Luminous Fronts in Pulsed Gas Discharges

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Recent experiments in which an intense luminosity was observed in side tubes connected to an electrodeless discharge ring have been duplicated using a discharge with electrodes. It is concluded that a large part of the luminosity observed is the result of a moving front of disturbance rather than the decay of an ejected tongue of excited gas. Measurements made of the velocity of advance of this front and its dependence on gas parameters show that the front advances into the side tube with a speed proportional to the estimated velocity of sound in the hot gas of the main discharge. Intense continua accompany discrete spectra in the fronts, particularly in hydrogen, indicating that recombination may play a large part in producing the luminosity observed.

I. INTRODUCTION

IN a previous paper[1] a description has been given of recent investigations of the phenomenon termed by Rayleigh[2] "the long lifetime of the Balmer lines in hydrogen." The fingers of luminosity which can be observed in side tubes connected to an electrodeless discharge tube have been shown to arise from excited systems created at or near the point at which the luminosity is observed. Earlier theories[3] had considered the luminosity to be of the nature of an afterglow in a thermally ejected jet of luminous gas.

Rayleigh observed that the effect found in hydrogen with his apparatus was not present in nitrogen. Further investigation of this limitation seemed desirable. It was suspected that the failure to observe these effects in nitrogen was in some way associated with insufficient energy transfer resulting from the rather poor coupling present in the electrodeless discharge apparatus. Accordingly, more effective means were sought for supplying pulsed energy to the tube. A simple and successful arrangement was found in which a charged condenser was connected abruptly to a pair of metal electrodes sealed into the tube. With this apparatus, the experiments described before[1] have been largely verified and greatly extended.

The apparatus employed in this investigation consisted of three main parts: a vacuum system of standard design, an electrical discharge circuit, and an optical system for studying the discharge.

While some variations in discharge tube construction have been made, the tubes used thus far had many common features. They were constructed of Pyrex glass, with cylindrical aluminum alloy electrodes 1.5 cm in diameter and 1.5 cm long sealed in opposite ends of a tube 15 cm long and 1.7 cm in diameter. Midway between these electrodes a side tube was sealed onto the main discharge tube and connected to the vacuum system.

The discharge is initiated by connecting a charged condenser to the tube through a vacuum switch, using a circuit in which inductance and resistance have been reduced to a low value by means of short heavy leads. Capacitors of 6 to 12 μfd capacitance have been used, charged to potentials ranging from a minimum value of around 800 volts up to 5000 volts. Oscillatory frequency and decrement measurements indicate total distributed inductances of approximately one microhenry and mean total resistances of the order of a tenth of an ohm in a typical circuit. Estimates of the maximum current in the discharge lie in the neighborhood of 10^4 amperes.

The optical system was arranged to give simultaneous photographs of the advance of the luminosity down the side tube with a rotating mirror, and of the spectral composition at every point along its course with a spectrograph. The entire discharge tube was masked, except for a slit 1-mm wide down the length of the side tube. This slit served jointly for the mirror and for the spectrograph; the latter was operated with an open collimator at a distance of several meters. The mirrors used were turned at various measured speeds up to 60 rps. Some of the data reported in Table I are less satisfactory than others because they were taken with an inferior mirror used in the early stages of the investigation.

Since no attempt was made to control the position of the slit image at the instant of discharge, a film holder was constructed as a section of a one-meter circle, center at the mirror, on which three $4'' \times 5''$ films could be mounted. Three photocells were arranged using an adjacent face of the mirror, so that when light struck any film, it also struck the corresponding one of the three photocells and thus tripped one of three glow tubes as a tell-tale, indicating which film had been exposed.

II. EXPERIMENTAL RESULTS

Studies conducted with the apparatus described above have duplicated qualitatively and quantitatively the results obtained previously in the electrodeless ring discharge.[1,2] Because of the better coupling which existed in the discharge between electrodes, the range of pressures over which the phenomenon could be observed was greatly extended. It was also found possible to

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[1] R. J. Lee and R. G. Fowler, Phys. Rev. **81**, 457 (1951).
[2] R. J. Strutt, Proc. Roy. Soc. (London) **183**, 26 (1944).
[3] H. Zanstra, Proc. Roy. Soc. (London) **186**, 236 (1946).

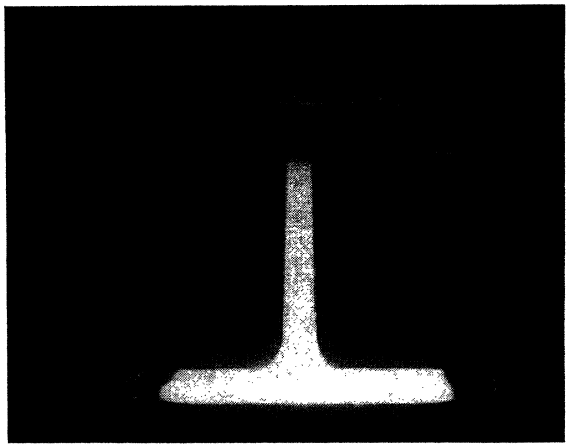


FIG. 1. Abrupt condenser discharge through a tube with side arm. Luminosity is sharply terminated by constriction.

produce fronts in every kind of gas examined, even nitrogen, in contrast to the results of Rayleigh. A direct photograph of a typical discharge is shown in Fig. 1. As would be expected, the discharge is extremely brilliant, related as it is to the well-known photoflash lamp. Two remarkable things which are indicated by the figure are, first, that the intensity in the sidearm is not a trivial luminosity, but is fully as bright as the discharge in the main tube, and second, that the luminosity has a definite point of termination. This point of termination coincided with a constriction in the tube, and is definitely related to it, since it was found impossible to force the luminosity past the constriction.

TABLE I. Measured velocities of luminous fronts under various conditions.

Gas	Pressure (mm Hg)	Condenser potential (volt)	Front velocity ($\times 10^{-5}$) (cm/sec)
Hydrogen[a]	0.2	5000	18
Hydrogen	1.0	2000	10.5
Hydrogen	1.0	3000	12.5
Hydrogen	1.0	4000	10.5
Hydrogen	1.0	5000	17.0
Hydrogen	5.0	3000	8.0
Hydrogen	5.0	4000	9.0
Hydrogen	5.0	5000	10.0
Hydrogen	11.5	5000	7.0
Hydrogen	25.0	5000	3.0
Hydrogen[b]	5.0	2000	7.0
Hydrogen	5.0	3000	8.0
Helium	0.9	2300	12.0
Helium	0.9	4200	15.0
Helium	1.2	3000	13.0
Helium	1.4	3000	10.0
Helium	2.5	2000	5.5
Helium	5.0	2000	6.0
Helium	9.0	2000	7.5
Neon	1.2	2500	5.0
Neon	4.0	2000	4.5
Neon	0.9	2800	9.0
Nitrogen	0.9	2800	9.0
Nitrogen	2.5	2500	7.5
Argon	0.7	2300	6.5
Argon	9.0	1900	3.5
Argon	10.0	2500	2.0

[a] At 6.0 μfd capacitance.
[b] These and all subsequent data at 12.0 μfd capacitance.

A summary of measurements of front velocity is given in Table I. Velocity measurements were made in the following manner. The discharge was photographed with the slit over the tube and the rotating mirror stationary in order to establish a vertical reference on the film. When the discharge was photographed with the mirror in motion, it was observed that the slit image was inclined to the vertical. The angle of inclination was related through the geometry of the optical system to the velocity of advance of the luminosity. Frontal velocities will be seen from Table I to increase directly with condenser energy, inversely with molecular mass, and inversely with pressure.

Two special aspects of frontal behavior were noted. The fronts, especially in heavy gases, decelerate as they advance. Figure 2 shows the curvature of front which accompanies this. Curvature of the fronts is one effect which has made velocity measurements uncertain thus far. Figure 2 is not a typical mirrorgram, since it shows an infrequently observed phenomenon which we have terms an "echo" front. A return front is seen to come up the tube after the primary front had gone down it. This effect is observed only in tubes in which the course of the primary front is impeded by a constriction, and represents a reflection of the front at and by the constriction. It is related to the termination of the luminosity seen in Fig. 1. The velocity of the echo will be seen to be greater than that of the primary front. Little is known yet about the echo fronts. They have been observed in argon, neon, and air; but so far, not in helium, hydrogen, or nitrogen. However, no special effort was made to produce them at the time they were first encountered. They were not consistently observed even in argon where they were most common. In the belief that this phenomenon contains a clue to the mechanism of the discharge, a careful investigation of it is currently under way.

It has been previously reported[1] that the fronts were observed to have a greater range in tubes of large diameter than in small ones. An attempt was made to measure this effect. Three tubes of different diameters were joined like spokes of a wheel to a main discharge tube of a larger diameter. By photographing the discharge tube from one end, it was possible to determine how far the fronts moved down each tube before reaching the same level of luminosity. A list of such ranges is given in Table II, taken at 5000 volts potential difference across a 6 μfd capacitor. As might be expected, an intensity function of the form $I=A(r_0^2-r^2)\times\exp(-\alpha z)$ fits the data to a fair degree.

Examination of Fig. 2 shows that the discharge is not completely described by the term "front," since other luminosity is observed in the side tube subsequent to the front. Frequently, photographs show belated extra fronts which travel with a great variety of speeds. Tests have shown that this later luminosity can be markedly affected by varying the discharge circuit constants, without any great effect on the primary fronts. The equipment used for these experiments heretofore has been inadequate to resolve these luminosities, if such resolution be possible. Far more precise equipment, freed from optical aberrations and uncertainties in the discharge circuit, is currently being set up for pursuit of this problem under sponsorship of the Office of Naval Research.

The spectra taken of the discharges showed a high level of excitation. HeII, NII, and NIII have been observed. Such a degree of excitation might well have been expected in the main discharge tube, since the discharge there is probably little more than a low pressure spark, on which a number of studies have already been made.[4] To find it, in what amounts to a backwater, off from the main stream of the discharge current is surprising and further evidence that this phase of the discharge cannot be regarded as a mere afterglow.

Spectra taken of the hydrogen discharges present an intense continuum setting in around H_ϵ, and extending beyond 3000A. The Balmer series is not complete, but terminates near H_θ, going beyond that point into a pure continuum. The suppression of the series at this point is probably caused by the intense local fields of the ion cloud from within which the atoms are radiating.

The continuum was observed to be little abated at 0.2 mm Hg pressure, and no trace of the multiline spectrum was detected at any pressure. We have concluded, therefore, that we were dealing with an atomic continuum enhanced by the intense local fields of the surrounding ion cloud. On this assumption, an experiment was performed to ascertain in what manner the continuous radiation and discrete radiation contributed individually to mirrorgrams made using the entire radiation. A mirrorgram taken through an NiO_2 filter which transmitted the entire continuum and the series members above H_θ was compared with a mirrorgram taken through a sodium nitrite solution which eliminated the continuum and series members above H_θ. No significant difference in form was noted between these mirrograms.

It was next undertaken to determine whether there was any appreciable difference between the times of emission of the quantized and unquantized radiation. The upper-half of the discharge tube slit was covered with the one filter and the lower half with the other. No appreciable relative displacement of the two segments of the trace could be distinguished. It was concluded that the quantized and unquantized radiations are therefore related in being emitted at each successive point of the tube within the same brief time interval. From the lateral breadth of trace on the mirrorgrams, it was estimated that the duration of emission is not over 1 or 2 microseconds. From the complete absence of dislocation of the trace in the two filter experiment, we estimate that the interval between emission of the continuous and discrete transitions cannot be more than 10^{-7} second, or roughly the mean relaxation time of an atomic system.

[4] L. B. Loeb, *Fundamental Processes of Electric Discharge in Gases* (John Wiley and Sons, Inc., New York), p. 476.

FIG. 2. Rotating mirror photograph of side arm of tube shown in Fig. 1. Stationary reference image at left. Lines parallel with stationary trace give instantaneous distributions of luminosity along side arm.

III. DISCUSSION

There seems little reason to believe that the phenomenon of the ejected luminosity is an afterglow, as suggested by Rayleigh and Zanstra. Rather, the evidence shows that it should be regarded as an active exciting process of considerable overall significance in the disposal of the energy supplied to the discharge. The near-sonic nature of the velocities observed, the reflection of an echo pulse returning at higher speed as if into a hotter gas, the general frontal character of the discharge, all combine to suggest kinship with shock waves and high amplitude acoustical effects.

A descriptive theory of the fronts is easily obtained. Treating them as shock waves shows, in first approxi-

TABLE II. Range of the luminosity in helium.

Pressure mm Hg	Tube diameters 3.30 mm	5.0 mm	8.9 mm
3.00	— cm	6.6 cm	9.6 cm
0.80	2.4	6.0	6.0
0.60	2.4	4.8	5.4
0.35	1.7	3.6	4.8
0.12	1.1	3.0	3.6

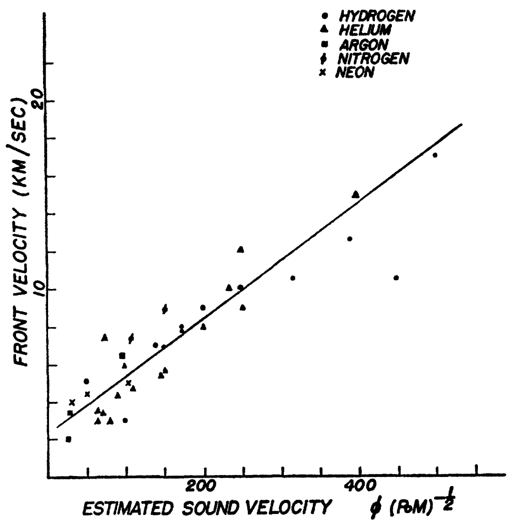


FIG. 3. Plot of front velocities of luminosity against an estimated sound velocity obtained by combination of capacitor potential (volts), initial gas pressure (mm Hg), and molecular weight.

mation, that the velocity of advance should be proportional to the velocity of sound in the hot gas which is advancing down the tube. That is,

$$V \propto p^{\frac{1}{2}} D^{-\frac{1}{2}}.$$

But if the pressure p is identified with the mean kinetic energy per unit volume in the hot gas, it can be approximately expressed as proportional to the initial condenser energy divided by the volume of the tube. The density D is jointly proportional to the pre-discharge gas pressure p_0 and the molecular weight m. It is therefore to be expected that if ϕ is the initial condenser potential,

$$V \propto \phi(p_0 m)^{-\frac{1}{2}}.$$

Within the experimental error, this expression accounts for the observed data of Table I. A graph of these results is given in Fig. 3. On a basis of this agreement it seems evident that the descriptive theory that has been suggested, i.e., that the frontal luminosity is a concommittant of a shock wave resulting from the abrupt discharge of the condenser, has merit. The problem of the mechanism by which the condenser energy is actually delivered to the front by the gas is not covered. Neither is the question of the radiative mechanism in the front, on which point the experimental indications are that recombination plays a major role. Answers to both of these questions will probably hinge on studies of the deceleration and reflection of the fronts and on improved spectrograms of the discharge. It seems unlikely that better measurements of the initial velocity can do anything more than confirm the results of Fig. 3, and hence assure us that the front is caused by an abruptly expanding hot gas. Although it has been necessary, owing to the experimental misapprehension on which it was based, to reject the theory of Zanstra as applying in its present form to this side-tube luminosity; nevertheless, a modification of it seems likely to be ultimately successful, since the level of excitation is so high in this luminosity that volume recombination appears to be an important process in the fronts themselves. This conclusion is based on the interpretation we place on the experiments, which show that the observed Balmer continuum, although extraordinarily intense, is properly associated with the atomic ion. This conclusion is strengthened by the fact that the radiation of these continuous quanta occurs at essentially the same spot as the radiation of the discrete quanta. Thus far this viewpoint is the simplest one which we have found to be qualitatively consistent with all observations.

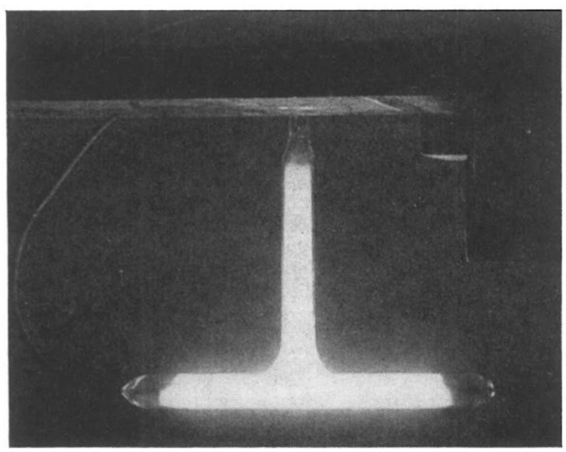
IV. CONCLUSIONS

Extension of the studies of the Rayleigh afterglow phenomenon have verified earlier conclusions that the luminosity is not an afterglow but is excited *in situ.*

Volume recombination is in all probability a major process in radiative disposal of gas energy in the phenomenon of Rayleigh luminosity. Large ion concentrations and a high degree of excitation have been found to exist, and must be contributing factors.

A major part of the luminosity moves as a front or wave of decreasing speed, for which the initial value has been shown to be related to the velocity characteristic of sound in the gas of the main discharge tube after adiabatic heating with the energy of the condenser.

Whatever mechanical process acts to advance the luminosity, it must be one capable of undergoing reflection at discontinuities in the tube.



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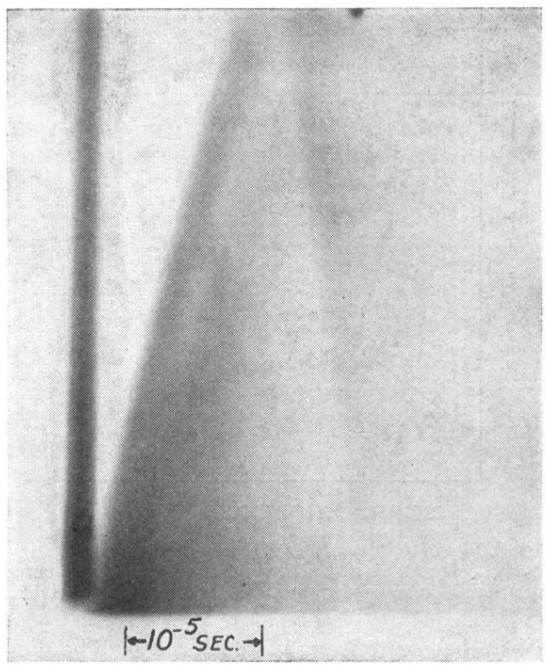

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