SPECTROSCOPIC DIAGNOSTICS OF A PLASMA EXPANDING INTO A BACKGROUND GAS AND A MAGNETIC FIELD

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Spectroscopic and optical diagnostics are widely used in experimental studies of transient processes in a cosmic plasma, in natural experiments in near-earth space, and in laboratory modeling of astrophysical phenomena [1-4]. A cosmic plasma (especially in explosive processes) is characterized by the interaction, collisionless with respect to ion momentum loss, of interpenetrating flows. The line emission from such a plasma is usually nonequilibrium and is determined by elementary processes: recombination, charge exchange with the background gas, and collisional excitation by high-energy electrons. Spectroscopy diagnostics of a nonsteady plasma have usually been used previously without clarifying the mechanism of excitation of the lines [2], or under conditions in which some one process — recombination or charge exchange — predominates [3].

In the present paper we consider for the first time the possibilities of spectroscopic measurements of an optically thin plasma under the conditions of variation of the mechanism of excitation of the ions. The line emission in the visible from a carbon laser plasma expanding into a background gas or an external magnetic field is investigated experimentally on a KI-1 bench [4]. The test parameters satisfied the conditions under which the ions are collisionless: the characteristic momentum-loss length of the plasma flow exceeded the size of the installation. We investigated the emission from the plasma and gas due both to individual elementary processes (recombination, charge exchange, and electron collision) and to the change in the predominant mechanism of excitation of emission (recombination to charge-exchange or recombination to collisional). On the basis of the results, a new method is proposed for determining electron temperature in the 1-10 eV range. Good agreement is observed between the experimental data and a simple model describing the relationship between the line emission from a plasma and its parameters.

1. Experimental Setup

A neodymium glass laser was used in the work. Radiation with a total energy of 2 J and a half-width duration of 30 nsec, after passing through the focusing lens, entered a vacuum chamber and struck the target. The radiation spot diameter on the target was 2 mm and the intensity was 10^9 W/cm^2. The target, a wafer of caprolon $H_{11}C_6ON$, lay in the plane perpendicular to the incident radiation. The pressure in the vacuum chamber was varied from $2.7 \cdot 10^{-2}$ to 13 Pa by admitting the working gas (molecular hydrogen or helium).

Radiation from the laser plasma was collected by a condenser and focused on the entrance slit of an MDR-12 monochromator, which had dimensions 0.01 × 10 mm. The image of the monochromator slit was shifted over distances of 20-95 mm along the plasma jet produced at the target. After the monochromator, the radiation fell on a FÉU-84 photomultiplier, the signal from which was fed to an S8-14 oscillograph.

The emission of lines of carbon ions in the visible spectrum in a wide range of excitation potentials was investigated. The designations and parameters of the lines used are given in Table 1.

In experiments with a magnetic field B_0, the motion of the plasma flow across that field was studied. The B_0 distribution was bell-shaped with a maximum $B_0 = 7.8 \cdot 10^{-2}$ T at a distance R = 60 mm from the target. The change ΔB along the axis of propagation of the plasma jet was detected by a probe with a spatial resolution $\sim$5 mm.

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TABLE 1

Designation	λ, nm	I, eV	Designation	λ, nm	I, eV
C^{+1}_1	426,7	21	C^{+2}_4	406,8	43
C^{+1}_2	657,8	16,3	C^{+3}_1	465,8	58,5
C^{+2}_1	451,6	39,4	C^{+3}_2	580,1	39,7
C^{+2}_2	569,5	34,3	C^{+4}	494,4	385
C^{+2}_3	464,7	32,2	C^{+5}	529,0	

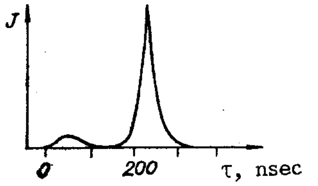

Fig. 1

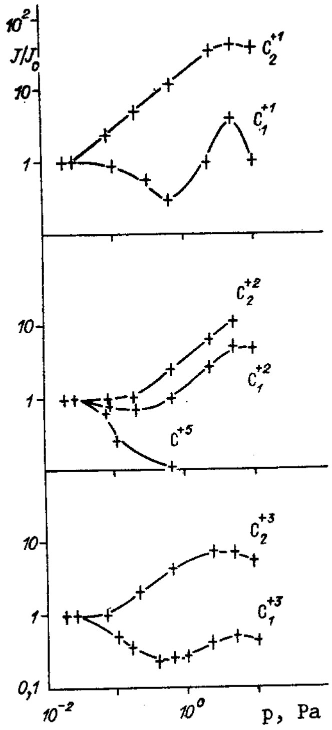

Fig. 2

2. Experimental Data

As is well-known [5], and as we established in preliminary experiments, the emission of a laser plasma expanding into a vacuum is of a purely recombination nature. At distances $R \gtrsim 10$ mm from the target, the intensity maximum of the emission of ions with $Z \geq 2$ lay mainly at the front of the laser plasma and was due to the successive recombination of highly charged ions (C^{+6}, C^{+5}, C^{+4}) into lower-charged ions. In our experiments the emission maximum of the lines of carbon ions with a charge Z = 2-5 propagated with a constant velocity $v_0 = 1.7 \cdot 10^7$ cm/sec. The emission intensity fell off with increasing distance from the target as $\sim 1/R^3$. The plasma was almost spherical, was always in contact with the target, and had a total number of particles $N_e \approx 10^{16}$.

A typical oscillogram of emission in a vacuum at R = 40 mm is given in Fig. 1.

In experiments with admission of the background gas (molecular hydrogen) we detected a dependence of the maximum of the emission intensity J for different lines of carbon ions on the pressure p of the background gas at a fixed R (Fig. 2) and, vice versa, a dependence on R for fixed p (Fig. 3). Graphs for R = 20 mm are shown in Fig. 2. It is seen that the background gas starts to affect the plasma emission starting with $p \sim 10^{-1}$ Pa. The emission of lines of a given ion with a lower excitation potential starts to increase monotonically with the pressure of the background gas considerably sooner than the emission of lines with a higher excitation potential.

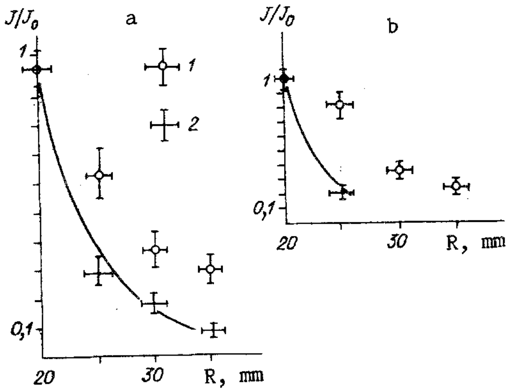

Fig. 3

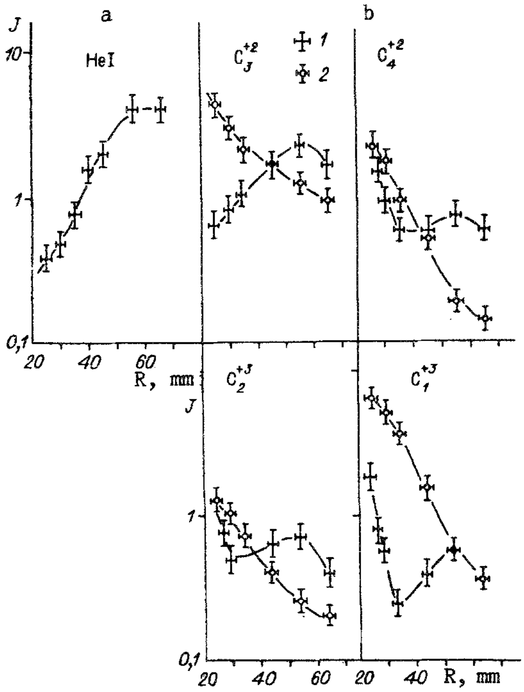

Fig. 4

Data for the $C^{+}{}_{1}{}^{2}$ line in the pressure range $2.7 \cdot 10^{-2} \leq p \leq 0.8$ Pa and for $C^{+}{}_{1}{}^{2}$ and $C^{+}{}_{2}{}^{2}$ at $p = 3$ Pa are given in Fig. 3a (points 1 and 2), and for C^{+4} at $p = 2.7 \cdot 10^{-2}$ and 0.8 Pa in Fig. 3b (points 1 and 2).

Heating of electrons by the diamagnetic current flowing at the front of the plasma cloud has been observed in experiments with expansion of a laser plasma in a magnetic field. The interaction of a laser plasma with a magnetic field has been investigated in [6]. Without going into details, we note that in the present work, in complete accord with [6], the flow of unmagnetized ions [$\varepsilon = R_H/R_B \gtrsim 1$, $R_H = Mv_0c/(ZeB_0)$ being the Larmor radius and $R_B = (3E_0/B_0{}^2)^{1/3}$ the limiting radius of the cavity], which by the time $t \approx 400$ nsec produced a magnetic cavity with a size $R' \approx 50$ mm, was not decelerated by the magnetic field and propagated to distances $R > R'$. In the process, the boundary of the cavity was washed out and the field penetrated efficiently into the cloud.

To detect heating of the electrons, a background gas was introduced: helium with a density $n_* = 10^{14}$ cm^{-3}. At such n_*, no collisional processes between plasma ions and helium play any significant role under the experimental conditions. In Fig. 4a we show the emission intensity of the 667.8 nm helium line at the front of the plasma cloud (in the region through which the diamagnetic current flows) as a function of R. Despite the decrease in plasma density with increasing R, the helium emission increases considerably in the section 25-60 mm, which indicates an increase in electron temperature T_e. Without a magnetic field, helium emission is absent under the same conditions.

In Fig. 4b we show the analogous data for C^{+2} and C^{+3} in a magnetic field and without it for comparison (points 1 and 2, respectively). Out to $R \approx 35$ mm the emission of the $C_4{}^{+2}$ line and lines of the C^{+3} ion decreases, and somewhat faster than in the case with no magnetic field. From 35 to 60 mm the emission of all of the lines increases.

3. Results and Discussion

In the expansion of a laser plasma into a background gas, recombination is joined by another elementary process, charge exchange (Table II, data taken from [7]). Excited ions are also produced in the process. The equations describing the dynamics of the densities of excited (n^{ex}) and unexcited ions have the form

$$n_{i-1}^{ex} = \frac{\tau_\gamma}{\tau_0} n_i \left(x_i + \frac{\tau_0}{\tau_r^i} \right); \tag{3.1}$$

TABLE 2

Reaction	σ, cm^2	E^*, eV
$C^{+1} + H_2 \rightarrow C^0 + H_2^+$	10^{-16}	
$C^{+2} + H_2 \rightarrow C^{+1} + H_2^+$	$5 \cdot 10^{-16}$	9
$C^{+3} + H_2 \rightarrow C^{+2} + H_2^+$	10^{-15}	32,5
$C^{+4} + H_2 \rightarrow C^{+3} + H_2^+$	$(3-6) \cdot 10^{-15}$	49

$$\frac{dn_i}{dt} = -3\frac{n_i}{t} - \frac{n_i}{\tau_0}\left(x_i + \frac{\tau_0}{\tau_r^i}\right) + \frac{n_{i+1}}{\tau_0}\left(x_{i+1} + \frac{\tau_0}{\tau_r^{i+1}}\right), \tag{3.2}$$

$$x_i = n_* \sigma_i R, \tau_0 = R/v_0.$$

Here R is the distance from the observation point to the target; n_* is the density of the background gas; σ_i is the charge-exchange cross section; and τ_r^i is the time of recombination of an ion of charge i into an ion of charge i − 1. The term $-3n_i/t$ describes the three-dimensional expansion of the laser plasma. It is assumed that the time τ_γ of radiative deexcitation of excited ions is much shorter than the other characteristic times ($\tau_\gamma \lesssim 10^{-8}$ is sufficient in our case). We write

$$\frac{1}{\tau_r^i} = \frac{\alpha_3 n_e^2 Z_i}{T_e^{9/2}} + \frac{\alpha_2 n_e}{T_e^{1/2}},$$

where $\alpha_3 \approx 5 \cdot 10^{-27}$ cm$^{-6}\cdot$sec^{-1} [8] is the three-particle recombination coefficient and $\alpha_2 \approx 10^{-11}$ cm$^{-3}\cdot$sec^{-1} [9] is the dielectronic recombination coefficient for carbon ions.

The third form of recombination, radiative, has the same functional form as dielectronic recombombination, but is usually about two orders of magnitude smaller.

As seen from (3.1) and (3.2), charge exchange becomes dominant at $x_i \gtrsim \tau_0/\tau_r{}^i$. An upper limit on the density of the background gas is imposed by the condition of a collisionless interaction of plasma ions with the gas: $n_* \sigma_{col} R \lesssim 1$. Charge exchange will therefore be the dominant elementary process for $\tau_0/\tau_r{}^i \lesssim x_i \lesssim \sigma_i/\sigma_{col}$.

Knowing $n_* \sim 2.6 \cdot 10^{13}$ cm^{-3} (see Fig. 2), at which charge exchange begins to affect the emission intensities of ion lines, from the condition $x_i \approx \tau_0/\tau_r{}^i$ we can estimate the electron temperature. Under our experimental conditions we obtain $T_e \approx 0.7$ eV at R = 20 mm. Three-particle recombination definitely predominates at such a temperature. Such an estimate of T_e depends very little on the parameters and changes only threefold with variation of x_i by two orders of magnitude.

The emission intensity of a specific line is determined mainly by the excitation potential of that line. For charge exchange with ion velocities $v \sim 10^7$ cm/sec, the most likely excitation level E* (see Table 2) depends on the difference between the ionization potentials of the newly formed ion and the neutral particle.

Figure 2 reflects the fact that the closer the excitation potential of an ion emission line is to the charge-exchange level E*, the sooner charge-exchange pumping of that line starts to dominate over recombination pumping, and the emission starts to increase linearly with increasing p in accordance with (3.1). For $x_i >> \tau_0/\tau_r{}^i$, when charge exchange dominates, for J we have from (3.1) and (3.2)

$$J_i \sim n_* n_{i+1} \sigma_{i+1} v_0 \exp[-n_* \sigma_{i+1} R] \sim \frac{1}{R^3} \exp[-n_* \sigma_{i+1} R]. \tag{3.3}$$

Here we have discarded the last term in (3.2) for simplicity, which is valid for $n_{i+1} \ll n_i$. At $x_i \approx 1$, J reaches a maximum, after which the emission intensity due to charge exchange, like the number of ions, decreases. The dependences of J_i on R and p that were obtained can be used to estimate the charge-exchange cross sections σ_i. According to Fig. 2, at p = 3 Pa the emission of the $C^{+}{}_{1}{}^{2}$ and $C^{+}{}_{2}{}^{2}$ lines will be due to charge exchange. As seen from Fig. 3a, in which the lines are plotted in accordance with (3.3), the agreement between Eq. (3.3) and experiment is good. The data for the C^{+3} ion are in satisfactory agreement with (3.3), while the results on the emission of C^{+4} (Fig. 3b) and C^{+5} ions enable us to estimate the reaction cross sections from (3.3);

$$C^{+5} + H_2 \rightarrow C^{+4} + H_2^{+},\ \sigma \approx 10^{-14}\ \text{cm}^2,$$
$$C^{+6} + H_2 \rightarrow C^{+5} + H_2^{+},\ \sigma \approx (3-6)\cdot 10^{-14}\ \text{cm}^2.$$

As T_e increasses, which occurs as the laser plasma expands into a magnetic field in a vacuum, the line emission from plasma ions becomes associated with two elementary processes: recombination and excitation by energetic electrons from the tail of the Maxwellian energy distribution. The emission is described, in general, by the equation

$$J_i \sim k_3 \frac{\alpha_3 n_e^2 n_{i+1} Z_i}{T_e^{9/2}} + k_2 \frac{\alpha_2 n_e n_{i+1}}{T_e^{1/2}} + n_e n_i \sigma_{ex} v_\varepsilon \exp\left[-\frac{I}{T_e}\right], \tag{3.4}$$

where I is the excitation potential of the observed line; σ_{ex} is its excitation cross section at an electron energy $\varepsilon \approx I$; $v_\varepsilon = \sqrt{2I/m_e}$; and k_2 and k_3 are the fractions of recombining electrons producing emission in the observed line.

Since the recombination intensity decreases with increasing T_e, while collisional excitation increases, the emission intensity will have a minimum at a certain temperature, which has been observed experimentally (Fig. 4b).

Emission in the $C^{+}{}_{3}{}^{2}$ line increases over the entire observed interval 25-60 mm. This is because the excitation potential of that line is the lowest of those given in Fig. 4b, and collisional excitation begins to dominate at lower T_e and smaller R for it.

An analysis of (3.4) shows that the T_e at which (3.4) has a minimum depends very little on the experimental parameters, which is related to the large exponent in the exponential and the strong $1/T_e{}^{9/2}$ dependence for three-particle recombination. In the ranges of parameters $0 \lesssim k_2 \lesssim 1$, $0.1 \lesssim k_3 \lesssim 1$, $1 \lesssim n_i/n_{i+1} \lesssim 10$, $10^9 \lesssim n_e \lesssim 10^{17}\ \text{cm}^3$, and $10^{-15} \gtrsim \sigma_{ex} \gtrsim 10^{-19}\ \text{cm}^2$, for example, we have $0.03 \lesssim T_e/I \lesssim 0.15$, which for lines with I = 40-60 eV means a range $1.2 \lesssim T_e \lesssim 9$ eV. We can therefore say that the effect of a minimum of ion line emission in a rarefied plasma expanding into a magnetic field is a clear indicator of temperatures in the 1-10 eV range.

A more definite estimate can be made in our case. Only three-particle recombination operates for the $C^{+}{}_{1}{}^{3}$ line (Fig. 4b), since dielectronic recombination is absent for the C^{+3} ion ($k_2 = 0$), and radiative recombination populates mainly the low levels. Furthermore, at $T_e \approx 5$ eV the recombining electrons will mainly enter above the excitation level of this line, and hence $k_3 \sim 1$. For $10^{-17} \gtrsim \sigma_{ex} \gtrsim 10^{-19}\ \text{cm}^2$ and $1 \lesssim n_{+3}/n_{+4} \lesssim 10$, assuming the spread in $k_3\alpha_3 n_e/\sigma_{ex}$ to be of the same order in both directions, at $R \approx 35$ mm we obtain $4.2\ \text{eV} \lesssim T_e \lesssim 6.2$ eV.

Our experiments have thus shown that an investigation of the line emission from an optically thin plasma under the conditions of a change in the mechanism of excitation enables one not only to reliably identify the dominant channel of excitation of the ions but also to determine the parameter that is the most complicated to monitor in explosive processes — the electron temperature. In nonsteady processes with a very wide range of T_e the proposed method can be used as an indicator for the plasma region with a temperature in the 1-10 eV range. The results obtained can be used for spectroscopic and optical diagnostics in modern cosmic and model laboratory experiments.

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STABLE REGIMES FOR A NONEQUILIBRIUM PULSED-PERIODIC DISCHARGE IN A STREAM OF MOLECULAR NITROGEN AT HIGH PRESSURE

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UDC 537.52:531

1. The requirements of laser technology and plasma chemistry have determined for a long time the increase in interest in studying nonequilibrium, high-pressure gas discharges in rapidly flowing systems. Now these studies are particularly important in view of development of the possibility of exciting the internal degrees of freedom of particles in electrodeless self-sustaining UHF discharges [1]. However, experiments show that with high specific energy contribution the electric strength of weakly ionized molecular gases is markedly reduced [2-4]. Applied to a nitrogen plasma this phenomenon may be caused by processes of associative ionization of electron-excited metastables $A^3\Sigma_u^+$ and $a'^1\Sigma_u^-$ (gas breakdown conditions taking account of these ionization processes and rapidly occurring reaction of extinction of the electron-excited state of molecules by unexcited molecules are found in [7]). It is assumed [3, 7] that processes of associative ionization stimulate development of ionization-heating instability with contraction of the plasma. According to [8] illumination of a gas by UV radiation (in order to maintain a self-sustaining discharge) may also lead to a marked reduction in the electric strength of a medium. In studying pumping regimes of oscillating levels of molecules apart from these reasons for instability of discharges "burning" in a stream, it is necessary to consider the possibility of arrival in the discharge region of gas dynamic disturbances which arise down the flow in an oscillating-excited gas (in the case of forming disturbances of the impact type under conditions of strong oscillating nonequilibrium this phenomenon may play a destabilizing role even in supersonic streams [9]). In the present work a theoretical study is made of the effect of excitation and deactivation processes for electron and oscillating levels of

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