greater the value of L.[17] Then the turbulence of greater scale is not much changed by the magnetic field belonging to turbulence of a smaller scale.

The motions which bring about the amplification in the largest dimension considered take place mainly in the plane of the galaxy. Hence, it must be concluded that the magnetic lines of force also run more or less parallel to this plane. Furthermore, for the reasons given above, the magnetic field should be rather homogeneous over distances comparable with this same L. Local differences are to be expected, especially in places where the mass density is above average.

The magnetic term in the equation of motion, Eq. (2), acts in the direction perpendicular to the plane of the galaxy—on the average as a force directed away from the plane. Also, the pressure exerted by the cosmic-ray particles acts in the same direction. Both must be compensated for by the gravitational force. It now seems likely that these are the most essential factors governing the lateral extension of interstellar matter.

The interstellar gas clouds commonly observed with high dispersion[16] should be strongly affected by the magnetic field. Components of motion perpendicular to H are not prohibited, but they must be of such character that no permanent lengthening of the lines of force results (e.g., oscillatory).

The influence of the non-ionized part of the gas has been considered in detail in our paper.[5] It is shown there that it does not lead to any essential modification of this picture, because the relative motion of the ionized and the non-ionized part of the gas ("ambipolar diffusion") is rather slow (probably $\leqslant 1$ km/sec). If the dissipation of turbulent energy corresponds to the values of v and L used above (from which results 10^{-4} erg/g sec), the ambipolar diffusion would provide a comparatively important mechanism converting turbulent into thermal energy. The dissipation of energy may be higher if the relatively fast moving clouds are frequent enough.

It follows from the analysis outlined before that the age of the galaxy determines essentially the value of L/v of the largest elements whose motion is just affected by the magnetic field. Their kinetic energy determines the magnetic field strength and their extension (namely, L) the approximate radius of curvature. On the other hand, the present field depends very little (by a logarithmic term) on the initial field.

From these considerations it seems likely that in other galaxies conditions may be fairly different, either in the sense that the dynamics of the interstellar gas are more greatly affected by the magnetic field or in the opposite sense.

The authors wish to express their indebtedness to Professor von Weizsäcker, Göttingen, Professor Schwarzschild, Princeton, and especially to Professor Unsöld, Kiel, for important remarks and suggestions concerning the topics treated in this paper.

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[17] This is equivalent to the statement that the mean square of the (irregular) velocity difference v between two points, whose separation is L, increases with increasing L. The Kolmogoroff-Weizsäcker theory of isotropic statistical turbulence predicts $v\sim L^{\frac{1}{3}}$ for an incompressible fluid.

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Electron Removal in Mercury Afterglows*

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Observations of the electron density, visible and near ultraviolet light intensity, and spectrum associated with a 2800-Mc pulsed electrodeless discharge through mercury vapor have been made. Our results indicate ambipolar diffusion as the principal mechanism of electron removal at low pressure, with attachment becoming increasingly important at higher pressure. The data also yield a considerable amount of information regarding electron temperatures, recombination coefficient, and other parameters necessary to a detailed description of the processes taking place in the discharge.

I. INTRODUCTION

As part of a general program of studying the mechanism of the disappearance of electrons from gas discharge plasmas, an investigation of mercury afterglows has been made. The method used includes simultaneous spectroscopic and electron density measurements together with relative and absolute light intensity measurements.

Previous work on metallic vapors has been confined largely to mercury and cesium. Mohler and Boeckner[1] and Mohler[2] have investigated cesium afterglows after cut-off of an intense direct current discharge at a pressure of 0.1 mm with electron densities of the order of 10^{12} electrons/cm^3. Electron temperatures in the afterglow were of the order of 1200°K. The spectrum was

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[1] F. L. Mohler and C. Boeckner, Natl. Bur. Standards J. Research 2, 489 (1929).

[2] F. L. Mohler, J. Research Natl. Bur. Standards 19, 446 (1937).

found to consist of lines with about the same intensity distribution as in the discharge, plus a continuous spectrum beyond the series limit which had less wavelength spread in the afterglow than in the discharge. Mohler[2] has also used a probe to measure electron density after cut-off and found a value for the recombination coefficient α (defined by the equation for electron density, n, as a function of time, t, as follows: $dn/dt=-\alpha n^2$) of 3.4×10^{-10} cm^3/ion-sec in the pressure range 0.01 to 0.03 mm. Using the same technique in mercury at 0.27-mm pressure for 2000°K electrons, Mohler[3] found a recombination coefficient of 2.3×10^{-10} cm^3/ion-sec. Mierdel,[4] however, has found that the relation between electron density and time under very similar conditions in mercury indicates an ambipolar diffusion-type electron loss rather than recombination. The electron temperature was found to be 2000°K and almost independent of pressure in this work, a fact which is attributed to collisions of the second kind between metastable mercury atoms and electrons.

II. METHOD AND APPARATUS

The method used is the same as the one described in previous papers by one of the authors,[5,6] and it will be enough to recall briefly how we measure the different variables of the experiment. The electron density is given by the frequency shift of a microwave (2800 Mc) resonant cavity. The conditions of the experiment are such that the electron density is directly proportional to the frequency shift observed. A gated photomultiplier, which is on for 40 microseconds at an adjustable time after cut-off, gives values of the light intensity as a function of time. A calibration of the photomultiplier is made in order to relate the signal of the photomultiplier to the *absolute* light intensity. A rotating disk provided with slits is used to observe the spectrum of the discharge and of the afterglow. The synchronization between the modulation of the microwave oscillator (which initiates the discharge in the quartz bottle) and the rotation of the disk is obtained with a continuous light source and a photomultiplier which generates the initial trigger a few hundred microseconds before the slit passes the discharge tube. Calibrated delay circuits are used to measure times between cut-off and the instant at which the measurement is made.

A block diagram of the apparatus is shown in Fig. 1. A two-chamber oven (Fig. 2) is used around the entire cavity and discharge tube. The pressure is determined by the temperature of the region containing the reservoir of metal; dimensions of the tube are chosen to avoid difficulties in pressure determination due to thermal transpiration. The temperature of the gas is determined by the temperature (independently varied) of the other half of the oven. The electron temperature is not measured directly in this investigation. Theoretical calculations can be made, including the effect of collisions of the second kind between metastable mercury atoms and electrons and of the Ramsauer effect.[7] Taking into account available experimental values, the electron temperature would be expected to decrease very rapidly to 2000°K, where it is kept fairly constant by collisions of electrons with metastable atoms. For pressures above 3 mm, however, the disappearance of metastables in the plasma may be fairly rapid, and thermal energies are probably reached in 1 millisecond or so.

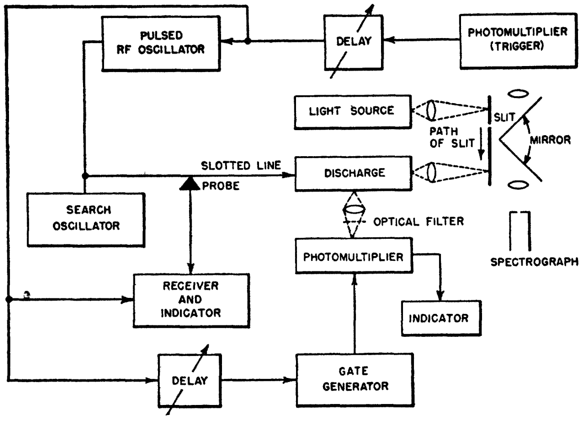

FIG. 1. Block diagram of the electron density and high speed spectroscopic apparatus.

III. RESULTS

Because of the great care taken in the purification of the gas, very pure samples were obtained. The only

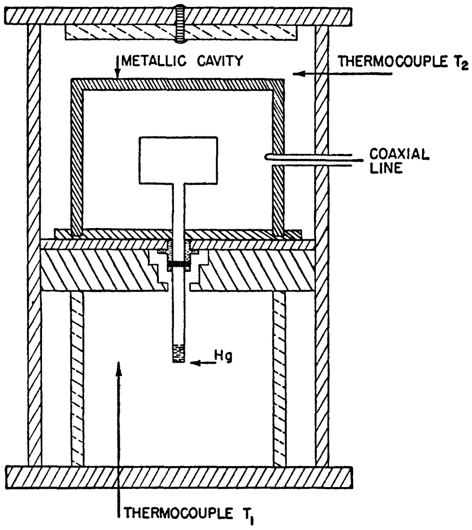

FIG. 2. Double-chamber oven used for varying pressure and temperature.

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[3] F. L. Mohler, J. Research Natl. Bur. Standards **19**, 559 (1937).

[4] G. Mierdel, Z. Physik **121**, 574 (1943).

[5] Holt, Richardson, Howland, and McClure, Phys. Rev. **77**, 239 (1950).

[6] McClure, Johnson, and Holt, Phys. Rev. **80**, 376 (1950).

[7] W. Allis and P. Morse, Z. Physik. **70**, 567 (1931).

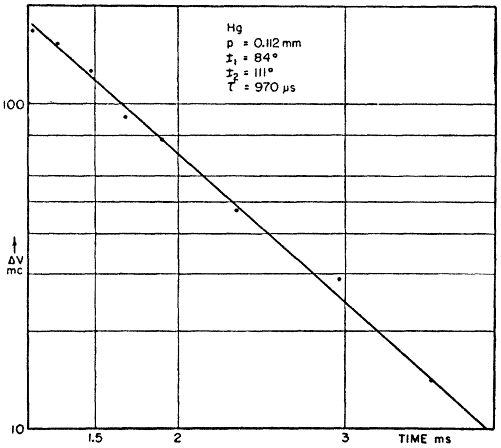

FIG. 3. Electron density as a function of time (case 1). The electron density is in arbitrary units.

lines observed on prolonged spectroscopic observation of the discharge are mercury atomic lines.

The simplest way to describe the experimental results is to distinguish four ranges of pressure and temperature.

Case 1. Pressures from 0.08 to 0.5 mm; Temperature below 120°C

The electron density n can be measured between approximately 1 and 5 milliseconds after cut-off. In this range, it is found that an exponential law of the type

$$n = n_0 \exp(-t/\tau_1) \tag{1}$$

is very closely verified (Fig. 3). The time constant τ_1 is of the order of 1 millisecond and, if the temperature is kept constant, is found to increase not quite proportionately with pressure. For a temperature of 112°C, for instance, τ_1 increases from 0.8 millisecond at 0.08 mm-pressure to 2 milliseconds at 0.5-mm pressure (Fig. 4). If the pressure is kept constant and the temperature varied, it is found that τ_1 increases at first, passes through a maximum, then decreases (Fig. 5). Light intensity *versus* time is a straight line on a semilogarithmic plot for times in the afterglow greater than 1 millisecond. In the first millisecond, however, the line is curved. The time constant τ_2 of the straight portion of the light curve is of the same order as τ_1, the mean value of the ratio being $\tau_1/\tau_2 = 1.1$, or

$$I = \text{constant} \cdot n^{1.1}. \tag{2}$$

An attempt to extend density measurements to short times by means of the light intensity curve is made in the following manner. The above relation is not thought to be valid at short times since it would give an initial electron density much higher than one can reasonably expect. If, on the other hand, one writes

$$I = An^2 + Bn,$$

it is possible to find A and B such that Eq. (2) is closely verified for t greater than 1 millisecond. Such a calculation shows that the quadratic terms would be more important at very short times. This would indicate that recombination-type electron removal is playing an important role. Our data indicates a value of the order 5×10^{-9} cm^3/ion-sec for α at these pressures. An estimate of the absolute light intensity emitted at 2537A can also be made. At 1.1 milliseconds in the afterglow the intensity radiated is of the order of 10^{-6} watt. If we assume that this emission comes only from recombination, thus neglecting the possible transitions from a metastable state to the 2^3P_1 state or the dissociation of molecules with 2^3P_1 excited atoms as one of the dissociation products, and also assume that only approximately one-fifth of the recombinations will eventually give rise to the 2537A line, we find that there are only 5×10^{-2} ev of light emitted per electron disappearing. This is not surprising, since we expect most of the electrons to be lost by diffusion to the walls. Spectrograms of the discharge show an intense atomic line spectrum of HgI both in the discharge and in the afterglow. The relative intensity of high members of the series ($2p_1 - 6d_1$, for instance) are very high in the discharge and immediate afterglow. At 400 microseconds in the afterglow, these lines have disappeared, whereas other lines are still visible. This suggests that the enhancement of high members of the $2p - md$ series as observed by Hayner[8] is associated with extremely high densities. A continuous spectrum is also conspicuous from about 4900A to 2547A. In the discharge the maxima of intensity are approximately located at 4500A (very strong), 3300A (strong), and 2650A (weak). A narrow and intense continuum extends on both sides of the 2537 line with two band heads at 2469A and 2476A visible. In the afterglow, the continuum intensity is well maintained in the neighborhood of the resonance line, at 3300A and especially at 4500A, and it has a higher relative intensity than the

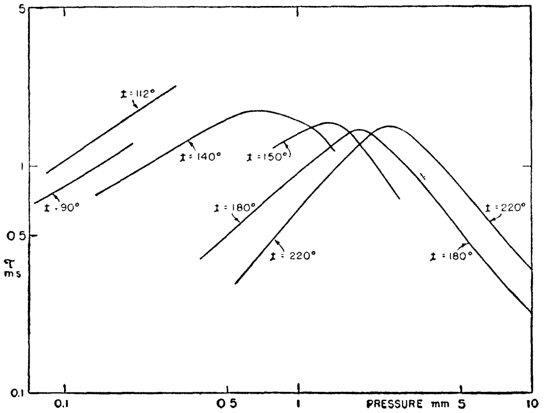

FIG. 4. Variation of electron density decay time constant with pressure.

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[8] L. Hayner, Z. Physik **35**, 365 (1925).

atomic lines. Four band heads at 3070, 3095, 3450, and 3480A appear in the afterglow.

Case 2. Pressure from 0.1 to 0.5 mm; Temperature above 130°C

At low pressures, electron density decay becomes more rapid with increasing temperature. Exponential decay is found for times greater than 1 millisecond, and τ_1 for a given pressure is smaller than in case 1. At constant temperature (e.g., 140°C), however, τ_1 is found to increase with pressure as in case 1. Light intensity measurements (Fig. 6) show that the initial curved portion of the plot is not very much affected by the increase in temperature, whereas the straight portion of the curve progressively disappears. Spectrograms show that the atomic lines have about the same intensity as in case 1, both in the discharge and the afterglow, with the same change in relative intensity. The continuum, on the other hand, is considerably weaker. In the afterglow, the continuum at 4500A shows up very weakly, while no continuous spectrum is observed at other wavelengths. This indicates that the straight portion of the light intensity curve corresponds to the continuous emission, particularly to the emission of the 4500A continuum, which is the strongest observed in this region.

Case 3. Pressure from 0.5 mm to 4 mm; Temperature below 190°C

The electron density measurement becomes more difficult under these conditions, since the real component of the complex conductivity of the gas is no longer negligible compared with the imaginary component. Nevertheless, exponential decay is found, the time constant τ_1 going through a maximum and then decreasing almost proportionately with pressure. At 140°C, the maximum value of τ_1 is 1.5 milliseconds, which occurs at about 0.8-mm pressure. As seen on Fig. 6, the straight portion of the light intensity curve extends to rather short times. The intensity in the afterglow is very high, and is about 10 times greater at 1 millisecond for 3.6 mm than for 0.19-mm pressure. The time constant associated with the light curve is found to go through a maximum at about the same pressure as the electron density time constant. After the maximum, it decreases faster with pressure, behaving very closely like the time constant found by Alpert and others[9] in experiments on imprisonment of resonance radiation. Simultaneous spectrograms show the reappearance of a very strong, continuous spectrum. Both in the discharge and the afterglow, maxima of light intensity are found at 3300A and 4500A. The maximum at 3300A is relatively much stronger than in case 1. Band heads at 3070, 3095, 3450, 3480A appear in the afterglow.

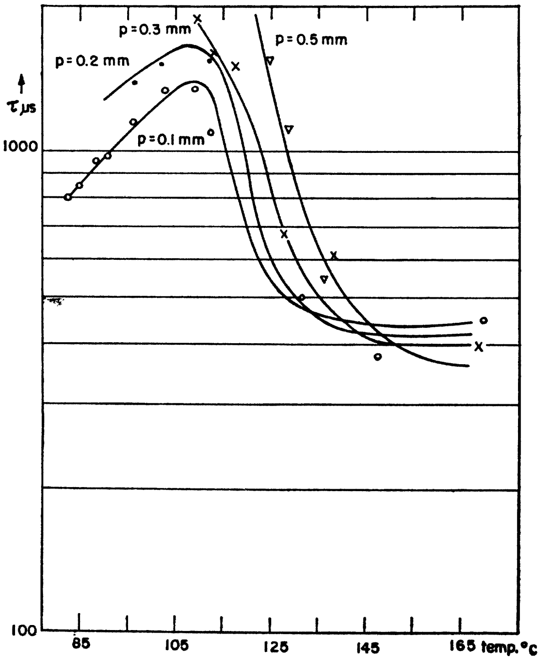

FIG. 5. Variation of electron density decay time constant with temperature.

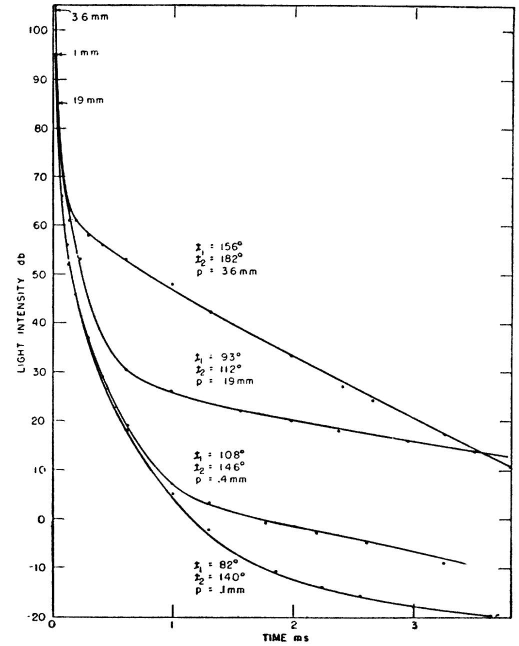

FIG. 6. Light intensity in the afterglow (case 2).

Case 4. Pressures 4 mm to 10 mm; Temperature below 230°C

In this region the real and imaginary part of the conductivity are of the same order of magnitude. This introduces some uncertainty about the absolute value of the electron density; however, once again exponential

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[9] Alpert, McCoubrey, and Holstein, Phys. Rev. 76, 1257 (1949).

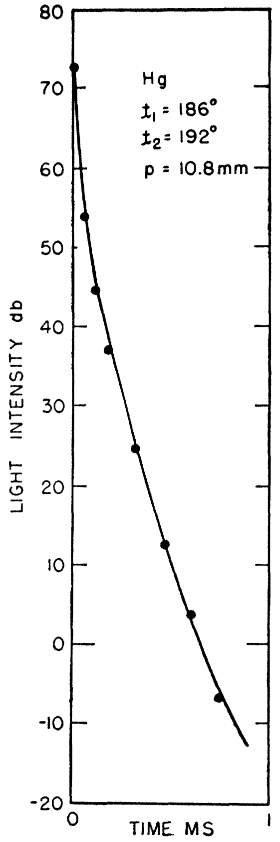

FIG. 7. Light intensity in the afterglow (case 4).

decay is found. The value of the time constant (which depends only on the ratio of two values of the electron density) is probably not too much in error. Electron density time constants are found to decrease almost proportionately with pressure. The light intensity is found to decrease very rapidly, giving time constants of the order of 100 microseconds (Fig. 7). In the spectrograms of the afterglow, an extremely intense band spectrum is observed together with persistent atomic lines. The band heads, although very diffuse, can be identified. Their wavelengths agree with values published by previous workers.[10–12]

IV. DISCUSSION

For pressures under 0.5 mm, the electron-density decay follows fairly well the predictions of ambipolar diffusion theory. The formula giving the time constant of the electron decay is

$$\tau_1=\frac{1}{(\pi^2/a^2)+(5.8/R^2)}\,\frac{e}{k}\,\frac{273}{300K_0}\,\frac{p}{T^+(T^++T_e)},$$

where a is the tube height; R is the tube radius; k is the Boltzmann constant; e is the electronic charge in

TABLE I.

p	T^+	T_e (calculated)
0.1 mm	355	2100
0.2 mm	371	2170
0.3 mm	388	1930

esu; K_0 is the mobility of Hg^+ at 1-mm pressure, 0°C in cm/sec/volts/cm; p is the pressure in mm; T^+ is the positive ion temperature in °K; and T_e is the electron temperature in °K. If we use for K_0 the value given by Mierdel[4] of 220 cm/sec/volt/cm, and if we consider experiments where the gas temperature is nearly equal to the temperature of the liquid mercury, we consistently find values around 2000°K for the electron temperature, as calculated from the above expression using our measured values of τ_1 (see Table I). With the same pressures but higher temperatures, on the other hand, we observe an unexpected increase of the time constant, which results in a smaller value of T_e (e.g., $p=0.1$ mm, $T^+=380$°K gives $T_e=1000$). This is presumably owing to the effect of heating, which reduces the density of metastables in the afterglow. Metastables would diffuse faster to the walls at higher temperature, thus increasing the probability of transitions $2^3P_0\rightarrow 2^3P_1$.

As we have previously stated, we can estimate the recombination coefficient as about 5×10^{-9} from the curved portion of the light intensity curve. This value is higher than the theory of such processes would predict for a radiative recombination of the type

$$Hg^++e\rightarrow Hg+h\nu.$$

This fact, although noted for many other gases, might lead us to expect that there are also some molecular ions present and that recombination between molecular ions and electrons proceeds at a much faster rate than expected from the theory. The molecular ions would be formed in triple collisions involving one atomic ion and two neutral atoms. The straight portion of the light curve is associated, as we have seen, with the emission of an intense continuum. It is quite probable that the excited molecules giving rise to this spectrum are produced in collisions between a metastable mercury atom and two neutral atoms in reactions of the type

$$Hg(2^3P_0)+Hg(1^1S)+Hg(1^1S)\rightarrow Hg_2'+Hg.$$

At low pressures, the density of metastable atoms is principally limited by diffusion to the walls. Using, for the diffusion coefficient of metastables, the kinetic theory value $D=el/3$, where c is the velocity and l the mean free path of the particle, D is about 25 at 400°K and at 1 mm pressure. This would correspond to

$$\tau_{\text{metastables}}=\frac{1}{(\pi^2/a^2)+(5.8/R^2)}\,\frac{1}{D}=12 \text{ milliseconds.}$$

At pressures of about 0.1 mm, the time constant should

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[10] Lord Rayleigh, Proc. Roy. Soc. (London) A116, 702 (1927).
[11] H. Hamada, Phil. Mag. 12, 56 (1931).
[12] J. Stark and G. Wendt, Physik. Z. 14, 564 (1913).

be about 1 millisecond, which is closely equal to the observed time constant for light intensity decay. This value is not very different from the value corresponding to electron density decay at the same pressure.

When the pressure is increased above 1 mm, the electron decay becomes faster. Since the electron density curve is found to be exponential, the possibility of recombination as the process responsible for electron removal is excluded. The hypothesis of attachment of electrons to neutral mercury atoms seems to explain the data fairly well. If η is the attachment coefficient, the electron density n satisfies the following equation:

$$dn/dt = -\eta n_a n,$$

where n_a is the density of neutral atoms. The associated time constant

$$\tau_1 = 1/(\eta n_a)$$

should decrease proportionately with pressure at constant temperature. This is found experimentally. At constant pressure, an increase with temperature is expected and is also observed. From our measured τ_1, we calculate

$$\eta = 1/(\tau_1 n_a) = 2\times 10^{-14}.$$

Attachment loss is often described in terms of the attachment probability per collision, which in this case would be about 2×10^{-7}. The appropriate quantum computation[13] shows that the attachment probability in Hg should increase with decreasing electron energies below 1 ev. The calculated attachment probability is of the order of 10^{-6}, using an electron affinity of 1.79 ev which had been found[14] by a semi-empirical method. Our results indicate that this value of the electron affinity is too high, a fact already suggested by the failure of some observers to find negative ions in mercury vapor.[15]

We find that the time constant associated with the light intensity decay goes through a maximum at about the same pressure as the one at which the slowest electron decay is observed. When the pressure is increased further, the light intensity decays extremely rapidly (Fig. 7) and time constants are about those observed by Alpert and others.[9] This is explained by the competition between two processes for the destruction of metastable atoms in the 2^3P_0 state. The first of these is diffusion to the walls, which becomes negligible as the pressure is increased; the second, transitions $2^3P_0 \rightarrow 2^3P_1$, which become more frequent as the pressure is increased. For example, at a pressure of 3 mm and at 50°C, we expect about 100 times more collisions with the necessary amount of energy for this transition than at 0.1-mm pressure and 80°C. Consequently, the continuum at 3300A is expected to become relatively more intense compared to the continuum at 4800A, a fact that we observed and which has already been noticed[16] after moderate heating of a discharge tube.

Electron density data becomes poor as the pressure reaches the range 5–10 mm. This is related to an increase of the real part of the complex conductivity. From the recent results obtained by Adler,[17] who observed a maximum of the real component at 9-mm pressure for a frequency of 8400 megacycles and an electron temperature of about 8000°K, it can be calculated that a maximum should occur in our case at about 7-mm pressure.

V. CONCLUSIONS

The rate of electron density decay is determined at low pressure by ambipolar diffusion and at higher pressures by attachment. Some recombination is present and probably accounts for the line spectrum and part of the band spectrum in the afterglow (especially the bands at 3448A and 3480A). The greatest part of the light intensity, however, probably comes from formation of excited molecules in collisions between neutral and metastable atoms. The density of metastable atoms, upon which the light intensity depends, is determined in the afterglow by diffusion at low pressures and by collision processes at higher pressures.

Interpretation of the results is made complex by the presence of metastables in the plasma. These are the source of many effects which are coexistent with the processes involving electrons and ions. The fact that in the pressure range studied recombination loss was not found to become predominant is quite remarkable. Our assumption that the high pressure decay is mainly due to attachment needs to be substantiated by other investigations; in particular, by introducing mass spectrography in the afterglow to identify the ions present.

One of the authors (P. D.) is greatly indebted to the Centre National de la Recherche Scientifique for the award of a generous scholarship, which made this work possible.

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[13] H. S. W. Massey and R. A. Smith, Proc. Roy. Soc. (London) **A155**, 472 (1936).

[14] George Glockler, Phys. Rev. **46**, 11 (1934).

[15] U. Stille, An. Physik **17**, 635 (1933).

[16] W. M. Nielsen, Phys. Rev. **38**, 888 (1931).

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