CALCULATION OF DEVELOPMENT OF A LASER EXPLOSION IN AIR WITH ALLOWANCE FOR EMISSION

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INTRODUCTION

Regions containing a high concentration of energy develop during the action of intense laser radiation on a target in air or during the breakdown of air by focused radiation. Multichannel laser installations [1-3], which provide omnidirectional almost uniform irradiation, are often used under the conditions of such experiments, as a result of which the distribution of the parameters in the plasma which forms is close to spherically symmetrical. The subsequent dispersion and cooling of such a spherical gas volume has the character of a strong explosion.

It is interesting to theoretically study the pattern of development of such a laser explosion and determine the effect of the emission of the hot plasma on the process of motion and the main parameters of the explosion. One of the practical applications of such calculations can be the determination of the energy of laser radiation absorbed in the plasma from the law of motion of the shock wave. In [1, 2] the energy absorbed in the plasma was found from the equations of a strong point explosion [4] using an estimated value of the average adiabatic index of an air or helium plasma. The results of a numerical calculation of an explosion with counterpressure in helium were used for the same purpose in [5]. Emission was not taken into account in this case, however. At the same time, radiation-transfer processes, just as for large-scale explosions [6, 7], can lead to the de-excitation of part of the energy from the fireball of the explosion and can affect the propagation of the shock wave through energy losses and the redistribution of the portion of energy remaining in the hot region.

The radiative–gasdynamic processes in high-power explosions were studied numerically in [8] in a multigroup approximation, and with a rather large number of groups (40), but also with a very rough allowance for the angular distribution of the radiation. The results of [6-8] cannot be used directly for the case being considered in the present report, however, because due to the great difference in the scale of the phenomenon the optical depths of the plasmas differ strongly and the very radiation-transfer processes have different characters.

The process of cooling of the fireball of a "microexplosion" in air (with an energy of several joules) was analyzed in [9], also with a rather large number of spectral intervals (50) but with detailed allowance for the angular distribution of the radiation. The splitting method was used to simplify the problem: The radiation-transfer equations were solved jointly only with the energy equation with an assigned law of variation of the pressure found from a separate calculation of the gasdynamics of the process. Such an approach could be applied successfully to the conditions of an explosion in air of normal density, when the de-excitation process occurs mainly in a rather late stage after the separation of the shock wave from the fireball. Under the experimental conditions of [1], however, the air had a reduced density (on the order of 0.02-0.03 of normal) and the radiative processes could be much stronger.

In [10] a straight-through calculation was made of the radiative–gasdynamic problem of an explosion, with allowance for the slowing of the detonation products of a spherical target in which the laser energy was released, in application to the experimental conditions of [1].

The angular distribution was taken into account in great detail through the use of the quasidiffusion method [11], but only a small number of spectral groups were used. The calculation of [10] was ended soon after the explosion products transferred most of their energy to the air (with an explosion energy of 200 J the explosion products–air boundary pulsated at a distance of 0.3-0.4 cm in the same time as the shock wave propagated a distance of 0.4-1.0 cm and the heating wave to a distance of 1.1-1.4 cm). In [10] it was recommended that the

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energy be determined from the results of the calculations which were made. However, it is more advisable to determine the energy from the law of motion of the shock wave at a later stage which is free from the effect of the concrete initial conditions of the explosion and from the complex physical processes in the initial stage. It is sufficient to point out that according to the estimates which follow from [7], at temperatures on the order of 1 keV and electron concentrations on the order of 10^{18} cm^{-3} the characteristic time of equalization of the electron and ion temperatures proves to be about 300 nsec, i.e., comparable with the time of the entire calculation of [10]. The approximation of thermodynamic equilibrium is admissible only for lower temperatures on the order of 30 eV.

In the present report we made systematic calculations of the later stage of laser explosions (at temperatures of less than 10-30 eV) in air of reduced density, and some results of these calculations are presented below. Since de-excitation from the hot region may play an important role in this stage, special attention was paid to making as detailed an allowance as possible for the spectral composition of the emission.

1. STATEMENT OF THE PROBLEM AND METHOD OF CALCULATION

In the series of calculations described below we presumed the instantaneous or sufficiently rapid energy release in a sphere of some radius with a density equal to the density of the surrounding air. The temperature within this sphere of radius R was taken as equal to some initial temperature T_0. The motion of the air at this moment was assumed to be negligibly small. A process of energy release close in character to the above can take place during the breakdown of air (with or even without the presence of a small "triggering" target in it) and the subsequent propagation of a supersonic radiation wave from the point of initiation [12]. According to the calculations of [12], for example, with a laser radiation flux density of 2.5 GW/cm^2 and an air density of 0.1 of normal the velocity of propagation of the plasma front toward the laser beam is 150 km/sec and the radiation wave propagates about 1.5 cm in 100 nsec. In this case the air density remains almost constant and equal to the initial density while the velocities of its motion do not exceed several kilometers per second. We note that the temperatures reached in the plasma (about 10 eV) depend weakly on the radiation flux density and the air density while the temperature distribution over the space is close to uniform.

Under conditions close to those of the experiments of [1, 2], almost all the laser energy is initially transferred to the target, and then the slowing of the explosion products in the air takes place. However, when all the energy has essentially been transferred to the air and the mass of the air exceeds the mass of the products by an order of magnitude or more, the average temperature is an order of magnitude or more lower than the initial temperature (300-1000 eV) and consequently comprises less than 30-100 eV. Moreover, as shown by the calculations of [10], the fraction of kinetic energy in this stage proves to be insignificant and the radiation essentially equalizes the temperature in the hot region. Thus, the results of the calculations presented below can also be used to determine the parameters during a laser explosion of a dense target at times sufficiently large in comparison with the characteritstic time of slowing of the explosion products and with a strong increase in the dimensions of the region of increased pressure in comparison with those adopted as the initial dimensions; i.e., in the stage when the effect of the initial data has decreased to a considerable extent because of radiative and gasdynamic processes.

Calculations in which the initial temperature T_0 was taken as equal to 23.7 eV while the relative air density was $\delta = 0.03$ were made for an energy E = 1 kJ with an initial radius R = 1.22 cm, which approximately corresponds to the conditions of experiments already conducted [1, 2], and for E = 10 kJ with R = 2.6 cm, which approximately corresponds to the conditions of the installations of [3]. To clarify the effect of the air density a calculation was made with the same initial temperature and with a relative air density $\delta = 0.1$, while to clarify the effect of the initial conditions on the subsequent pattern of motion a calculation with $\delta = 0.1$ was also made with a lower value of $T_0 = 8.6$ eV (R = 0.82 and 1.15 cm for E = 1 kJ).

We used detailed tables of the thermodynamic properties of hot air [13] and its optical properties with allowance for continuous absorption and lines [14], while for temperatures T > 20,000°K we used an extension of the tables of [14] kindly presented by Yu. P. Vysotskii, G. A. Kobzev, and V. A. Nuzhnyi. In these tables of the spectral coefficients of absorption $k_\varepsilon(T, \rho)$ of air there are 600 points with a uniform spacing in the region of ε up to 18.6 eV. In addition, these tables are extended to 250 eV with the help of calculations of the values

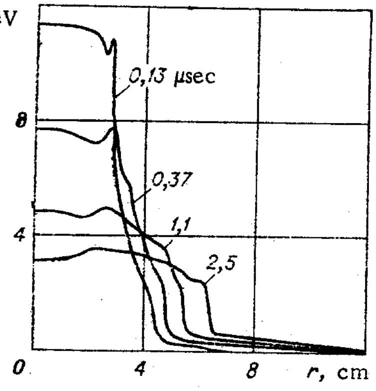

Fig. 1

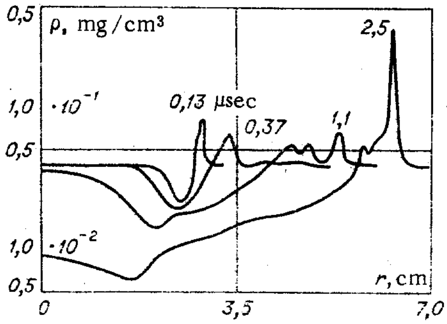

Fig. 2

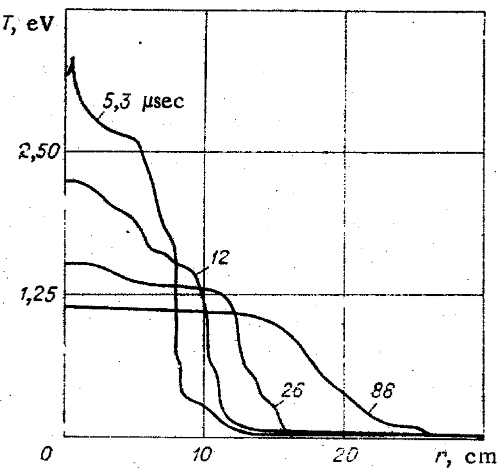

Fig. 3

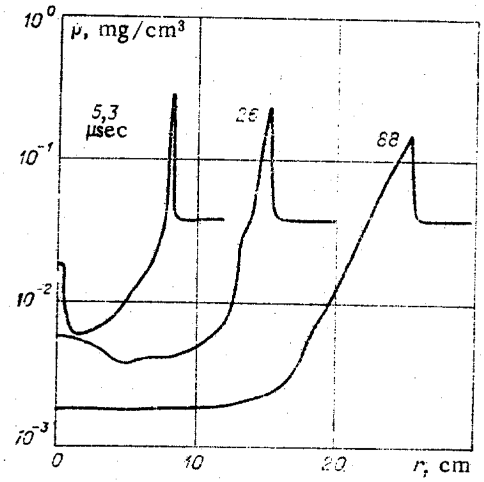

Fig. 4

of k_ε at 55 points with a nonuniform spacing (without allowance for lines). An analysis of these tables showed that in some neighboring intervals the values of k_ε differ little at all temperatures, and these intervals were combined into larger intervals with the appropriate averaging. As a result, the tables were shortened to 455 spectral intervals with nonuniform spacing without an appreciable loss of accuracy in comparison with the original tables; i.e., it can be considered that the computation was conducted with almost full use of the most detailed of the known tables on the optical properties of air. The angular distribution was taken into account by calculating the transfer equations along 13 rays (from 0 to 90°) in their direct and reverse directions. Such detailed allowance for the spectral and angular distribution of the radiation in a nonsteady radiative–gasdynamic problem has evidently been made for the first time.

Since the determination of the field of radiation propagating along different directions, at different wavelengths, at all nodes of the calculation grid in space, and at different times is very laborious and difficult to perform even on modern computers, we used the method of averaging the transfer equations of [15]. The effectiveness of this method essentially depends on the means of storage of the dimensionless coefficients in the averaged radiation-transfer equations in the intervals between averagings and on the choice of the principal variable on which these coefficients primarily depend. A preliminary analysis and the results of trial calculations showed that the temperature can be taken as the principal variable for the problem under consideration.

The averaging was carried out for six groups with the limits of 0...6.52...7.95...9.96...18.6...80.5...248 eV. The division into groups seemed necessary because the variation in the average coefficients of absorption with temperature is different in different regions of the spectrum.

The efficiency of the averaging method proved to be quite high: With a total of about 2500 calculating layers the number of averagings was about 20-25, with the change in the

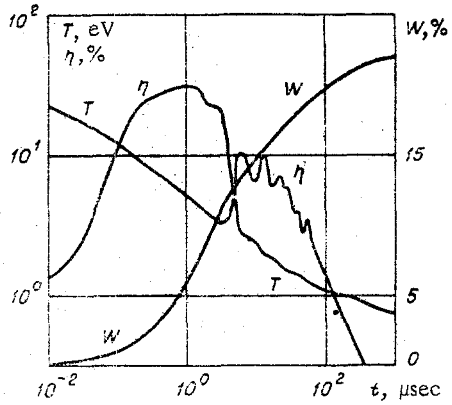

Fig. 5

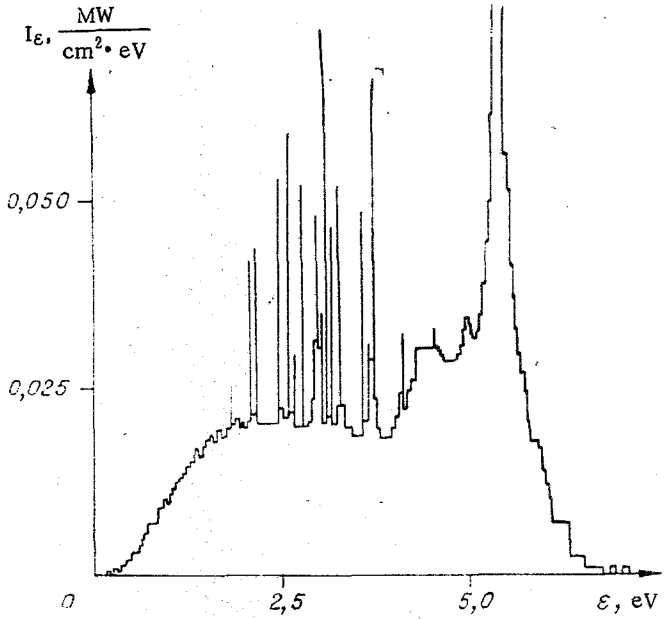

Fig. 6

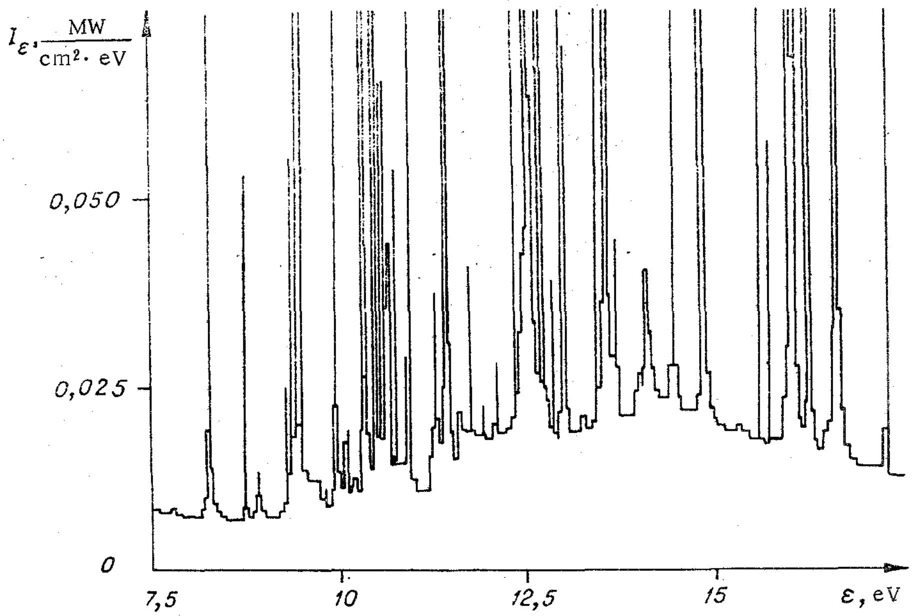

Fig. 7

explosion parameters in a step of "calculation" and "recalculation" being small.

A rather dense spatial grid of 200-250 points with clustering at the places where sharp temperature fronts occur was used in the calculation (the placement of the points was done with the condition that the temperature drop between neighboring points not exceed some given value).

2. RESULTS OF CALCULATIONS

Let us describe the pattern of development of the explosion on the example of the calculation of the explosion variant with an energy E = 10 kJ and a relative air density $\delta = 0.03$.

The pattern of development of the explosion with emission differs essentially from what would occur in the absence of emission. The radial distributions of temperature and density at the times which are indicated on the respective curves are presented in Figs. 1 and 2. In the initial moments a rarefaction wave propagates toward the center from the point of discon-

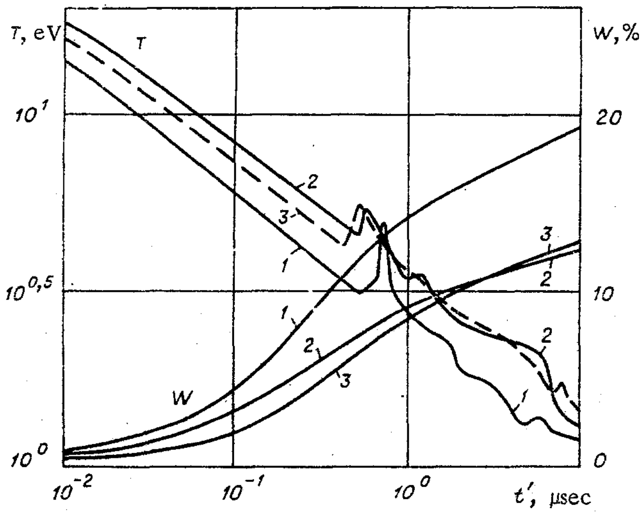

Fig. 8

tinuity of the initial data while a shock wave propagates toward the periphery. In the process the gas in the hot region is rapidly cooled by emission while that ahead of the shock wave front is heated to considerable temperatures. The compression behind the shock wave front is 1.5-2. The contact discontinuity due to the initial data is rapidly smoothed out by emission.

At the time t = 0.37 μsec the shock wave front lies at a distance of 3.5 cm. The air temperature behind the front (5.5 eV) slightly exceeds the temperature ahead of the shock wave front (4.5 eV). The gas heated ahead of the shock wave front can be divided into two regions. In the first region directly ahead of the shock wave the air heats to a temperature of more than 2 eV, and there is a rather sharp front of a nonequilibrium (in the emission sense) thermal wave at a distance of about 4.7 cm. Ahead of this hot layer there is another region with a lower temperature, on the order of 0.5 eV, extending out to 8-9 cm. We note that the advance of this "tongue" is due to quanta of the second and third groups with energies of 6.5-10 eV, while the first heated layer (with a higher temperature) develops owing to radiation of the fourth and fifth groups, i.e., quanta with higher energies.

As the emission fluxes decrease and the motion of the front of the hot heated layer slows down, intensive motion begins behind the front of the thermal wave. The departures from the initial density are already appreciable at t = 0.37 μsec (see Fig. 2). The compression behind the front grows and by t = 2.5 μsec it reaches a value of 10. The strong shock wave formed separates from the fireball; the first weak shock wave overtakes the latter. The compression shock moves for some time through the layer heated to temperatures of 0.5-0.2 eV and then moves into the region of cold air. This is seen in Figs. 3 and 4, where the temperature and density distributions are shown for later times. The amplitude of the shock wave gradually falls after its separation, and by t = 88 μsec the compression behind the shock wave front, located at a distance of 25.5 cm, has a value of about 4 while the temperature behind the front approaches the temperature of the cold air (being about 0.08 eV at these times).

We note that after the rarefaction wave reaches the center of symmetry a compression wave forms which moves toward the center (see Figs. 1 and 2, t = 2.5 μsec) and collapses at the center. This produces considerable heating and compression of the gas in the central part of the explosion (see Figs. 3 and 4, t = 5.3 μsec). The amplitudes of the disturbances propagating through the hot region at later times are small. Cooling fo the fireball occurs in this stage.

In Fig. 5 the following quantities are shown as functions of time: the maximum temperature T_{max}, the fraction W of energy departing to infinity through emission, and the "emissivity" η at the center of symmetry, i.e., the ratio of the emission flux in one direction to the flux of a black body with the temperature at the center. It is seen that the fireball of the explosion is quite transparent. In the early stage the values of the parameter η are small in connection with the long mean free paths of the photons of high air temperatures. With a decrease in T_{max} the quantity η grows from 0.01 to the maximum value, equal to 0.32

at T_{max} = 5 eV, and then declines again to values on the order of 0.01 in proportion to the dispersion and cooling of the gas. The de-excitation W reaches about 20% by t = 100 μsec; this is far greater than was obtained in [9].

A laser explosion can be used as a powerful source of light emission with a continuous spectrum. The intensity I_ε of the radiation emerging radially (at a distance of 30 cm) at the time 2.5 μsec, when the temperature in the hot region is 3.0-3.5 eV, is presented in Fig. 6 to illustrate the spectral characteristics of the problem. It is seen that the role of the lines is rather large. We note that 155 spectral intervals fall in the section of quantum energies of from 0 to 7 eV. At earlier times with higher temperatures the role of lines in the emerging spectrum is not so important, and the spectrum has a rather smooth form resembling a Planckian spectrum but cut off at ε = 7 eV. Conversely, at later times, i.e., at lower air temperatures and densities and consequently longer mean free paths of the radiation, the role of lines and bands in the emerging spectrum grows.

The emission intensity I_ε at the center is shown in Fig. 7 at the same time as the emerging spectrum in Fig. 6. The emission spectrum at the center for quantum energies $\varepsilon \leqslant 7$ eV has the form similar to that of the emerging spectrum and is not shown in Fig. 7. It is seen that while ultraviolet radiation is practically absent from the emerging spectrum, it is dominant for the outer regions.

As follows from Figs. 6 and 7, as well as from an analysis of the spectra at other points and at other times, for these conditions the resolution of the tables used (an elementary interval of 0.03 eV) is fully adequate to describe the contours of the broadest lines in the spectrum, although it allows only a rough designation of the contours of the narrow lines. It is also clear that since considerable overlapping of the wings of the lines occurs one cannot use the separate calculation of the individual lines and the continuum, and this leads to the necessity of introducing a large number of spectral intervals for the description of the spectrum.

Lines with ε > 18.6 eV were not taken into account in the spectrum, but this can scarcely have a significant effect on the parameters of the explosion, since the main de-excitation occurs at T < 6 eV when the maximum of the Planckian function lies within the interval in which the lines are taken into account. The ultraviolet radiation emitted by the hot region does not travel far, for all practical purposes, and it determines the temperature profile at the edge of the fireball, indirectly affecting the energy losses.

To verify this fact we made a control calculation in which the lines were not taken into account at all for T > 20,000°K. Because of the decrease in the number of lines analyzed it proved sufficient to use 155 spectral intervals. The quantity W changed by only 1-2% in this case, and the changes in T_{max} and the other characteristic parameters were just as slight, which gives reason to assume that the calculation described above with a detailed allowance for the spectral composition of the radiation is sufficiently reliable in this respect. Using such a solution as a standard, one could try to determine what number of spectral intervals is sufficient to determine the explosion parameters with one or another given accuracy. This was not done in the present report, however, partly because the expenditure of computer time for the calculation of the spectral problem with 455 spectral intervals only exceeded by 2 to 3 times the expenditure of time for the calculation of the same variant in a multigroup approximation with 15 groups; i.e., the reduction in the volume of calculations is already rather great with the use of the averaging method.

An analysis of the results of the calculation of the shock wave trajectory showed that beginning with a certain time its law of motion can be approximately described by the solution of the problem of a strong point explosion [4]:

$$r_s^5 = \alpha \frac{E}{\rho} (t + t_0)^2,$$

where r_s is the coordinate of the shock wave front; E is the energy of the explosion; t is the time; α and t_0 are constants which are found from the numerical calculation. For the variant analyzed above α = 0.41 in the time range of 2.5 < t < 6 μsec and for distances of 6 < r_s < 9 cm. The quantity W was 10% at the start of this interval and 14% at its end. In the ranges of 6 < t < 30 μsec and 8 < r_s < 16 cm the best agreement with the calculation is given by α = 0.46. For an energy E = 1 kJ in the ranges of 3 < r_s < 7 cm and 1.5 < t < 12 μsec we have $\alpha = 0.51$. At the start and end of this interval $W = 7$ and 11%. This same variant calculated without any allowance for emission led to a value of $\alpha = 0.60$, i.e., to a decrease in α by 23%.

With an increase in the air density to 1/10 of normal the constant α changed, but slightly. For $E = 1$ kJ, $\alpha = 0.53$ in the intervals of $1.75 < r_s < 6$ cm and $0.5 < t < 12$ μsec (the quantity W varied from 4 to 12% in this interval). A decrease in T_0 to 8.6 eV did not lead to an appreciable change in the quantities W and α. We note that the values of α obtained in the present calculations turned out to be considerably lower (by 2.0-2.5 times) than in the calculations of [10] and than in the analysis of the experiments in [1] at an earlier stage ($\alpha \approx 1$).

When the power of the explosion and the air density are varied the parameters of the explosion at and near the shock wave front can be scaled on the basis of hydrodynamic similarity theory with the accuracy of the small variation in α. However, the time dependences of the quantity W and the maximum temperature T_{max} are not subject to such scaling. This is seen from Fig. 8, where the dependences of W and T_{max} on the variable $t' = t(E_0\delta/E)^{1/3}$ are plotted for $E_0 = 1$ kJ. Curves 1 and 2 correspond to $E = 10$ and 1 kJ with $\delta = 0.03$ while curve 3 corresponds to an energy $E = 1$ kJ and $\delta = 0.1$ (in all cases $T_0 = 23.7$ eV). The departure from hydrodynamic similarity for these parameters is connected with the important effect of radiation-transfer processes on them.

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