Dynamics of shock waves excited in a low-density gas during laser plasma heating

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Experiments on the excitation of an intense shock wave in the atmosphere of a diagnostic gas around a target during laser plasma heating are reported. The behavior of the shock wave deviates substantially from the self-similar solution for an instantaneous point explosion.

As a laser plasma expands into an atmosphere of a low-density gas, it excites an intense shock wave. Shock waves have been studied in spherical-geometry experiments primarily for the purpose of developing a method for determining the laser energy which is absorbed by the plasma.[1] Sedov's model of an instantaneous point explosion[2] has been used for energy estimates. In this model, the motion of the shock wave is described by $R \simeq At^{0.4}$, and the energy is an integral of motion. There are conditions, however, under which there may be deviations from this behavior. It has been mentioned in several papers[3,4] that the motion of the shock wave may deviate from $t^{0.4}$, but the low-energy level of the experiments has prevented a reliable establishment of this deviation. In the present letter we are reporting the results of experiments on the asymptotic stage of the expansion of a shock wave in experiments on the laser heating of shell targets, carried out in order to evaluate the validity of Sedov's model.

The experiments were carried out at the high-power Del'fin-1 laser installation.[5] The laser output energy ranged from 100 J to 1 kJ at a pulse length of 3 ns. The power density at the target ranged from 2×10^{13} W/cm^2 to 10^{14} W/cm^2. As targets we used glass microballoons with a diameter $2R = 400$–600 μm and an aspect ratio $R/\Delta R = 100$–200 (ΔR is the thickness of the target shell). We used deuterium or helium at a pressure of 10–20 torr.

The shock waves were detected by a multiframe ultrahigh-speed Schlieren photography system,[6] which was capable of detecting the position of the shock front with a spatial resolution of 0.3 mm and a time resolution of 2 ns. This apparatus could record 19 frames at intervals ranging from 6.6 ns to 200 ns, with a maximum observation time of 500 ns. The field of view was 6 cm.

Figure 1 shows some typical R-t diagrams of the asymptotic stage of the expansion of the shock wave in deuterium (pressure of 10 torr). Curve 1 corresponds to a laser energy $E_L \approx 100$ J, curve 2 to $E_L = 805$ J, and curve 3 to 958 J. We see from this figure that for curves 2 and 3, beginning at 60 ns, the expansion of the shock wave is self-similar in nature and can be described by

$$R = At^{\alpha}, \qquad (1)$$

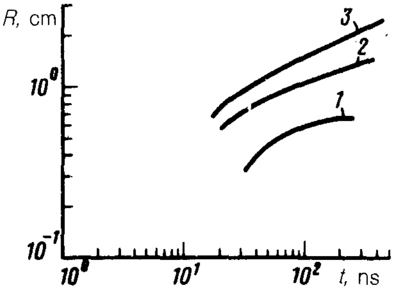

FIG. 1. Typical R-t diagrams of the asymptotic stage of the expansion of a shock wave in deuterium (pressure of 10 torr). 1—$E_L \approx 100$ J; 2—$E_L = 805$ J; 3—$E_L = 958$ J.

where A and α are quantities which are constant over time. We observe no deviation from self-similarity throughout the observations ($t_{19} = 400$ ns). For curve 1 there is no linear region on the R-t diagram, indicating that at these low laser energies the shock wave does not reach the regime of self-similar expansion. Analysis of extensive experimental results revealed the minimum laser energy at which the region describable by expression (1) could be distinguished on the R-t diagram of the shock wave. This energy is 100 J. We detected no substantial differences in the nature of the expansion of the shock wave depending on the particular gas (deuterium or helium).

The slopes of the linear parts of curves 2 and 3 in Fig. 1 are different. This difference implies that the exponent in expression (1) is different for different experimental conditions. To determine the value of α from these R-t diagrams, we used the method of least squares. As the unknown function we adopted $R = A(t + t_0)^\alpha$, where t_0 is a time delay introduced in order to eliminate the initial stage of the expansion of the shock wave, before the wave has reached its asymptotic behavior. This approach made it possible to avoid an increase in the error due to the errors in the synchronization time for the experimental apparatus (6 ns). The magnitude of this delay, which differed from experiment to experiment, was determined for each specific case. The

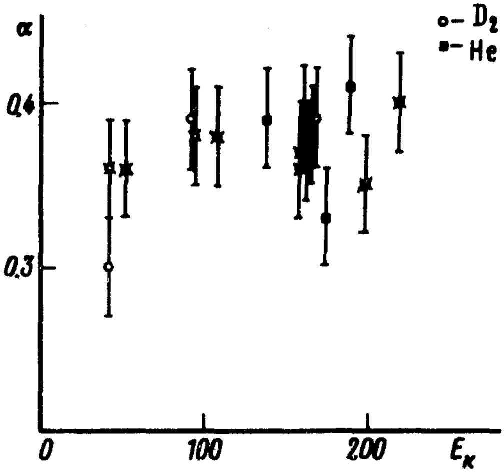

FIG. 2. The exponent α versus the absorbed laser energy.

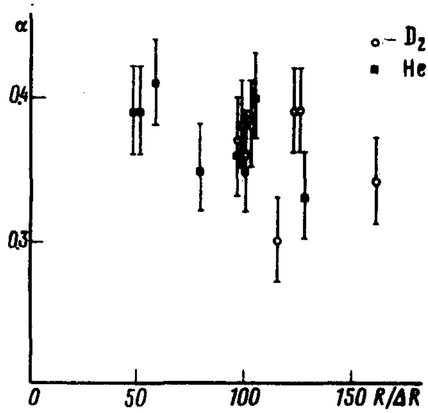

FIG. 3. The exponent α versus the aspect ratio of the target.

constant A is determined by the energy transferred to the shock wave and by the state of the gas. Since this constant can have different values, it also had to be calculated for each experiment. The method proposed here yields the value of the exponent α within an error of 10%, which is determined by the error in the determination of the radius of the shock wave, by the number of points on the R-t diagram which are analyzed, and by the number of approximation steps.

Analysis of the experimental R-t diagrams in this series of experiments revealed that the exponent α varies from experiment to experiment, lying between 0.3 and 0.4. Figure 2 is a plot of α versus the absorbed laser energy, found by means of calorimetric balance measurements.[7] It can be seen from this figure that α does not depend on the energy. This result is seen particularly clearly when we compare the points represented by crosses, which correspond to experiments with targets having the same aspect ratio ($R/\Delta R \approx 120$). Figure 3 shows a plot of α versus the aspect ratio of the target. With increasing aspect ratio, this exponent decreases. A possible reason for this decrease might be a significant effect of the processes by which energy is transferred from the plasma to the gas on the nature of the self-similar motion of the shock wave. Further theoretical and experimental research will be required in order to find a more comprehensive explanation of this result.

In summary, as intense shock waves are excited by a laser plasma in experiments with spherical shell targets, one can observe a substantial deviation of the behavior of the shock wave from the self-similar solution for an instantaneous point explosion. The validity of using Sedov's model for determining the energy of the shock wave must be tested in each specific experiment.

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