments in which the oscillations have manifested themselves as travelling waves. It is believed that such waves and oscillations may be of great importance in the structure of stellar atmospheres, and theoretical work along these lines is being continued.

APPARATUS

The discharge tube and its connections are shown diagrammatically in Fig. 1. The remainder of the apparatus consisted of a two stage mercury vapor pump, kept running during the observations, and the usual vacuum system. A pressure of less than 10^{-6} mm of residual gas was maintained. Several differently shaped tubes were used, but the majority of observations were with a spherical bulb of 9 cm diameter and a long cylindrical tube of 10 cm diameter and 130 cm length. The tubes were provided with water-cooled ground joints. The cooling water served to keep the mercury vapor at an almost constant pressure of 0.0006 mm for the temperature of the water supply did not vary by more than 0.5°C. A little mercury condensed inside the joints, and as the tube was maintained at a much higher temperature by the heating from

[1] Commonwealth Fellow.

[2] Penning, Phys. Zeits. **27**, 187 (1926); Webb and Pardue, Phys. Rev. **32**, 946 (1929); Fox, Phys. Rev. **35**, 1066 (1931); Chow, Phys. Rev. **37**, 574 (1931); Brown and Cowan, Phys. Rev. **38**, 376 (1931).

[3] Tonks and Langmuir, Phys. Rev. **33**, 195 (1929).

[4] J. J. Thomson and G. P. Thomson, *Conduction of Electricity through Gases*, Part II, page 353.

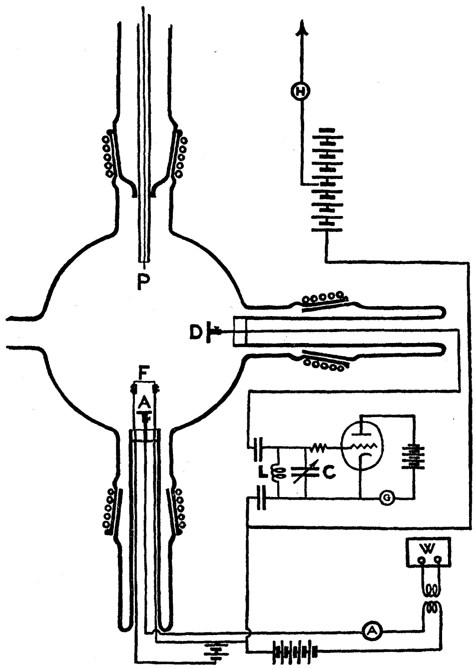

FIG. 1. The discharge tube and control circuits.

the filament, the pressure of the mercury vapor was that of the condensation. The tube was carefully screened with an electrostatic shield. One of the ground joints carried the filament *F* and the anode *A*, which was a circular nickel disk 1 cm in diameter, placed behind the filament in a position that was unimportant. Filaments of various forms were used, either of 5 mil tungsten, straight or spiral, or of oxide coated platinum. Immediately opposite this joint was a second carrying a probe *P*, whose position in the discharge could be altered by means of an electromagnet. The probe was either a small nickel disk or a short fine tungsten wire. The third joint, *D*, carried another plate which could be used as an additional anode, or a collector on which to detect the oscillations. The long tube was provided with a similar set of ground joints and sliding probes, one for moving along the tube axis and another for moving radially across the tube.

The external circuits comprised: (a) The filament heating circuit. (b) The anode circuit, consisting of a battery of 30 accumulators, to provide the arc current, and a milliammeter. The leads were made as short as possible and the resistance of the circuit was reduced to a minimum by shortcircuiting the meter with a key. At times, a coil of 6 turns of copper wire was introduced into this circuit to act as a pickup for the oscillations by coupling it loosely with a wave meter, *W*. The presence of this coil was in no way essential for the production of the oscillations. (c) A detector circuit for oscillations of radiofrequency, consisting of an inductance and capacity, and a three electrode valve, which could be connected either across the filament and anode or the filament and plate *D*. This circuit was also unnecessary to produce the oscillations. (d) The probe-filament circuit, which contained a battery, giving voltages up to 60 volts, and a galvanometer.

Method of Observation

When the emission from the filament was relatively small, corresponding to an arc current of 20 milliamperes at 40 volts or so, the conditions within the arc were normal. No oscillations could be detected, and there were present in the arc no electrons with energies much higher than would be expected from the potential applied at the anode. The electron temperature was of the order of 10,000 to 20,000°C, by which it is meant that the electrons had a Maxwellian distribution of velocities corresponding to this temperature.

As the filament current was increased, however, a point was reached at which a discontinuity appeared in the anode current, and the glow was thrown into violent oscillation. The value of the filament current at which this set in varied with the anode potential, being, in general, higher with greater voltages. The glow changed its appearance from a uniform discharge filling the tube to a more tenuous glow around the filament, and, in the long tube, failed to reach the end remote from the filament. At the same time, the tube emitted a very faint and highly pitched note. There was then practically no resistance, inductance, or capacity in the whole circuit, nor did the addition of these markedly affect the pitch of the note, except insofar as the applied voltages across the tube were interfered with.

The current-potential characteristics of the probe at this point at which oscillations commenced underwent a remarkable change as shown in Fig. 2. In these graphs are shown the logarithm

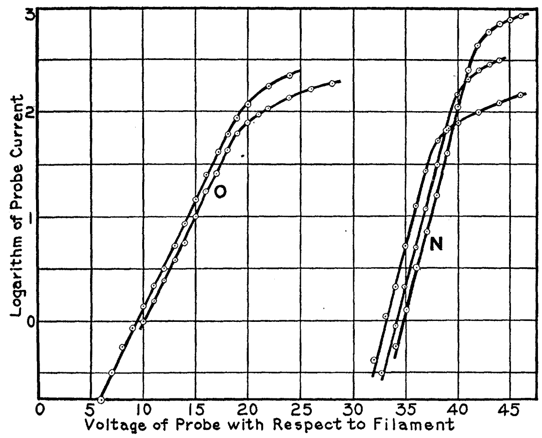

FIG. 2. Semilogarithmic plots of the volt-ampere characteristics of the probe for oscillating (*O*) and nonoscillating (*N*) arcs.

of the probe currents plotted with respect to the potential difference between the probe and the filament. The group marked *N* are for the normal arc, before oscillations commenced, those marked *O* are for the oscillatory arc immediately afterwards. The general character of the change is independent of the anode voltage, and corresponds to a large increase of the electron temperature, as shown by the decreased slope of the straight portion of the curves. It is remarkable, both for the normal and the oscillatory arcs, for how wide a range of probe current, several hundred-fold, the Maxwellian distribution holds. This change of the electron temperature is, of course, to be expected when the glow is set oscillating, for there will be imposed upon the electrons all the motions of the oscillations, which may have any of a wide range of frequencies.

The oscillatory state is very critical and easily destroyed by a magnetic field. The approach of a magnet to the tube caused the arc current suddenly to jump back to its normal value. For this reason, the shape of the filaments and the heating currents they require probably play a fundamentally important part in the experimental study of these oscillations. With the oxide coated filaments, which required small currents to heat them, the oscillations appeared at lower densities of ionization than with the tungsten wires. Oscillations were more easily produced when straight wire filaments were used than when the filaments were of spiral form.

The Anode Glow

At certain values of the anode voltage and current, a bright blue glow appeared behind the anode. It was not necessarily associated with an oscillatory condition in the rest of the arc, and would appear and disappear without affecting the main discharge. It was generally elusive, and would be present with an anode voltage of say 38 volts and absent when the voltage was 36 or 40. It could be generated or removed with a magnet, and in some runs it did not appear at all. It appears definitely to be associated with the anode, for when the rest of the discharge was oscillatory and its space potential much diminished, the potential in the glow, as measured by another probe, was that of the anode itself.

Measurements of the Frequencies of Oscillation

The frequency of the strongest oscillation was within the audible range, although near the upper limit. It was measured with a wave meter. Besides this oscillation, its fifth and octave and a range of upper partials could be detected. At all times, even when the low frequency oscillation could not be detected audibly, there was a series of oscillations of frequency 10^6 or so within the radio range. The variations of these frequencies with anode current and potential were extremely complicated. Over wide ranges of the arc current, the frequency would remain constant and then, at a certain value of the current, drop or increase suddenly to remain constant for another range of variation of the current. This seemed to indicate that the discharge favored one mode of oscillation at one time, changing discontinuously to another just as does an organ-pipe. These oscillations of radiofrequency appeared to be higher harmonics of the fundamental. A long series of them was detected with the circuit marked *LC*. The frequency of the fundamental remained practically constant over the range of current and anode voltage investigated, although a magnetic field altered the pitch of the note. For this reason, combined with the observations with the sliding probes, one is led to the belief that the glow was vibrating as a whole in a manner similar to the air in a Helmholtz resonator.

Investigations of the Glow with a Sliding Probe

When the sliding probe was made about ten volts positive with respect to the filament, and slid across the oscillatory discharge, the electron current collected showed variations with two or three marked maxima or minima as it passed from an initial position near the filament to the wall on the opposite side of the bulb. In the long tube, no such variations were shown on sliding a probe lengthwise down it. There was merely a decrease in the current collected, which fell off gradually and showed no maxima or minima. But a probe moved across the cylindrical tube showed marked maxima and minima just as with the spherical bulb. These observations are to be taken as proof that the glow is oscillating as a whole under the influence of travelling waves through the charged particles, for maxima and minima develop when reflection is possible. In the case of the long tube there was such a decrease in the intensity of the ionization away from the filament that the waves could not travel down it and form standing oscillations along the tube axis. In the case of the smaller bulb, and the radial section of the long tube in the vicinity of the filament, the density of ionization was high throughout and conditions for a reflected wave from the walls to form nodes and antinodes much more favorable.

In Fig. 3 are shown some of the results. The positions of the nodes and antinodes do not change with the position of the filament, as is indicated by curves *3a*, *3b*, *3c* taken for the same anode voltage and current but with three different positions of the filament as indicated by the dotted lines. Curves 1 and 2 correspond to small current densities with presumably the fundamental and its fifth present, *3a*, *3b*, and *3c* to the octave, which was the favorite mode of oscillation. The appearance of an antinode in curve 2 at the middle of the spherical tube requires some explanation. It might be that the slab of gas between the filament and the back of the tube was at that time undergoing plane and not spherical oscillation.

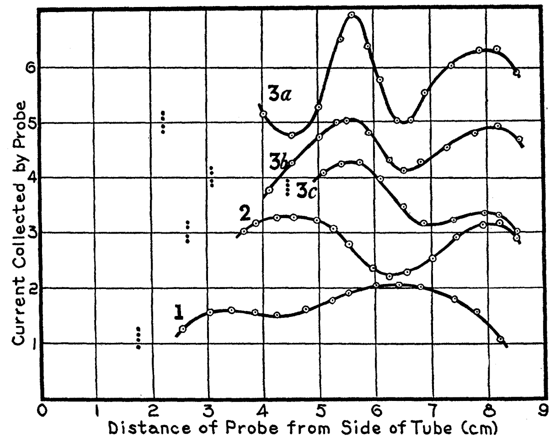

FIG. 3. Variation of the currents collected by the probe with the position of the probe. The dotted lines indicate the positions of the filament.

Discussion

It has been shown by Sir J. J. Thomson[4] that travelling waves with velocities lying between $(kT_i/M_i)^{\frac{1}{2}}$ and $[(kT_i+kT_e)/M_i]^{\frac{1}{2}}$ can be propagated through an ionized gas, where T_i and T_e are the ion and electron temperatures and M_i the mass of the positive ion. Other waves are also possible, corresponding to the electron oscillations, but these carry little energy. The waves with velocities tending towards the first limit written down above are highly dispersive, and so the oscillations to be expected are those whose frequency is small compared with the free frequency of the electrons. That is, when the frequency is much less than $(ne^2/\pi m)^{\frac{1}{2}}$, where n is the number of electrons or ions per cc and m is the electron mass, the ion waves travel with a velocity approximately given by the second limit above. Since, in this case, the electron temperature is so much greater than that of the ions, this velocity reduces to $(kT_e/M_i)^{\frac{1}{2}}$.

The electron temperatures measured were of the order of 50,000 to 80,000°C, the mass of the mercury ion about 3.32×10^{-22} g, the velocity is about 1.5×10^5 cm per sec. This gives as the fundamental frequency of oscillation of a bulb

TABLE I. *Anode voltage 38 volts.*

Anode current	Frequency of fundamental
200 m.a.	2.00×10^4
300	1.96
400	1.94
500	1.88
600	1.90
700	1.88
800	1.90

9 cm in diameter approximately 1.7×10^4 per sec. The frequencies measured were, on the average, slightly higher than this, although the agreement is to be regarded as highly satisfactory, considering the disturbances in the glow rendering it non-uniform. Table I gives some of the measured fundamental frequencies, determined by the wave meter. The radiofrequencies were between 10 and 100 times as great.

It seems to be established that an ionized gas is capable of generating and transmitting oscillations of its constituent ions. In the highly ionized gases of the stars and their atmospheres, these oscillations may be of profound importance, especially in disturbed areas such as sunspots, granulations, and faculae.

In conclusion, the author wishes to thank most heartily Sir J. J. Thomson for his continued advice and help, and the Governing Body of Emmanuel College, Cambridge for a studentship which made the work possible. The experiments were completed at the University of Michigan while the author was a Fellow of the Commonwealth Fund.