Afterglow of a free plasma column when the microwave power is abruptly turned off

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The described experimental setup has been used to study the visible-light afterglow of a microwave discharge observed when the power supply to the discharge is suddenly cut off. The results obtained for a discharge in deuterium at a pressure 0.8 to 2 atm and an input power up to 12 kW indicate the presence of a high-temperature core with an electron temperature of the order of 10^6 K.

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1. INTRODUCTION

P. L. Kapitza[1] has modulated the power supply to a discharge, and observed in the visible part of the spectrum the oscillations and intensity of the plasma-pinch radiation. Oscillations of the integrated-radiation intensity were observed only when the frequency of the modulation did not exceed 10^5 Hz. Estimates have shown that this corresponds to the relaxation time of the hot plasma. Kapitza has also shown that the fully ionized core of the plasma pinch with an electron temperature $\sim 10^6$ K makes a small contribution to the radiation in the visible region of the spectrum and the radiation is determined mainly by the external layers—the "jacket" of the plasma filament. It would be of interest in this connection to observe the afterglow of a microwave discharge after the power is turned off, since the core of the plasma filament should undoubtedly manifest itself in this afterglow. On the other hand, it is known that in the case of a nonequilibrium low-temperature plasma, relaxation methods make it possible to measure the disparity between the electron and ion temperatures, and also the recombination and ionization coefficients.[2–4] Thus, by studying the afterglow of a plasma filament it is possible to obtain information concerning both the core of the plasma filament and its jacket.

This paper reports the principal experimental results obtained in an investigation of the afterglow of a high-frequency pinch and diffuse discharges in deuterium at 0.8–2 atm absolute and a power supply up to 12 kW after abruptly turning off the microwave power.

The following were registered in the discharge afterglow: the integrated radiation of the entire discharge and of various parts of it in the wavelength range 2000–7000 Å, the line and continuous spectral emission in the wavelength range 3500–12 000 Å. High-speed photography was also carried out of the decaying discharge. This was preceded by the recording of the spectra of the stationary discharge in the wavelength range 3500–12 000 Å, which were used for calibration purposes at the switching-off instant.

To determine the role of diffusion and recombination of the electrons in the afterglow of the plasma pinch, we measured the dependence of the half-width of the line D_β on the time in the decaying discharge.

2. EXPERIMENTAL SETUP

The setup for obtaining the plasma pinch in a high-frequency field at high pressure was developed under the direction of P. L. Kapitza at the Physics Laboratory of the USSR Academy of Sciences, and its detailed description is contained in[1,5]. The high-power generator, the nigotron, which fed the load resonator with the plasma pinch, was also developed by Kapitza and described in[6,7]. We shall not dwell therefore on this part of the installation, and proceed to describe the system used to distinguish the discharge, as well as the recording apparatus.

To turn off the nigotron we used a high-power mercury thyratron TR 15-40, which was connected through a resistor $R_1 \approx 1500\ \Omega$ in parallel with the anode circuit of the nigotron (see Fig. 1). When a triggering pulse was supplied to the grid of the thyratron, the latter conducted and the voltage on the nigotron was decreased by several hundred volts on account of the voltage drop across the balast resistor $R_2 \approx 180\ \Omega$. The nigotron generation was then interrupted and the discharge was extinguished. The resistors R_1 and R_2 were chosen such that the time required for the anode voltage of the nigotron to leave the generation range was much shorter than the damping time of the working wave, and to prevent the nigotron from falling in other generation bands. Several milliseconds after the application of the triggering impulse, the nigotron voltage was completely removed and the apparatus was ready for another triggering.

The shutoff of the high-frequency power was monitored with magnetic loops installed in the nigotron and in the load resonator. The thyratron rise time to the maximum value was 0.1–0.2 μsec. The damping time of the high-frequency power was determined by the Q of the

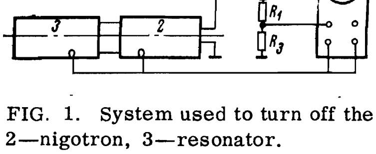

FIG. 1. System used to turn off the nigotron: 1—power supply, 2—nigotron, 3—resonator.

nigotron–resonator–discharge system and was of the order of 0.5 μsec.

The discharge afterglow time was practically always of the order of 5 μsec and longer. Thus, the influence of the damping of the high-frequency power on the afterglow process manifests itself only during the initial instants, which lasted not more than 10% of the total afterglow time, and it is just in this sense that we can say that the microwave power was shut off abruptly.

The radiation was registered with photomultipliers feeding a two-beam long-persistence oscilloscope S1-42 with a resolution time on the order of 0.1 μsec. To study the integrated radiation of the plasma pinch, the discharge was projected on the photocathode of an FÉU-39A photomultiplier by a pinpoint camera. To separate different parts of the spectra, light filters were placed between the pinpoint camera and the photocathode.

When registering the afterglow of individual parts of the discharge, the latter was projected with the aid of a quartz lens on an adjustable slit, which was rigidly mounted on the housing of the photomultiplier and could rotate together with the latter. Thus, we observed the radiation of a discharge section cut out diametrically or in length. In the former case the signal was independent of the displacements of the discharge in the resonator and good reproducibility was observed from extinction to extinction. In the second case the intensity was strongly dependent on the discharge position and varied from extinction to extinction by dozens of times, since the image of the discharge was not stabilized (see[1], p. 1814 of the original, p. 000 of the translation), and therefore these measurements are qualitative in character, although it was possible to identify the observed section of the discharge from the magnitude of the signal.

The spectral measurements in the range 3650–12000 Å were carried out with an SPM-2 mirror monochromator, the discharge being projected on the entrance slit, and a photomultiplier (FÉU-39 or FÉU-62) placed behind the exit slit. When the stationary-discharge spectrum was recorded the discharge remained in the field of view of the monochromator during the course of its motion in the resonator, owing to the large relative aperture of the SPM-2 instrument, and the output signal was hardly altered by the oscillations of the discharge. The result was a discharge spectrum averaged over the cross section.

The investigations were carried out with and without purification of the gas in the resonator. The purification was with the aid of a nitrogen trap connected in one of the leads of the closed gas system, ensuring rotation of the gas in the resonator to stabilize the plasma pinch. The degree of gas purity was monitored against the molecular CN and CH bands in the near ultraviolet region 4315–3870 Å.

The high-speed photography of the discharge was carried out in the integral light by means of an LV-03 time magnifier.

3. AFTERGLOW OF PINCH DISCHARGE IN DEUTERIUM

The afterglow of a pinch discharge in deuterium was investigated in the discharge supply-power range from 2.5 to 12 kW and in the pressure range from 0.8 to 2 atm abs. Figure 2 shows oscillograms of the afterglow as seen in the D_β line and of the continuous emission near the line, and also oscillograms of the integrated radiation of the entire pinch at stationary discharge power 8 kW and pressure 1 atm abs. The scale of the signal amplitude and the time scale are shown on the oscillograms, and the observed spectral interval in angstroms is listed in the figure caption.

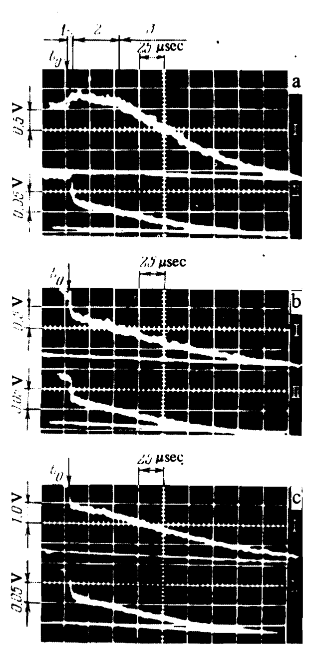

FIG. 2. Radiation intensity of the D_β line, $\Delta\lambda = 20$ Å (a): and $\lambda \approx 4650$ Å, $\Delta\lambda = 60$ Å (b); and $\lambda = 5200$ Å, $\Delta\lambda = 80$ Å (c)—trace I. Trace II (a, b, c) represents the integrated radiation of the entire pinch, $P = 8.0$ kW, $p = 1.0$ atm abs.

The afterglow process, both in the lines and in the continuous spectrum, breaks up into three time phases, as is particularly clearly seen at high discharge powers, Fig. 2. The first and the shortest phase is an abrupt rise of the radiation intensity in the lines and an abrupt decrease of the radiation intensity in the continuous spectrum. The second afterglow phase of the plasma pinch, a linear decrease of the radiation intensity, and then the third, consisting of a faster exponential decrease, were the same for the line and the continuous spectra.

In the investigation of the lines, the first phase of the afterglow of the plasma pinch is most distinctly observed at low discharge powers. The dependence of the duration of the first phase on the power at a pressure 1 atm abs is shown in Fig. 3. The ratio of the maximum intensity of the radiation to the stationary value has a maximum at low power in the discharge and decreases sharply with increasing power (Fig. 4).

The duration of the second phase, just as that of the first, depends strongly on the power. It amounts to 2–2.5 μsec at ~4 kW and increases to 50–70 μsec when the power is increased to 8 kW. At powers less than 4 kW, the second phase of the afterglow is difficult to discern, since it merges with the third phase.

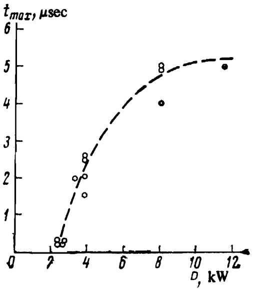

FIG. 3. Time required to reach the maximum intensity of the D_β line in the afterglow of a plasma pinch vs the power at a pressure ~1 atm abs.

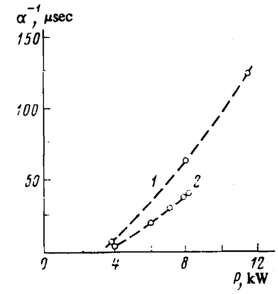

FIG. 5. Dependence of the afterglow time on the power in the D_β line and in the continuum near the line: curve 1—$p=1$ atm abs, 2—$p=2$ atm abs. Accuracy ±10%.

The third phase of the faster decrease of the radiation intensity is well described by the exponential $I=I'e^{-\alpha t}$. The dependence of $1/\alpha$ on the power and on the pressure is illustrated in Fig. 5.

Generally speaking, the experimental oscillograms constitute the sum of the intensities of the line and of the continuous emission. However, from a comparison of the scales of Fig. 2 it is seen that the continuous emission amounts to several percent of the intensity of the line and can be neglected.

The emission in the other deuterium lines, D_α, D_γ, and D_δ behaves after the power is turned off in the same way as in the D_β line. The ratio of the line intensities remains constant with good accuracy, at least during the first and second phases of the discharge afterglow, and is equal to the ratio of the lines in the stationary discharge. For the lines D_β and D_δ this ratio is 4–5.

For a discharge in deuterium at 4 kW and 2 atm abs, the dependence of the half-width of the D_β line on the time, after turning off the power, was obtained by comparing the intensity signals at the center of the line and at half-height. It turned out that during the characteristic time of the afterglow the line width remains constant. We could not perform such measurements at greater powers and lower pressures, since the line width decreases sharply with increasing power and with decreasing pressure, while the resolution of the SPM-2 monochromator could not be made better than 1.5 Å.

The character of the afterglow in the continuous spectrum differs substantially from the afterglow in the line spectra. At low powers (up to 4 kW) and a pressure 1–2 atm abs, all three phases coalesce into an exponential decrease of the radiation intensity: $I=I_0e^{-\alpha t}$, where I_0 is the intensity of the stationary-discharge radiation. With increasing power, the character of the

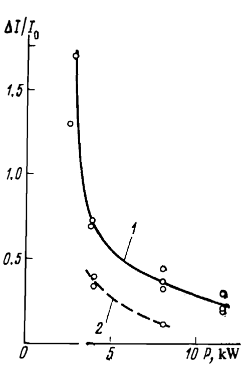

FIG. 4. Jump of intensity of the D_β line as a function of the power; at $p=1$ atm abs (curve 1) and at $p=2$ atm abs (curve 2); $\Delta I=I-I_0$.

afterglow in the region of the continuous radiation changes. At first one observes a sharp decrease of the radiation intensity to a value $\sim I_0/2$ at a pressure 1 atm abs, and at a pressure 2 atm abs the intensity decreases to $I_0/6$–$I_0/8$. The dependence of the decrease on the power is weak. Then, just as in the line spectrum, a linear decrease (the second phase) is observed, followed by the phase of the faster exponential decrease of the radiation intensity $I=kI_0e^{-\alpha t}$. The dependence of $1/\alpha$ on the power at pressures 1 and 2 atm abs is the same as in the line spectrum and is shown in Fig. 5. The durations of all the afterglow phases in the continuous radiation agree well with the durations of the corresponding phases in the line spectra.

When the pressure is increased from 1 to 2 atm abs and the power is kept constant, the general rule for both the lines and the continuous spectrum is that the jump of the intensity in the first phase decreases and the time of the afterglow decreases by approximately 20%.

The integrated radiation of the entire pinch and of the diametrically truncated central part of the pinch at a pressure 1 atm abs is similar to the behavior of the continuous radiation when the power is turned off. At a pressure ~2 atm abs and a power ~8 kW, the integrated radiation of the outer layers is similar to the radiation of the continuous spectrum, and the integrated radiation of the central part of the pinch, diametrically truncated, is similar to the line radiation. On the other hand, the integrated radiation of the entire pinch remains practically constant for approximately 50 μsec after the power is turned off, after which it decreases exponentially, $I=I_0e^{-\alpha t}$, where $1/\alpha\approx 40$–50 μsec and I_0 is the radiation intensity of the stationary discharge.

We investigated also the afterglow of a diffuse discharge.[1] No difference was observed in its behavior in the line spectrum, in the continuous spectrum, or in the integrated light of the afterglow. This result can be attributed to the fact that when the pinch discharge becomes diffuse, the intensity of the lines decreases by an approximate factor of 400, and the intensity of the continuous radiation by a factor of 20. The observations were carried out with wide monochromator slits, owing to the low radiation intensity, so that the contribution of the continuous radiation to the output signal was proportional to the square of the slit width, while the contribution of the lines was proportional to the width of the monochromator slits.[8]

On the other hand, at parameters close to those of the diffuse case, the afterglow of a pinch discharge agrees with the above-described behavior of the pinch discharge at $P \approx 4$ kW and $p = 1$ atm abs, except that its integrated radiation is similar to the line radiation.

4. DISCUSSION OF RESULTS

In the case of low-temperature and sufficiently uniform non-equilibrium plasmas, the relaxation research methods have by now been well developed and make it possible to determine such parameters as the disparity between the electron and ion temperature $(T_e - T_a)$ or $(T_e - T_a)/T_a$, and the recombination and ionization coefficients.[2-4] In fact, according to the model of local thermodynamic equilibrium (LTE) the populations of the upper levels are closely connected with the states of the free electrons. When the current is abruptly turned off, a rapid decrease of the electron temperature, down to the temperature T_a of the heavy particles, takes place during the first cooling phase. The relaxation time of this process for dense partially ionized plasmas at a pressure on the order of atmospheric and with $T \approx 1$ eV is close to 10^{-8} sec.[9] Thus, the upper-level population $n(k)$ increases, and consequently the intensity of the corresponding lines also increases. This follows from the generalized Saha equation

$$n(k) = \mathrm{const}\cdot n_e n_+ T_e^{-3/2} \exp\{[\chi - E(k)]/kT_e\} \tag{1}$$

(χ is the ionization potential, $E(k)$ is the energy of excitation of the level k), since $n_e = n_+$ varies more slowly than T_e, and can be regarded as constant, at any rate during the course of the first phase of the afterglow.

The first phase is followed by the second, non-equilibrium cooling phase. The electron concentration in it exceeds the equilibrium value corresponding to the gas temperature, and the ionization equilibrium is shifted towards recombination. From the time variation of the radiation in the lines and in the continuous spectrum at the start of the second phase we can determine the recombination coefficient of the electrons if we know their initial concentration.

The last is the third equilibrium phase of discharge cooling. In this phase the electron temperature is equal to the gas temperature, the electron concentration is close to the equilibrium value and is determined by the temperature. The rate of cooling in the third phase is determined mainly by thermal conductivity and convection.

Let us compare the behavior of the radiation in the afterglow of a cold plasma with the microwave-discharge afterglow described above.

We note first that after attainment of the maximum of the total line intensity and the abrupt decrease in the continuous radiation, i.e., in the second and third phases, the plasma-pinch afterglow process agrees well with the results of analogous experiments with low-temperature non-equilibrium plasmas. We note that when we investigated the afterglow in mixtures of deuterium with inert gases, it turned out that actually the duration of the third phase of the afterglow is determined by the transport coefficient and is longer the worse the thermal conductivity of the mixture in which the microwave discharge is produced. The coefficient of the electron-ion recombination α, determined from the slope of the continuous-radiation oscillograms at the start of the second phase is, just as in[3], in satisfactory agreement with the results of[10] (see Table I).

TABLE I.

Gas	P, kW	p, atm abs	$\alpha\cdot 10^{11}$, cm^3/sec	$T_a\cdot 10^{-2}$, K	$T_e\cdot 10^{-2}$, K	$T_e^{eq}\cdot 10^{-2}$, K
D_2	2.6	1.1	3.6	57	83	91
	3.9	1.0	3.1	53	63	82
	8.0	1.0	1.9	50	55	71
	11.5	1.0	0.95	47	50	65

In the determination of α we have assumed that the radiation in the second phase is due to recombination. In this case we obtain $I \propto n_e^2$ for the intensity of the continuous radiation. On the other hand, $dn_e/dt = \alpha n_e^2$. Taking the initial concentration of the electrons in the pinch from[1] (p. 1821 of original, p. 000 of the translation), we determine the recombination coefficient from the slope of the afterglow oscillograms in the continuous spectrum at the start of the second phase.

The table lists, besides the recombination coefficient α obtained from the experimental data at a pressure 1 atm abs and at a discharge power from 4 to 12 kW, also the corresponding gas temperature. To determine the gas temperature we used the temperature dependence of the recombination coefficient of the electrons in hydrogen, which is well known both experimentally and theoretically ([10], Fig. 9). It should be noted that although the results have been averaged over the pinch cross section,[1,5] owing to the strong dependence of the recombination coefficient α on the temperature the possible errors in the determination of the initial concentration do not lead to noticeable errors in the determination of the gas temperature. Furthermore, the radiation in the afterglow is determined mainly by the hottest part of the cooling discharge, i.e., by the center of the pinch. It can therefore be assumed that the gas temperature at the center of the pinch is somewhat higher at the start of the second phase than the temperature obtained from the averaged experimental data.

When determining the recombination coefficient we disregarded the fact that during the time of the first phase the electron concentration decreases somewhat on account of recombination and ambipolar diffusion. It is easy to verify, however, that this decrease is small. Furthermore, we chose an initial concentration determined by spectral measurements from the broadening of the D_β line, whereas the microwave measurements[11,12] indicate that the concentration of the electrons at the center of the pinch exceeds the value measured by spectral methods. This makes us certain that the values obtained for the recombination coefficient α are close to the true ones.

Greatest interest, however, attaches to the initial section of the afterglow oscillograms obtained in the line and continuous spectra (Fig. 2), which cannot be explained by means of the properties of the low-temperature plasma.

As indicated above, in a cold dense plasma ($T\sim 1$ eV, $p\sim 1$ atm abs) the electrons cool down to the temperature of the surrounding gas in a time on the order of 10^{-8} sec. The time of turning off the microwave power exceeds this value appreciably and amounts in our experiments to $\sim 5\times 10^{-7}$ sec. If it is assumed that T_e in the pinch is several electron volts, then the electron temperature should follow the power and the time of electron cooling to the temperature of the surrounding gas should be of the order of the shutoff time. At the same time, in our experiments (see Fig. 3), the duration of the first phase is ~ 2.5 μsec at a discharge power ~ 4 kW and increases to 5 μsec at $P=8$ kW. This behavior of the radiation does not agree with the model of a low-temperature plasma. One of the possible explanations is that the hot electrons cool down more slowly in the core of the plasma pinch, since the energy transferred from the electrons to the ions is proportional to n_e^2 and inversely proportional to T_e, while the initial electron concentration decreases with increasing power.[1]

Let us estimate the time of cooling of the hot electrons of the core to the temperature of the jacket surrounding the core, when the microwave power is turned off, but let us first describe the cooling process qualitatively.

When the power is turned off, the electrons begin to cool, and this should lead to a decrease of the pressure in the core of the pinch. The core, however, is surrounded by a cold gas, the volume of which is much larger than the discharge volume, and therefore the pressure in the cooling core is maintained constant and equal to the gas pressure p in the resonator. The pressure is maintained constant by energy drawn from the surrounding gas and is dissipated in the cooling core of the plasma pinch; its value is pV, where V is the volume of the nucleus in the stationary discharge (since $T_e\approx 10^6$ °K and the temperature of the surrounding gas is $T_a\approx 10^4$ °K). In a stationary microwave discharge, the energy is released in the core of the pinch (anomalous skin effect[1]), and consequently the state of the jacket is determined by the energy lost by the core. When the microwave power is turned off, the state of the jacket continues as before to be controlled by the energy lost by the core, up to the instant when the electron and gas temperatures become equalized.

The time of cooling of the electrons in the core of the plasma pinch after the power is turned off can be obtained by using the well known formula for the change of the electron temperature in Coulomb interactions ([13], p. 58):

$$-\frac{dT_e}{dt}=B\frac{T_e-T_i}{T_e^{3/2}}, \tag{2}$$

where we must put $T_i=\mathrm{const}$ in order to take into account the cooling losses, and the quantity B, which in the case of cooling at constant concentration is equal to $n_e/17A$ (A is the atomic weight), must be replaced by

$$B=\frac{n_e}{17A}\frac{T_{e0}+T_{i0}}{T_e+T_i},$$

to take into account for the fact that the cooling takes place at constant pressure. As a result, formula (2) takes the form

$$-\frac{dT_e}{dt}=\frac{n_e}{17A}\frac{T_{e0}+T_{i0}}{T_e+T_i}\frac{T_e-T_i}{T_e^{3/2}}. \tag{3}$$

For the start of the cooling process, when $T_i\ll T_e$, , expression (3) can be simplified in the following manner:

$$-\frac{dT_e}{dt}=\frac{n_e}{17A}\frac{T_{e0}}{T_e^{3/2}}. \tag{4}$$

According to (4), the rate of change of the electron temperature increases with time, whereas according to formula (3) this quantity has a maximum at $T_3\approx 3T_i$. It must be taken into account, however, that formula (3) does not describe the cooling of the electron in our case at low temperatures, for in this case an important role is played by collisions with the neutral atoms, which greatly increase the rate of cooling. Thus, formula (4) describes more accurately the cooling of the electrons at low temperatures than formula (3). From (4) for the case $T_e\approx 10^6$ °K and $n_e=10^{16}-10^{15}$ cm^{-3} [1] we obtain respectively

$$\tau\approx 1.4\cdot(10^{-7}-10^{-6})\ \text{sec}.$$

It is easy to show that allowance for the contraction energy approximately doubles this time. The obtained estimates of the time of equalization of the electron and ion temperatures $\tau=3\times(10^{-7}-10^{-6})$ sec is in good agreement with the duration of the first phase of the afterglow of the plasma pinch when the power is turned off, and thus confirms the correctness of the explanation proposed above for the afterglow process in the first phase, demonstrating at the same time the need for taking into account the compression energy released in the core as the latter cools down.

We present now a qualitative explanation of the dependence of the duration of the first phase of the afterglow on the supplied power. We start from simple energy considerations.

It can be assumed, at least at the start of the first phase, that the rate of energy transfer from the electronic component to the ionic component at the instant when the power is turned off remains unchanged and equal to the power P supplied to the discharge in the stationary state. The time τ of equalization of the electron and ion temperatures is determined by the energy

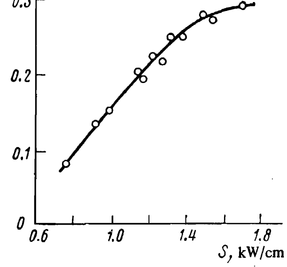

FIG. 6. Dependence of the discharge radius on the supplied power.

reserve of the electron component of the plasma and its order of magnitude is $(T_e - T_i)n_e/P$. For a microwave-discharge plasma with $T_e \sim 10^6$ °K $\gg T_i$, the value of τ is proportional to pV/P. In the experiment one observes the radiation of that part of the discharge which is bounded by the vertical slit. Therefore $\tau \propto pr^2/S$, where S is the power per unit discharge length and r is the discharge radius.

From the experimental dependence of r on S (Fig. 6) it is seen that at sufficiently large r the $S(r)$ dependence is close to quadratic and consequently, τ does not depend on the power delivered to the discharge, whereas at low powers $S(r)$ is close to linear and consequently τ is proportional to r.

Let us dwell in conclusion on the possibility of determining the difference between the electron and gas temperatures from the discontinuity in the radiation intensity in the line spectrum during the first phase of the afterglow. In the case of a low-temperature plasma it is easy to determine T_e from (1) if we know the temperature of the gas T_a and the discontinuities of the radiation intensity in the line (see Fig. 4).

In the case of a microwave discharge, the central part with electron temperature $T_e \approx 10^6$ °K could make during the course of its cooling some contribution to the intensity discontinuity in the line. However, it follows from the microwave-pinch cooling process considered above that the hot core determines the duration of the first phase of the afterglow, and the magnitude of the discontinuity of the line-emission intensity is determined mainly by the jacket of the plasma pinch. Assuming that the contribution of the pinch core and the discontinuity of the radiation intensity in the line is small, we determine from (1) the difference between the electron and gas temperatures in the jacket of the plasma pinch. The results are given in the table, from which it is seen that with increasing power supplied to the discharge the difference between the electron and gas temperatures in the jacket decreases together with the decreasing gas temperature. The equilibrium concentration of the electrons, corresponding to the measured electron temperature, turns out to be lower than the experimental value, as expected.

Thus, the investigations of the afterglow confirm the microwave plasma-pinch model assumed in[1]. The experimentally determined gas and electron temperatures in the plasma-pinch jacket are in good agreement with measurements by others.[14]

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