PHENOMENA IN GASES EXCITED BY RADIO FREQUENCY CURRENTS.

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Synopsis.

Undamped Radio Frequency Vacuum Discharges through Hydrogen, Oxygen and Air.—(1) *The spectra*, 5000–3500 Å., were found to be the same for frequencies of 3×10^5 to 4×10^6 as for 60 cycles, with currents of the same strength. (2) *The minimum discharge potentials* for electrode distances from 5 to 30 mm. and pressures of from 1 to 5 mm. of mercury were also found to be independent of the frequency and the same as for direct currents. A theoretical discussion of this result leads to the conclusion that the discharge is initiated by collisions of electrons, rather than of gaseous ions, with gas molecules. (3) *Persistence* of each discharge was studied with the aid of a mirror rotating 200 times per second. Damped discharges with a frequency of 10^6 cycles or less showed separate flashes but those with higher frequencies were blended together. This difference may perhaps be due to the limitations of the apparatus used. With damped oscillations the color of the discharge changed with the voltage as would be expected.

Introductory.

LITTLE is known of the behavior of gases stimulated into luminosity by alternating electric currents of radio frequency and the present investigation was undertaken for the purpose of obtaining information on this subject. By radio frequency we mean the range of frequencies usually employed in the radio art, *i.e.*, the range between 10^5 and 10^7 alternations per second. The description of the work is taken up in three parts as follows, the radio frequency spectra, the potentials necessary to set up luminosity, and the radio frequency flashes of light.

The Radio Frequency Spectra.

Numerous experiments on electrically excited gases have been performed concerning the relations between the type of electrical excitation and the spectrum of the luminous gas and in some cases[1] potentials alternating at radio frequencies have been used. Recently Dunoyer[2] has discovered new spectra from certain metallic vapors by the use of damped radio frequency currents. None of these experiments, however, tell definitely the effect, if any, on the spectrum of the gas occasioned by the frequency of the alternating current. The advent of the oscillating electron-tube methods of generating radio frequency currents has ren-

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[1] Wiedemann and Ebert, Wied. Ann., 50, 221, 1893; Himstedt, Wied. Ann., 52, 473, 1894.

[2] Comptes Rendus, 173, 350, 1921; 173, 472, 1921.

dered possible a direct answer to this question and the present work has been undertaken with this in view. It may be stated in advance that for the cases here investigated the spectrum of the gas remained unchanged when the frequency was increased from sixty to a million or more cycles per second, other factors being kept constant.

An electron-tube oscillating circuit was arranged for the production of currents of frequencies from 0.43×10^7 to 10^5 cycles per second, *i.e.*, wave-lengths from 70 to 3,000 meters. The tube was a fifty watt power tube with 1,000 volts on the plate and a filament current of 6.5 amperes. By means of this generating circuit radio frequency current could be induced in coil *b*, Fig. 1, which was in series with a variable air condenser *c* and a hot wire ammeter *a*. By means of a switch *s* the end-on discharge tube *d*, which was in series with the thermogalvanometer *t*, could be connected either across *c* or to the high potential terminals of a ½ kw., 25,000 volt transformer *p* actuated by 60-cycle current. The discharge tube was of glass with aluminum electrodes arranged out of line with the capillary. The capillary was 10 cm. long and with an internal diameter of 5 mm. Hydrogen, oxygen, and air, purified by sodium hydroxide solution, sulphuric acid and phosporous pentoxide, at a pressure of 3 mm. or less were used in the tube. The generating circuit and the circuit *bc* were tuned to the desired frequency. With 4 amperes through *a* and with *c* adjusted to, say, 500 $\mu\mu F$, the discharge tube glowed brilliantly. The increase in the current through the tube when luminosity occurred was about one half of a milliampere. When the 60-cycle transformer was used the current through *t* was adjusted to be one half of a milliampere.

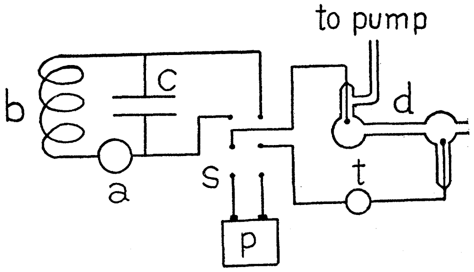

Fig. 1.

The spectra were photographed throughout the region from 5000 A to 3500 A in the first order of a concave grating of two meters radius of curvature ruled 14435 lines to the inch. The spectra of hydrogen, oxygen and air excited by currents of frequencies 60, 3×10^5, 10^6 and 0.43×10^7 were recorded, and in all cases the spectrum was found to be unmodified by the change in frequency. With hydrogen about three hundred lines of the secondary spectrum and a faint continuous background appeared on the plates. The Balmer lines were faint. Oxygen exhibited the fine-lined band spectrum. Air showed the oxygen and nitrogen lines.

The Potential Necessary to set up Luminosity.

Measurements of the potentials just sufficient to set up luminosity in a gas for radio frequency and direct currents yielded information concerning the cause of the luminosity. For this purpose a bulb was equipped with disc electrodes 1.5 cm. in diameter whose distance apart could be varied. The potential difference of the electrodes was measured by an electrostatic voltmeter. The maximum reading of the instrument was 1,000 volts and above 200 volts the indications were accurate within 10 volts. To make a measurement the potential difference of the electrodes was increased very slowly and the voltage observed when the bulb suddenly burst into luminosity. Table I. shows a series of readings for hydrogen when the electrodes were 14 mm. apart. In the table the numbers for the alternating voltages were the maximum values of the voltages, and were obtained by multiplying the electrometer readings by $\sqrt{2}$. The conclusion from Table I. and from similar tables for hydrogen and oxygen, for electrode distances from 5 to 30 mm. and for pressures from 1 to 5 mm. of mercury, was that for a specified electrode distance and gas pressure the voltage just sufficient to produce luminosity did not change when the frequency was varied over a wide range.

Table I.

Pressure in Mm. of Hg.	Frequency.			
	0	60	0.86×10^6	5.3×10^6
3.4..............	640 volts	635	652	642
2.0..............	430	436	436	424
0.9..............	410	424	404	409

We turn to a consideration of the electron theory in this connection. It is known that luminosity is set up when collision occurs between a molecule of the gas and an electron or ion which has acquired a certain critical velocity. A molecule or atom may acquire sufficient energy to become luminous not only by a single violent encounter but also by the accumulation of energy from a succession of milder encounters. It is reasonable to suppose that the luminosity is *begun* by a single violent encounter, for this process is conceivably much quicker than the other. We proceed to find an expression for the critical velocity of the ion partaking in the violent encounter in the case of a steady electric field and of an alternating electric field.

We assume a Lorentz contractile electron of charge e and mass m for small velocities. The electron moves from rest under the influence of a homogeneous steady electric field E which is in the direction of the X axis. The effects on the motion due to radiation from the accelerated electron are neglected. If c.g.s. electromagnetic units are used the equation of motion of the electron is in Newtonian notation

$$x = E\frac{e}{m}\left(1 - \frac{\dot{x}^2}{c_2}\right)^{3/2}, \tag{1}$$

where x is the positional coördinate of the electron, and c is the velocity of light *in vacuo*. With initial conditions $t = x = \dot{x} = 0$, the solution of (1) is found to be

$$x = \frac{ct}{\sqrt{\frac{c^2m^2}{E^2e^2} + t^2}} \tag{2}$$

and

$$x = c\sqrt{\frac{c^2m^2}{E^2e^2} + t^2} - \frac{c^2m}{Ee}. \tag{3}$$

Eliminating the time t between (2) and (3) gives

$$\dot{x} = \frac{\sqrt{\frac{x^2}{c^2} + \frac{2xm}{Ee}}}{\frac{x}{c^2} + \frac{m}{Ee}}. \tag{4}$$

Suppose the electron to move in an alternating electric field of amplitude E_1, and frequency $\omega/2\pi$. The effects upon the motion due to radiation from the field and the electron are neglected. Letting the subscript 1 denote the alternating potential case, the equation of motion of the electron is

$$\ddot{x}_1 = E_1\frac{e}{m}\left(1 - \frac{\dot{x}_1^2}{c^2}\right)^{3/2} \cos \omega t. \tag{5}$$

With initial conditions $t = x_1 = \dot{x}_1 = 0$, the solution of (5) is

$$\dot{x}_1 = \frac{\frac{E_1ec}{m\omega}\sin \omega t}{\sqrt{c^2 + \frac{E_1^2e^2}{m^2\omega^2}\sin^2 \omega t}} \tag{6}$$

and

$$x = \frac{c}{\omega}\left[\cos^{-1}(\alpha \cos \omega t) - \cos^{-1}\alpha\right], \tag{7}$$

where

$$\alpha = \frac{\dfrac{E_1 e}{m}}{\sqrt{\dfrac{E_1^2 e^2}{m^2} + \omega^2 c^2}}. \tag{8}$$

Eliminating t between (6) and (7) gives

$$\dot{x}_1 = c\,\frac{\sqrt{\alpha^2 - \cos^2\left(\dfrac{\omega x_1}{c} + \cos^{-1}\alpha\right)}}{\sin\left(\dfrac{\omega x_1}{c} + \cos^{-1}\alpha\right)}. \tag{9}$$

When E and E_1 are the potentials just sufficient to set up luminosity we may equate (4) and (9).

This leads to

$$\frac{\sqrt{\dfrac{x^2}{c^2} + \dfrac{2xm}{Ee}}}{\dfrac{x}{c^2} + \dfrac{m}{Ee}} = c\,\frac{\sqrt{\alpha^2 - \cos^2\left(\dfrac{\omega x_1}{c} + \cos^{-1}\alpha\right)}}{\sin\left(\dfrac{\omega x_1}{c} + \cos^{-1}\alpha\right)}. \tag{10}$$

Where α is given by (8), and x and x_1 are now the distances the electron travels before it attains the critical velocity for the direct and alternating potential cases, respectively. When $\omega = 0$ (10) becomes an identity. Further, if e/m refers to the charged atom or molecule and not to the electron, the variation of mass with velocity may be neglected, and (10) simplifies to

$$E_1 x_1 - Ex = \frac{x_1^2 \omega^2 m}{2e}. \tag{11}$$

We now make use of the experimental fact that within the error of experiment E was equal to E_1 for all the cases examined. The following numerical values were chosen: $e/m = 1.77 \times 10^7$ for the electron, $\omega = 10^7$, $x = x_1 = 1$, and $c = 3 \times 10^{10}$. x and x_1 were unknown, but since they could not be greater than the distance between the electrodes we have taken them to be of the order of one centimeter. Their exact values are of little importance in the calculations from (10). When these values are substituted in (10) it is found that E_1 is greater than E by a quantity of the order of magnitude of one thousandth part of a volt, and that not until ωx_1 becomes as large as c does $E\delta$ differ appreciably from

E_1. This is in accord with the experimental results. If we chose the value of e/m for the hydrogen molecule, *i.e.*, 0.5×10^4, $\omega = 10^7$, $x = x_1 = 1$, and $c = 3 \times 10^{10}$, upon substitution in (11) we find $E_1 - E = 100$ volts and for the oxygen molecule $E_1 - E = 1600$ volts. Of course it is not permissible to use $x = x_1$ in (11), but since x_1 must always be greater than x the values of $E_1 - E$ just given are minimum values. Further it is seen from (11) that $E_1x_1 - Ex$ increases with ω^2. These results are clearly at variance with the experimental results. We therefore conclude that the charged particle which collides with the gaseous molecule, thereby originating the luminosity in the gas, is the electron. After luminosity has once set in subsequent ionization is caused by both electrons and charged molecules or atoms as J. J. Thomson and others have shown.

THE RADIO FREQUENCY FLASHES.

In order to determine whether the luminosity of a gas stimulated by radio frequency current flickered at a radio frequency the discharge tube *d*, Fig. 2, excited by damped-wave radio frequency current was pointed at a mirror *m*, 3 cms. square, about four meters distant, which rotated 12,000 times per minute. The light reflected from the mirror was observed in a low-power telescope *h*. Fig. 2 shows the arrangement. The 25,000 volt transformer *p* charged the condenser *c* which discharged through the coil *b*, the tube *d*, the hot-wire ammeter *a*, and the spark gap *g*. When the mirror was rotated the flashes from the tube were seen spread out into streaks of light. Each streak consisted of a series of separate flashes occurring at the frequency of the radio frequency current through the gas. The general appearance is sketched in Fig. 3. Observations on hydrogen, oxygen, air, and argon showed that the radio frequency striations were discernable for frequencies as high as 10^6, but for frequencies greater than this the streak appeared continuous. The shortness of the time of a dark striation is worthy of remark. For example, in the case of hydrogen at 3 mm. pressure a frequency of $0.86 \times$

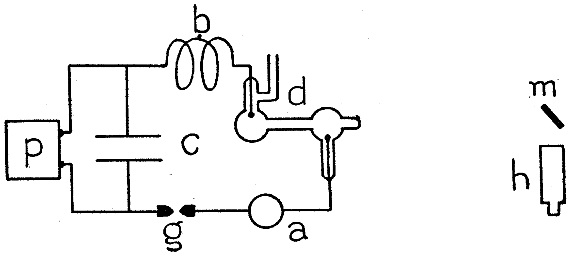

Fig. 2.

10^6 produced dark striations whose length and intensity were perhaps one tenth of the length and intensity of a bright striation. Thus in 6×10^{-8} seconds the intensity of the gas passed from a high value to a low one and back to a high value again. The fact that there was an upper limit of frequency above which no striations could be seen was due in part to the limitations of the apparatus, and in part to the greater damping of the oscillations at the higher frequencies as shown by the shortness of the streak and the logarithmic decrement of the circuit. The non-appearance of the dark striations may also have been caused by the persistence of the luminosity, for W. Wien[1] and G. Mie[2] have shown in the case of the light from canal rays of hydrogen and oxygen that the time for the luminosity to decrease to $1/\epsilon\delta$th of its value was of the order of 10^{-8} seconds.

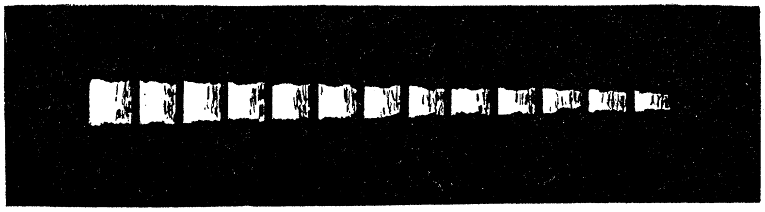

Fig. 3.

With hydrogen or argon in the discharge tube the first one or two flashes of a radio frequency series, such as pictured in Fig. 3, were nearly white, the next few flashes pink, and the last flashes red. The cause of this was attributed to the energy distribution in the visible spectrum of the gas. In the case of hydrogen the condenser discharge brought out the Balmer lines strongly with the secondary spectrum relatively weak. The first few flashes owed their whiter color to the predominance of H_β and H_γ caused by the relatively great intensity of the first few oscillatory discharges of the condenser. As the discharges become less violent H_α became more prominent and colored the later flashes red.

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[1] Ann. d. Phys., 66, 229, 1921.

[2] Ann. d. Phys., 66, 237, 1921.