

*GAS-DYNAMIC STRUCTURES OF A PLASMA FLARE PRODUCED DURING THE
EVAPORATION OF METALS BY HIGH-INTENSITY OPTICAL RADIATION*

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Theoretical and experimental studies are reported of the gas dynamics of vapor produced during the evaporation of metals by high-intensity optical radiation in the form of millisecond pulses. The laser radiation is found experimentally to heat the vapor near the target. The initial conditions for the motion of the vapor are investigated. The measured gas-dynamic parameters are used to calculate the gas phase flow. The dependence of this on the intensity of the incident radiation shows that the limiting temperature corresponding to the transition from the liquid metal to the liquid dielectric is attained on the surface of the target.

1. We report the results of an experimental study and of a theoretical analysis of the dynamics of vapor near the surface of a metal target during the exposure of this target to high-intensity optical radiation.^[1] The heating of vapor near the target in the one-dimensional flow region by the laser radiation has been established experimentally. The distribution of the vapor temperature along the flare has been obtained, and the vapor temperature near the target has been estimated. The validity of the relation established in^[1] for the size of the shock wave, at rest relative to the target, has been confirmed in a broad range of variation of experimental conditions.

The study of the initial conditions for the motion of the vapor from the irradiated surface of the metal, using measurements on the gas-dynamic structure of the plasma flare, which was suggested previously,^[1] has now been carried out. Experimental data have been used to determine the amount of matter leaving the target in the gaseous phase. The vapor flow as a function of the light intensity reaches saturation at high intensities, and this shows that the temperature at which the metal-dielectric transition occurs in the surface layer of the target is, in fact, reached.^[2] Measurements of the vapor flow are compared with the theory of evaporation of metals by high-intensity optical radiation.^[2]

2. Figure 1 shows the distribution of radiation emitted by the vapor in a plasma flare, which is typical for a metal. This photograph was obtained in experiments on bismuth, lead, aluminum, brass, and other materials with light intensities $I \sim 10^7$ W/cm² incident on a metal target area with linear dimensions $d \sim 1$ cm for an interaction time $\tau \sim 10^{-3}$ sec and extraneous medium pressure $p \lesssim 1$ atm. Figure 1 shows the radiating-vapor region near the target, whose size is $\sim d$. This is separated by a dark space from the radiating vapor on the front of the shock wave which is stationary relative to the target, and whose size is substantially greater than the diameter d of the irradiated spot. Behind the shock wave front the vapor radiates mainly along the path of the laser beam. It is important that the radiating-vapor distribution pattern is stationary, which

shows that the motion of the vapor remains unaltered at each point within the plasma flare.

A theoretical description of the motion of the vapor has been developed using the data of high-speed photography of the plasma flare given in^[1]. In the region next to the surface of the metal at a distance of the order of the diameter of the irradiated spot, the motion of the vapor can be approximately regarded as one-dimensional. Next, since the vapor pressure near the surface of the target under our experimental conditions is much higher than the external atmospheric pressure, the vapor expands adiabatically out of the region of one-dimensional motion. The velocity of this motion becomes ultrasonic, and in the region of the adiabatic outflow the motion is three-dimensional. The ultrasonic flow of the vapor changes to subsonic motion on the front of the shock wave which is stationary relative to the target. The front of the shock wave, when this wave is large in size, has the form of a sphere which touches the irradiated part of the target. The shape of the shock wave can probably be explained by the fact that the angular dependence of the density of the evaporated material is $\rho \sim \cos \theta$, where θ is the angle between the normal to the surface of the metal and a given direction, which is valid for large shock-wave sizes $L \gg d$, when the collisions between particles in the outflowing material are important. The shock wave is followed by a region of subsonic vapor flow which is separated from the external gas by a surface of tangential discontinuity. The pressure of vapor in this part of the flare is equal to the pressure of the external atmosphere.

The theoretical analysis given in^[1] leads not only to a qualitative description of the distribution of radiation within the plasma flare (Fig. 1) and, above all, its stationary character, but also to values of the shock-wave size and the distributions of temperature, density, and velocity of vapor before the shock wave front (in the region of adiabatic outflow), i.e., results which can be verified quantitatively in an experiment. This type of verification was carried out in the present work in the case of the relation connecting the shock-wave size L (see Fig. 1), the diameter of the irradiated spot d , the

density ρ_1 and velocity v_1 of vapor in the one-dimensional motion region, the vapor velocity before the shock wave front v_2 , and the external pressure $p^{[1]}$:

$$L/d = \sqrt{\rho_1 v_1 v_2 / 2(\gamma + 1)p} \tag{1}$$

where γ is the Poisson adiabatic exponent (for a monatomic gas $\gamma = 5/3$).

It is important to note that the determination of the gas-dynamic structure of the plasma flare reported in^[1] is possible because of the use of the high-intensity neodymium laser (up to 10 kJ in a pulse of $\tau \sim 10^{-3}$ sec^[3]). The basic importance of this is that it enabled us to produce light beams of the necessary intensity over a large portion of the target surface with linear dimensions substantially greater than the depth of the resulting crater. On the one hand, this eliminates the distortion of the motion of the vapor produced by a deep crater in the metal target and brings the experimental situation closer to the plane evaporation model discussed in the theory. On the other hand, the fact that d is large ensures large-scale motion [see Eq. (1)] and this makes the situation accessible to direct observation.

The gas-dynamic theory of a plasma flare produced above the surface of a target during the evaporation of metals by a laser beam was developed in^[4,5]. It is based on the solution of one-dimensional time-dependent problems and, therefore, does not include the main experimental details in Fig. 1. It is not, as a whole, valid for the description of the stationary gas dynamics of vapor produced during the evaporation of metals by millisecond pulses of laser radiation. The use of the gas-dynamic results^[4,5] is, in principle, possible only

over the time period corresponding to the establishment of the stationary evaporation picture, and only in the region of the one-dimensional motion, i.e., at distances from the surface of the metal of the order of the size of the irradiated spot.

3. The experiments reported here were carried out on bismuth and aluminum targets placed in a helium atmosphere, whose pressure could be varied between 0.25 and 1 atm. As before, the detailed studies were carried out in the case of bismuth, for which fully developed evaporation occurred at relatively low light fluxes. High-speed photography of the radiation emitted by the vapor in the flare was used to determine the vapor velocity before the shock-wave front as a function of the light intensity, and the dependence of the shock-wave size L on the incident intensity I and the diameter d of the irradiated spot.

Figure 2 shows a typical development of the evaporation process. It is noticeable that the amplitude of the "spike" modulation of the laser radiation beam, which can be seen in these photographs, is quite small. Oscillograms of the laser pulse have shown that this modulation amounts to 30–40% of the pulse envelope over its central portion. This pulse shape is determined by the properties of the laboratory laser installation which is in the form of three parallel lasers.^[3] The superposition of the three radiation channels on the surface of the target smooths out the spike structure. In fact, the radiation emitted by the target is continuous in time over most of the photographs (although it is modulated in brightness); the radiation from the shock wave front is continuous throughout the scan.

Figure 2 shows that the size of the shock wave re-

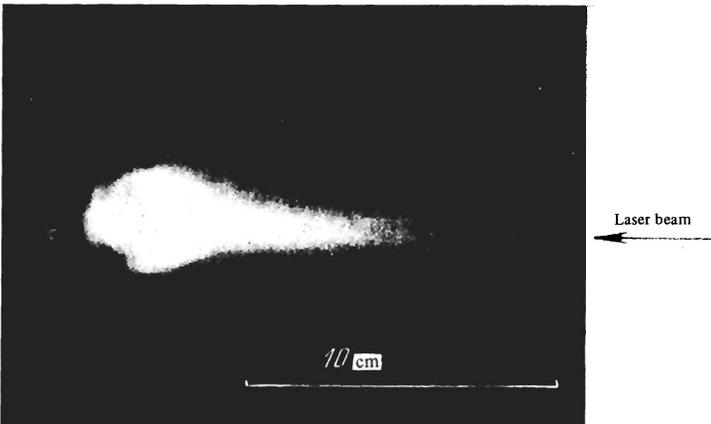


FIG. 1. Plasma flare from a bismuth target with $I = 5.5 \times 10^6$ W/cm², $\tau = 0.8$ msec, $p = 1$ atm (exposure time greater than the length of the laser pulse).

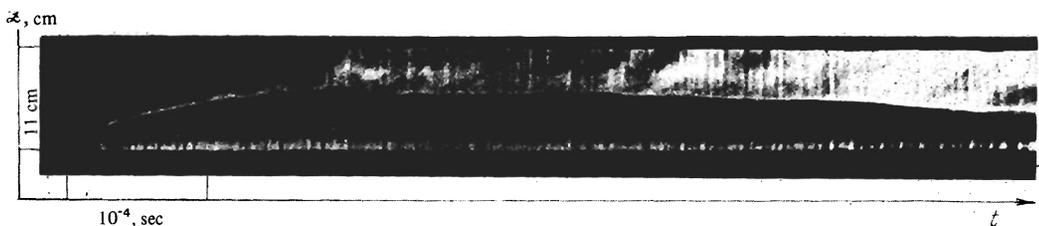


FIG. 2. High-speed photography of the evaporation of bismuth. Experimental conditions: $p = 0.5$ atm, $I = 1.8 \times 10^7$ W/cm², $d = 0.8$ cm, $\tau = 0.8$ msec, $L = 6.2$ cm. The slit is mounted along the beam axis. The target surface lies at the bottom of the picture. The laser beam is directed downward.

mains approximately constant during the interaction between the laser beam and the metal, which clearly demonstrates the stationary nature of the gas-dynamic picture of the evaporation process. The transient process during which the shock wave is established at the beginning of the scan occupies a small proportion of the interaction time. The fact that the shock wave size L remains constant means that the intensity incident on the target is also constant. Moreover, the length of the flare behind the shock-wave front increases with time. Hence it follows that the absorption of light in this part of the flare is low. As regards the absorption of the light traversing the region near the target in the zone of the one-dimensional plane outflow of vapor, the stationary nature of the gas-dynamic structure and the distribution in it of the vapor radiation show that if this absorption does occur it must be constant in magnitude.

It is important to note that these conclusions, which were, in fact, reported in^[1], refer to the region of low values of the external pressure (for bismuth $p \lesssim 1$ atm) when the processes illustrated in Figs. 1 and 2 take place. In general, since the vapor pressure in the flare behind the shock wave is equal to the external pressure, the absorbing properties of the plasma and hence the gas-dynamic picture as a whole, which is largely determined by the intensity of the laser beam on the target, are very dependent on this intensity. At sufficiently high pressures and comparable values of the intensity, the shock wave which appears at the beginning of the radiation pulse subsequently decreases in size and disappears altogether during the time interval corresponding to the interaction between the laser beam and the metal. This occurs because of the increase in the optical thickness of the plasma in the flare behind the shock-wave front with time. The target may also be highly screened from the incident radiation by the flare, and the evaporation process may cease altogether. The flare may then break off from the target. This type of effect was observed for bismuth for pressures $p > 1$ atm, $I = 10^6 - 10^7$ W/cm² (see Fig. 3). The first reports on experiments involving such screening and separation

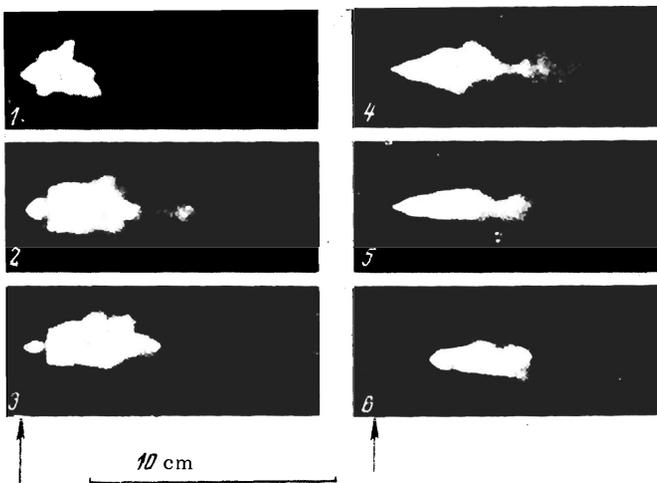


FIG. 3. High-speed photography of the development of a flare from a bismuth target: $p = 2.6$ atm, $I = 10^7$ W/cm², $d = 0.8$ cm, time between frames 1.6×10^{-4} sec. The arrow shows the position of the target surface.

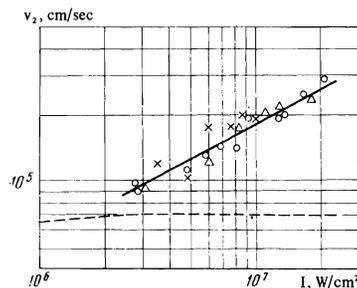


FIG. 4

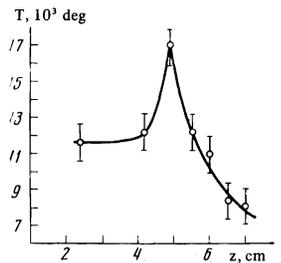


FIG. 5

FIG. 4. Vapor velocity v_2 in front of the shockwave front as a function of the incident intensity I in the case of bismuth. The pressure (atm) was as follows: \times — $p = 0.25$, Δ — $p = 0.5$, \circ — $p = 1$.

FIG. 5. Temperature along the plasma flare in the experiments on aluminum: $p = 0.1$ atm, $I = 0.9 \times 10^7$ W/cm², $d = 0.8$ cm.

of the flare from the target were given in^[6].

Let us now consider the experimental data indicating the presence of light absorption before the shock-wave front in the region of the one-dimensional flow of vapor near the target. This absorption differs from the absorption behind the shock wave front in that it is independent of the external pressure in the pressure range $p \lesssim 1$ atm, where the motion illustrated in Figs. 1 and 2 is found to occur. The reason for this is that the absorption zone is separated from the ambient gas by the region of ultrasonic flow of vapor.

High-speed photography of the emission by vapor similar to that shown in Fig. 2 was used to determine the vapor flow velocity behind the shock wave front (v_3) as a function of the incident intensity I . Since the shock wave is strong,^[1] the velocity of the vapor before the shock wave front (v_2) differs from v_3 by a constant factor:

$$v_2 = v_3(\gamma + 1) / (\gamma - 1) = 4v_3. \quad (2)$$

The experimental data are shown in Fig. 4 in the form of a plot of the function $v_2(I)$. It is clear that the velocity is independent of the pressure p , and that $v_2 \sim I^{1/2}$. The magnitude of v_2 can be used to determine the initial velocity v_1 near the target, using the properties of the adiabatic outflow of vapor from the target.^[1] Assuming that the gas-dynamic velocity v_1 is equal to the local velocity of sound, we can then estimate the temperature $T_1 = Mv_1^2/\gamma$ (M is the mass of an atom of the metal) near the target over the initial part of the adiabatic outflow. It turns out that v_2 and v_1 are related by the simple formula $v_2 = 2v_1$. In fact, the corresponding law of conservation of energy is

$$c_p T_1 + \frac{1}{2} v_1^2 = c_p T_2 + \frac{1}{2} v_2^2.$$

Since for large values of L , when the adiabatic outflow of vapor is very effective, $T_1 \gg T_2$, we have

$$v_2 = v_1 \sqrt{1 + 2c_p/\gamma} = 2v_1, \quad (3)$$

where $c_p = 5/2$ is the specific heat of a monatomic gas at constant pressure. The formula given by (3) has been verified experimentally. This was done with the aid of a laser beam with strong "spike" modulation. The high-speed photography shows individual jets of vapor separated by evaporation "pauses." We have measured the velocity of vapor in the jets near the target and at the

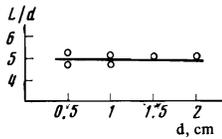


FIG. 6. Size of the shock wave as a function of the diameter of the irradiated spot on a bismuth target: $p = 0.25$ atm, $I = 3 \times 10^6$ W/cm².

end of the adiabatic outflow region (at a distance corresponding to the separation of the shock-wave front from the target). The ratio v_2/v_1 was found to be equal to 2 to within 20%.

For the sake of comparison, the experimental relation $v_2 \sim I^{1/2}$ is compared in Fig. 4 with the curve $2v_1(I)$ obtained from the theory of developed evaporation.^[2] This curve was obtained with allowance for the fact that for bismuth and $I > 3 \times 10^6$ W/cm² the metal-dielectric transition takes place in the surface layer, and the temperature of the surface does not increase further as the light intensity is increased.^[2]

It is clear that the measured velocity v_1 in this particular range of intensities is much higher, and its dependence on I is stronger, than one would expect from the phase-transition theory.^[2] This fact clearly indicates the presence of absorption and of the heating of vapor near the target in the region of the one-dimensional motion. Estimates of the absolute magnitude of T_1 , using the data of Fig. 4 and Eqs. (2) and (3), yield $T_1 \approx 2.5 \times 10^4$ K for $I = 2 \times 10^7$ W/cm², which is much higher than the maximum possible temperature of the bismuth surface, i.e., $T = 2500^\circ$ K (according to^[2]). An analogous result is obtained in the case of aluminum. Figure 5 shows the temperature profile in the flare along the z axis which is perpendicular to the surface of the metal. The profile was obtained by comparing the intensities of spectral lines emitted by the vapor throughout the region of motion (these measurements were performed by V. A. Bogatyrev, N. K. Sukhodrev, et al.). The temperature maximum $T_3 = 17\,500^\circ$ K corresponds to the position of the shock wave front. The temperature of the vapor near the target is $T_1 \approx 11\,000^\circ$ K, which is also substantially higher than the critical temperature of the material.

The above experimental data and estimates, and the results reported in^[2], suggest that, when the metal is evaporated by the laser beam with $I \sim 10^7$ W/cm² for $p \lesssim 1$ atm, we have a situation where, near the target, which is at a temperature of a few thousand degrees, there is a stationary absorbing plasma with a temperature several times higher than the maximum possible temperature of the target. This plasma is located at a distance from the surface of the order of the size of the irradiated spot. The fact that the picture is stationary means that the optical thickness of the plasma is constant (general considerations suggest that it should be of the order of unity).

4. The above situation demands answers to a number of questions. These include the mechanism responsible for the formation of absorbing plasma with $T_1 \sim 10^4$ K out of transparent vapor at a temperature of a few thousand degrees during the time $t \approx 10^{-5} - 3 \times 10^{-5}$ sec (according to the high-speed photography data) in the case of the relatively low intensities $I \sim 10^6 - 10^7$ W/cm². The mechanism responsible for the stationary maintenance of absorbing plasma by the laser beam is also of

considerable interest. Further, it is essential to explain the observed result $v_1 \sim I^{1/2}$ in terms of the absorbing properties of the plasma. Finally, an explanation must be provided of the effect of absorption and heating on the size of the shock wave given by Eq. (1), obtained in^[1] without taking into account the heating of the vapor by the laser beam.

The mechanism responsible for the formation and maintenance of the plasma in the laser beam will not be considered here. We shall merely note that it has been experimentally demonstrated^[7] that a plasma can be maintained in air by a laser beam with $I \sim 10^7$ W/cm². The temperature jump in the region of the one-dimensional motion near the target occurs within the ionization front which is stationary relative to the target and separates the region of motion of the cold vapor from the plasma (there is a deep analogy here between the ionization front and the front of slow chemical combustion^[7]).

Since $v_1 \sim T_1^{1/2} \sim I^{1/2}$ and is independent of the pressure p , the relation $T_1 \sim I$ must be present in the equation of balance between the absorbed power and the power losses for a stationary highly ionized plasma. The equation of balance at a point is of the form

$$\alpha I = Q_{\text{rec}}, \quad (4)$$

where $\alpha \sim n_1^2/T_1^{3/2}$ is the bremsstrahlung absorption coefficient, n_1 is the plasma density, and $Q_{\text{rec}} \sim n_1^2/T_1^{1/2}$ is the rate of loss through recombination emission of light per 1 cm³. Losses by thermal conduction and bremsstrahlung emission in the low-temperature plasma can be neglected in comparison with Q_{rec} . It follows, therefore, that, according to Eq. (4), the properties of the plasma explain the observed (Fig. 4) relation $T_1 \sim I$ or $v_1, v_2 \sim I^{1/2}$.

Let us consider Eq. (1) again. It can be rewritten in the form

$$L/d = \gamma j_1 v_2 / 2(\gamma + 1)p. \quad (5)$$

In this expression $j_1 = \rho_1 v_1$ is the vapor mass flux. The size of this flux is determined by the conditions on the surface of the metal, where the phase transition from the liquid metal to the vapor takes place, and remains the same on the plasma ionization front in the region of the one-dimensional flow. When the heating of the vapor by the laser beam near the target is taken into account, this does not change the form of the formula in comparison with that reported in^[1], i.e., the beam intensity I does not directly enter Eq. (5). Equation (5) was subjected to a detailed experimental verification. The experiments with bismuth^[1] showed that up to pressures close to $p = 1$ atm we have $L \sim p^{-1/2}$. Figure 6 shows a graph confirming the fact that $L \sim d$ for constant p, I .

The greatest interest attaches to the dependence of L on I . According to^[2], one could expect that, in the case of bismuth and $I \lesssim 3 \times 10^6$ W/cm², when the target temperature T is less than the metal-dielectric transition temperature T_{md} , the result should be $j_1 \sim I$. According to Fig. 4, the velocity v_2 is still weakly dependent on I , i.e., the increase in the velocity due to heating is still relatively small. It follows that, in this case, we should have $L \sim I^{1/2}$. For intensities much higher than $I \approx 3 \times 10^6$ W/cm² we reach the limiting temperature of the target $T = T_{\text{md}}$. According to^[2], we then

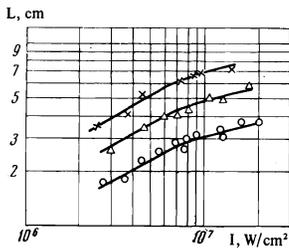


FIG. 7

FIG. 7. Shock-wave size as a function of the incident intensity for different pressures (atm): \times — $p = 0.25$, Δ — $p = 0.5$, \circ — $p = 1$.

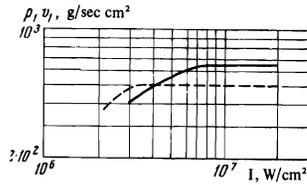


FIG. 8

FIG. 8. Comparison of the function $j_1(I)$ deduced from measurements on the gas-dynamic picture (solid curve) and the analytic relation calculated from the formula reported in [2] (broken curve).

have $j_1 = \text{const}$ and $v_2 \sim I^{1/2}$ for $I \gtrsim 10^7 \text{ W/cm}^2$. Therefore, for intensities $I \gtrsim 10^7 \text{ W/cm}^2$ we would expect that $L \sim I^{1/4}$.

Measurements of L as a function of I are shown in Fig. 7 for three values of the pressure. The shape of the $L(I)$ curves is the same for all pressures, and is well approximated to by the formula $L \sim I^{1/2}$ for I in the range between 3×10^6 and $8 \times 10^6 \text{ W/cm}^2$, and by the formula $L \sim I^{1/4}$ for $I > 10^7 \text{ W/cm}^2$. We thus have a satisfactory experimental confirmation of the prediction based on Eq. (5).

The observed result $L \sim I^{1/4}$ is the most interesting feature of Fig. 7. This requires that $j_1 = \text{const}$ and is a further new confirmation that the maximum temperature is reached on the surface of the bismuth target ($T = T_{\text{md}}$) at which the metal-dielectric transition takes place (see [2]).

5. We have thus carried out an extensive verification of Eq. (5), so that this equation can now be used to determine the flux of matter in a gas medium from the surface of the target with a view to a quantitative experimental verification of the theory of developed evaporation of metals reported in [2]. The function $j_1(I)$ is shown in Fig. 8. In the same figure we show the theoretical curve calculated from the formula given in [2] (this curve was obtained without taking into ac-

count the jump in the reflection coefficient for $I \approx 3 \times 10^6 \text{ W/cm}^2$; when this is taken into account, the curve for $I > 3 \times 10^6 \text{ W/cm}^2$ lies higher by a factor of 1.6). We see that there is satisfactory quantitative agreement (to within experimental error of 20%). This opens up the possibility of an experimental separation of the ejection of liquid and gaseous phases from the target by measuring the characteristics of the gas-dynamic structure of the plasma flare.

We note in conclusion that for high p (for bismuth $p > 1 \text{ atm}$) the structure of the flare may be substantially different from that described above. The decisive role in this context is the absorption of light in the flare and the screening of the target.

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