SHOCK-WAVE FOCUSING IN A THREE-TEMPERATURE PLASMA

N. A. Bardin

UDC 533.951:519.62

Improvements in numerical methods have now enabled one to calculate the convergence and focusing of a spherical shock-wave SW in a three-temperature plasma. There are differences from the one-temperature case [1, 2] and the two-temperature case (T_e and T_i) [3, 4] in that the calculations reveal new regularities at short distances from the center.

1. Qualitative Interpretation and Characteristic Estimates. SW convergence and focusing in a completely ionized plasma have some specific features. In particular, there are exceptionally marked temperature differences ($T_i/T_e \sim 3$, $T_e/T_f \sim 30$) at the SW front near the center because the material at a short distance from the center does not have time to cool by radiation, i.e., the energy cumulation at the SW front is more rapid than the dissipation. This results in even greater accentuation of the cumulation at the SW front and considerable temperature differences, which in turn produce a sharp increase in the radiation output, which all the same is not able to halt the cumulation.

We call this phenomenon a three-temperature corona (T corona), since the effects are of three-temperature type, while the term corona denotes the usually bright emission from low-density gas, which in this case is associated with accentuated losses in the low-density material (ahead of the SW front), which is transparent to its own radiation. It is true that the corona occurs on the outside, not on the inside, but the correspondence to the physical processes is reasonably complete, and that is the most important point.

The existence of a T corona is not essentially novel. An analogous situation occurs in the theory of planar stationary waves: a narrow temperature peak $T_+ = (3 - \gamma)T_1$, where T_1 is the temperature behind the SW front, whose size is negligibly small by comparison with the spread in the SW front due to thermal conduction [5].

The radius R_k of the SW front at which the T corona arises is related as regards order of magnitude to the linear scales in the temperature relaxation and emission $L_{mf} \sim A^{3/2}Q_{mf}^{-1}\cdot\rho_0^{-1}T_1$ behind the SW front, since this is also a measure of the linear scale below which radiation does not have time to cool the heated material.

We note that a T corona in the form of a narrow temperature peak exists also at larger radii, but it is reasonable to speak of it only for those distances from the center at which the temperature rise is considerable.

We use an approximate formula for the pressure increase at the front $p = \alpha R^{-k}$ [6] to get an estimate for our spherical case:

$$R_k = 0.213\left[\frac{A^{1/2}a}{Q_{mf}\rho_0^2}\right]^{\frac{1}{1+k_T}}, \qquad (1.1)$$

where $a = (1/2)(\gamma + 1)\rho_0 u_0^2 R_0^k$ is the nominal intensity of the self-modeling SW, Q_{mf} is the temperature relaxation coefficient associated with the inverse bremsstrahlung, A is the coefficient in the equation $P = A\rho T$, and U_0, ρ_0, and R_0 are the initial values of the velocity, density, and radius. Numerical calculation gives $k_T = 0.6$, which is less than for an adiabatic SW, where $k = 0.90536$, since allowance for the thermal conduction reduces k. The dimensionless numerical coefficient in (1.1) is derived from the calculation itself.

When the T corona occurs, one gets a further interesting phenomenon associated with the splitting of the initial SW into two (small and main ones), which converge to the center. Evidently, this splitting is simply discontinuity breakup.

Chelyabinsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 4, pp. 52-55, July-August, 1984. Original article submitted June 30, 1983.

0021-8944/84/2504-0545$08.50

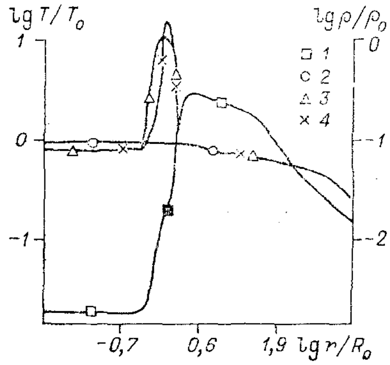

Fig. 1

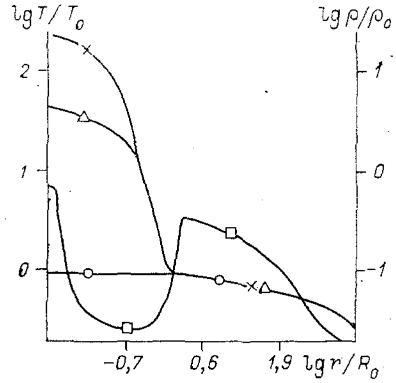

Fig. 2

We note that the SW splitting and the T-corona formation are due to the same factor The cumulation greatly exceeds the bremsstrahlung losses. As a result, the photon thermal conductivity ($S_f \sim T_f^m \rho^{-n} \partial T_f/\partial r$) in the small SW is unimportant, whereas its action is decisive in the main SW. Correspondingly, the material entering the front is first adiabatically compressed in the small SW ($h_1 = (\gamma + 1)/(\gamma - 1) = 4$), and then there is the main compression in the main SW ($h_2 \sim 20$), so the total compression is $h \sim 10^2$.

We note that ionic viscosity has no effect on this splitting; this was checked in an additional calculation. In fact, the characteristic scale is $L_x \gg L_i$, where L_i is the front broadening due to the nonlinear ionic viscosity. Also, the maximum temperature in the T corona corresponds to the front of the small SW, while the temperatures always equalize behind the front of the main SW.

In the initial stage ($T_m = T_e = T_i \neq T_f$), the temperature maximum in the T corona is described by

$$AT_m/(\gamma - 1) = u^2/2, \tag{1.2}$$

where u is the speed at the small SW front. This formula is derived from the conditions at an infinitely thin discontinuity in the absence of thermal conduction.

Formulas (1.1) and (1.2) agree well with the numerical calculation shown in Fig. 1, where 1 — ρ, 2 — T_f, 3 — T_e, r — T_i. The point where the small SW is generated is shown on the density profile as a filled square. Figure 1 also shows the generated electronic thermal wave TW. The latter stages in the development of this involve amplification and focusing. The ionic temperature profile is then as in Fig. 1. Then the anomalous separation between T_i and T_e occurs ($T_i/T_e \sim 3$) together with the focusing of the ionic TW. Then the small SW is focused (Fig. 2).

We note that the electronic and ionic thermal conductivities ($S_e \sim T_e^{5/2}\partial T_e/\partial r$, $S_i \sim T_i^{5/2}\partial T_i/\partial r$) become important as the small SW converges, so the compression at the front of the small SW increases (Fig. 2). At the instant of small SW focusing, the ionic viscosity limits the cumulation, since the SW front is of finite dimensions and cannot approach the center indefinitely, such as would occur with unrestricted cumulation. A similar result has been derived in [4].

We note that we always have $L_i \sim L_T \sim \lambda_i$ in a strong SW, where L_i is the broadening of the SW front due to ionic viscosity, L_T is the broadening due to ionic thermal conductivity, and λ_i is the ion range. This follows from the equations for motion and energy transfer. In the first case, the ions transfer momentum over the mean free path, while in the second they transfer energy.

Then the focusing of the ionic thermal wave and that of the small SW should be simultaneous, which is confirmed by the numerical calculations. The ionic thermal wave and the leading part of the front of the small SW broadened by ionic viscosity reach the center simultaneously. Here the main mass of the material (the density maximum) in the small SW is still at some distance from the center.

Then the material ahead of this maximum begins to be compressed uniformly (on account of the pressure on it from the main mass of the small SW moving towards the center and because of the ionic viscosity) and attains the density maximum in the small SW. In the closing stage of the small SW focusing, the density profile takes a certain characteristic

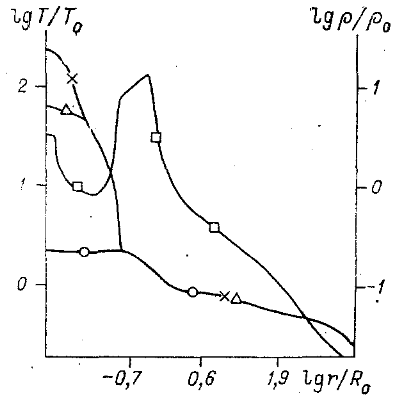

Fig. 3

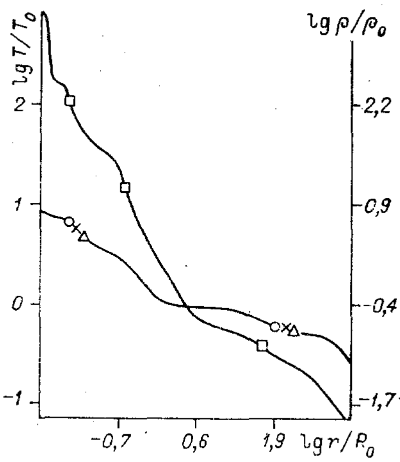

Fig. 4

form in a fairly extended region around the center. This focusing mechanism involves a substantial role for the ionic viscosity.

We note that in calculations neglecting the ionic viscosity, the jump is replaced by a pronounced density maximum at the center of the converging SW.

Figure 3 shows the focusing of the reflected SW arising after reflection of the small SW from the center and then from the main SW. The total compression behind the front of the main SW continues to rise ($h \approx 10^4$). Then the main SW is focused (Fig. 4). The temperatures behind the front of the main SW coincide not only during focusing but also in the final stage of reflection. In fact, S_e and S_i are large, which means T_e and T_i hardly increase. On the other hand, the density increases, and consequently the heat transfer factors Q_{ei} and Q_{ef} increase, i.e., the substance is cooled by radiation.

In the two-temperature calculation (T_e, T_i), a D corona (double) was observed without the corresponding SW splitting. Strictly speaking, a D corona is a large stage in the evolution of a T corona (when $T_e \neq T_i \neq T_f$ in the T corona), which corresponds to focusing of the electronic TW and the start of the anomalous separation between T_i and T_e, but this does not lead to splitting of the small SW, as we have seen. The absence of SW splitting in a D corona is explained by the substantial electron-ionic transfer and the marked electronic thermal conduction (the ionic thermal conduction is negligibly small at the time when the D corona occurs), so the instant when the D corona arises is somewhat nominal, in contrast to the T corona, although the phenomenon as a whole is reasonably clear-cut and justifies the separate name.

We note that in a sufficiently weak SW ($a \approx 10^5$ erg·cm^{k-3}) one gets a D corona, not a T one, since in such an SW the broadening of the front in the initial SW is produced not by photon thermal conduction but by electron. The emission in such a D corona will always be unimportant, since the electron heating is slight.

2. Energy Deposition Calculation and Solution Applicability. The T corona and the SW splitting were incorporated in calculations of the burning of a homogeneous DT target. This reduces the energy required. For example, preliminary data indicated that a was reduced by 50%.

It may be that it is convenient to measure the initiation energy in terms of a, which is dependent on the density, target size, and initial speed.

In our calculations, the reflected SW was absent, since the energy of the initial SW was less ($a \approx 10^{14}$ erg·cm^{k-3}). Also, the maximum temperature of the entire process corresponded to focusing of the small SW ($T_i \approx 30$ keV), and if the focusing of the main SW ($h \approx 10^4$) occurred before T_i could fall, then the burning occurred after the focusing of the main wave (for large a, burning may be expected after focusing of the small SW).

We note that introducing impurities of high z increases the density rise in the main SW by reducing a. Also, one can evidently produce coincidence between the density and temperature peaks for a certain sequence of initial SW.

We now discuss the applicability range. Clearly, the ionic viscosity and ionic thermal conductivity in a T corona have to be examined on the basis of the physical kinetics, since the characteristic scale is provided by the ion range $L_x \sim L_i$, but behind the SW front one should use gas dynamics in view of the high density ($h \sim 10^5$, $L_x >> L_i$), i.e., the discrete structure is unimportant, and the process is of macroscopic character.

It is also necessary to examine the spectral treatment, since the formation of the T corona is accompanied by the production of quanta in the x-ray range.

A description has been given [7] of the mathematical formulation considered here. We merely note that introducing the temperature T_f implies that a Planck spectrum is applicable.

I am indebted to V. A. Lykov and A. I. Zuev for useful discussions and advice.

LITERATURE CITED

1. E. I. Zababakhin and V. A. Simonenko, "A converging shock-wave in a thermally conducting gas," Prikl. Mat. Mekh., 29, No. 2 (1965).
2. A. A. Makhmudov and S. P. Popov, "The effects of thermal conductivity on a strong shock-wave converging to a center of symmetry," Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 1 (1979).
3. E. A. Barchenko and V. P. Korobeinikov, "Numerical study of converging shock and thermal waves," Dokl. Akad. Nauk SSSR, 230, No. 6 (1976).
4. V. S. Imshennik, "Convergent shock-wave cumulation in the presence of dissipated processes," Zh. Prikl. Mekh. Tekh. Fiz., No. 6 (1980).
5. Ya. B. Zel'dovich and Yu. P. Raizer, The Physics of Shock-Waves and High-Temperature Gas-Dynamic Phenomena [in Russian], Fizmatgiz, Moscow (1963).
6. E. I. Zababakhin, "Unrestricted cumulation phenomena," in: Mechanics in the USSR over Fifty Years [in Russian], Vol. 2, Nauka, Moscow (1970).
7. E. N. Avrorin, A. I. Zuev, N. G. Karlykhanov, V. A. Lykov, and V. E. Chernyakov, The Specifications for Targets and Laser Equipment Parameters to Produce Thermonuclear Fusion, Preprint, IPM Akad. Nauk SSSR [in Russian], No. 48 (1980).

POSSIBILITY OF THE DEVELOPMENT OF OSCILLATIONS DURING THE HEATING OF A TRANSPARENT SOLID DIELECTRIC BY OPTICAL RADIATION

Yu. I. Lysikov

UDC 535.343

Interest in the study of breakdown mechanisms in transparent solids has not diminished in the last two decades. New ideas have appeared regarding the breakdown of media both with a pronounced band structure of the energy levels and amorphous materials with broadened bands. Under certain conditions the difference between these two becomes insignificant. Beginning in the 1970's concepts of the breakdown of transparent solids by the heating of the medium near strongly absorbing admixtures or inhomogeneities were developed [1, 2]. Concepts of linear and nonlinear heating mechanisms and breakdown of materials were developed [1-4]. The nonlinear model of the development of breakdown leads to good qualitative agreement of theory and experiment in a rather large number of cases. However, recent experiments [5] show that in glassy systems the behavior of the breakdown threshold as a function of the freedom of the material from admixtures does not agree with ideas corresponding to the nonlinear model of the development of breakdown at trace impurities. Ideas have been expressed on the effect of fluctuations of the microstructure of a material on the corresponding behavior of the characteristics of the breakdown of the medium. All this indicates the need for further study of the processes occurring during the heating by optical radiation of a material which does not contain an appreciable number of microinclusions. Papers have appeared on the effect of the temperature dependence of the thermal conductivity on the overall development of the heating of the material. The results indicate the formation of a region in which the thermal conductivity is large, and the temperature and the characteristics related to it are practically constant over the coordinate [6]. This result was obtained under certain assumptions, and in particular without taking account of the possibility of the interaction of relaxations through thermal and elastic channels. In certain regions of the medium the heat-transfer rate can become comparable with the rate of propagation of elastic perturbations. This shows that

Voroshilovgrad. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 4, pp. 56-59, July-August, 1984. Original article submitted June 10, 1983.

 0021-8944/84/2504-0548$08.50