PHYSICAL PHENOMENA THAT OCCUR WHEN BODIES COMPRESSED BY STRONG SHOCK WAVES EXPAND IN VACUO

Ia. B. ZEL' DOVICH and Iu. P. RAIZER

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The glow of an initially solid opaque body that appears after its compression by strong shock wave with subsequent expansion into a vacuum is studied. Condensation of the vapor of the substance and recombination of ions and electrons under these conditions are also considered.

EXPLOSIVES can be used to produce very strong shock waves in solids. Pressures of the order of ten million atmospheres are achieved, with temperatures behind the shock front of the order of tens or hundreds of thousands of degrees.[1-3] It is natural to inquire whether the radiation from a shock-compressed body can be used for the measurement of its temperature.* Such measurements have recently been performed for a transparent body (Plexiglass),[2] but transparent substances are, of course, exceptions. It would be most interesting to investigate compressed metals, even very thin layers of which ($\sim 10^{-5}$ cm) are opaque to visible light. A fundamental difficulty is presented by the fact that before the shock wave reaches the surface the compressed material is covered with an undisturbed opaque layer. Expansion begins immediately after the shock wave reaches the surface; between the compressed material and the observer there is a layer of material which undergoes compression followed by expansion. Therefore the radiation observed when the wave emerges at the surface of an opaque body cannot be used to measure the temperature reached during compression. However, the study of this radiation is of independent interest. Experiments performed by Kormer, Sinitsyn, and Kuriapin have shown that the optically measured temperatures of opaque bodies are much lower than the calculated compressional temperatures. The measured temperature falls off considerably in the time interval, from 0.1 to 2 or 3 microseconds, when measurements can be obtained. The lower limit, 0.1 microsecond, is set by the resolving power of the apparatus. These experiments have led to the theoretical study of optical and other physical phenomena that should occur on the surfaces of expanding bodies following shock compression.

*The glow of gases, particularly air, in shock waves has been considered theoretically in references 4 and 5. For further bibliography see the review article, reference 6.

1. THE HYDRODYNAMICS OF EXPANSION

When a shock wave reaches the interface between the solid and air or a vacuum the material begins to expand from the surface. The hydrodynamic solution for a rarefaction wave is well known (see references 7 and 8, for example). This is the self-similar solution, in which all hydrodynamic quantities depend only on the ratio x/t, where x is distance from the initial position of the boundary and t is time computed from the instant when the shock wave reaches the boundary. The motion is isentropic and each particle of matter expands adiabatically.

When a relatively weak shock wave reaches the surface with energy that is insufficient to cause evaporation of the solid the velocity of the matter while being unloaded to atmospheric pressure (or zero pressure when bounded by a vacuum) becomes $2u_0$, which is double the velocity u_0 acquired in the shock wave. The material, which is heated irreversibly by the shock wave, remains in a final solid phase.

The unloading process is entirely different when a solid body is heated by a strong shock wave to a temperature of the order of tens of thousands of degrees so that its thermal energy is considerably above the heat of vaporization. The adiabatically expanding and cooling material in the unloading region is then in its gaseous phase. The adiabatic curve passes above the critical point, and the material density at the leading edge of the unloading wave falls to practically zero together with the temperature and pressure when the substance unloads into a vacuum.

In first approximation we find, when the material is assumed to be a gas with the adiabatic exponent γ, that the velocity of particles on the surface of the body during expansion into a vacuum is $[1+\sqrt{2\gamma/(\gamma-1)}]u_0$ where u_0 is again the velocity of the shock-compressed material. Taking the effective value $\gamma \approx 1.3$ (with account of ionization), we obtain approximately $4u_0$ for the velocity of the boundary.

In the unloading zone the density passes continuously through a very wide range of values from zero to the density of the shock-compressed solid. The density of an individual particle obeys the law $\rho \sim t^{-2/(\gamma+1)}$. A number of interesting phenomena occur in the unloading zone.

2. GLOW DURING UNLOADING

The surface of the unloading wave glows brightly. The radiation is the typical emission from a gas with a steep temperature distribution. The absorption and emission of visible light in the case of a monatomic gas, such as a metallic vapor, are due principally to photoelectric transitions from highly excited atomic levels and to the reverse process of photorecombination. The absorption coefficient is sharply reduced with decreasing temperature following the Boltzmann law* and is proportional to the density:

$$\varkappa_\nu \sim \rho \exp[-(I-h\nu)/kT],$$

where I is the ionization potential, which may be somewhat reduced through the strong Coulomb interaction of the plasma in regions of high density.

At sufficiently low temperatures, where the range of light is greater than the characteristic distance u_0t, the gas is transparent; on the other hand, at sufficiently high temperatures the gas becomes absolutely opaque. Therefore the radiating layer corresponds to temperatures at which $l_\nu(T) \sim u_0t$.

More precisely, the effective (visual) temperature is given by the condition

$$\int \varkappa_\nu dx = 1,$$

where the integral is taken from the gas-to-vacuum interface up to the radiating layer with a temperature approximately equal to the effective temperature T_{eff}.

Making use of the equation of the adiabate, $\rho \sim T^{1/(\gamma-1)}$, and the hydrodynamic solution $\rho = \rho(x/t)$, we go over to the new independent variable, the temperature

$$T = T(x/t), \quad x = tf(T), \quad dx = tf'(T)\,dT.$$

*In accordance with the number of atoms whose excitation energy is high enough so that a light quantum of frequency ν can induce ionization.

We obtain our condition in the form

$$\text{const} \cdot t \int_0^{T_{\text{eff}}} \exp[-(I-h\nu)/kT]\,T^\alpha dT = 1,$$

where α is a constant on the order of a few units. The behavior of the integral is determined principally by the exponential function. Approximate integration leads to the transcendental equation

$$T_{\text{eff}} = (I-h\nu)/k \ln(tT_{\text{eff}}^\beta \cdot \text{const})$$

where β, which is a constant of the order of a few units, depends on the adiabatic exponent γ.

A numerical estimate shows that the effective temperatures of metals with $I \sim 5$ to 8 ev, range from 3000 to 7000°, beginning already with very small times, $\sim 10^{-10}$ sec.

The screening of radiation in the unloading region fundamentally limits the possibility of observing temperatures of hundreds or thousands of degrees in the region not yet reached by the rarefaction wave. This region becomes invisible when the unloading region becomes of the order of the range of light, i.e., $u_0t \sim 10^{-6}$ cm, which at velocities $u_0 \sim 10^6$ corresponds to $t \sim 10^{-12}$ sec. Thus it is impossible to follow the frequently-advanced suggestion that the temperature in a shock wave be measured from the brightness of the glow when the wave reaches a vacuum-bounded surface. (Even if an instrument with time resolution $\sim 10^{-12}$ sec is constructed, it is practically impossible to make the wave front parallel to the surface of the body with accuracy $\sim 10^{-6}$ cm.) Therefore at present the temperature of the wave front can be measured from the brightness of the glow only in the case of transparent bodies, as was suggested in reference 2.

However in a more detailed study of the optical properties of a gas the curve of $T_{eff}(t)$ may yield some information regarding the gas density in the emitting region, where the temperature $\approx T_{eff}$, i.e., it may be possible to estimate the entropy of the gas, which in virtue of the isentropic motion equals the entropy in the shock wave.

It must be noted that the measured mechanical parameters of a shock wave do not indicate directly the entropy and temperature in the wave.[9]

3. CONDENSATION DURING UNLOADING

Under certain conditions the brightness of the unloading wave may be affected by vapor condensation at the low temperatures that exist on the leading edge. Condensation is of interest independently of the wave brightness. The adiabate of the vapor during expansion must intersect the curve of equilibrium between the condensed material and saturated vapor since in the adiabate T and ρ are related by the power law $T \sim \rho^{\gamma-1}$ and in the phase equilibrium curve by the exponential law $\rho \sim \exp\{-q/kT\}$, where q is the heat of vaporization. The number of condensation nuclei is determined by the adiabatic vapor cooling rate; the degree of supersaturation at which strong condensation begins, thus preventing further supersaturation, increases with the adiabatic cooling rate, i.e., with the shock wave amplitude.

Vapor condenses on nuclei which are formed at the initial moment when maximum supersaturation is reached; new drops are then no longer formed. A kind of quasi-stationary state is established in which the degree of condensation "follows" the further expansion of the material. Calculation shows that the number of condensed drops is so large that even with total condensation of the vapor the drops are considerably smaller than visible light wavelengths. This indicates that the drops absorb light volumetrically, i.e., only in proportion to the total quantity of condensed vapor, which increases with time. After sufficient time this absorption can screen the glow completely.

It would be very interesting to investigate how small drops of a condensate diffusely scatter light from an outside source illuminating the unloading wave. The scattering of light by small droplets is proportional to the square of their volume, unlike the case for absorption. Therefore such an experiment would enable us to investigate both the total quantity of condensate and the droplet size.

It should be noted that diffuse scattering of light depends strongly on the existence of condensed drops, since a gas scatters very weakly. Therefore the method of recording the scattered light is a very sensitive means of detecting condensation.

4. CONDITIONS AT THE LEADING EDGE DURING UNLOADING INTO A VACUUM

A small quantity of matter at the leading edge of the unloading wave is subjected to nonadiabatic conditions, since it absorbs light that proceeds from deeper layers. This nonmechanical transfer of energy from deep layers to outside layers increases the velocity of the leading edge compared with the velocity of adiabatic unloading. The conditions at the leading edge approximate those in an isothermal rarefaction wave, where the velocity of the leading edge is known to be infinite as the density drops exponentially. It would be of great interest to investigate electrical conduction in a rarefaction wave just as the electrical conductivity of a plasma is studied in a shock tube.

As a result of the rapid drop in density, recombination processes, which require triple collisions, do not reach equilibrium at the leading edge. The kinetic equation of these processes is

$$dc/dt = f(c)\rho^2; \quad \int dc/f(c) = \int \rho^2\,dt,$$

where c is the specific concentration of atoms, electrons or ions, and $f(c) \sim c^2$ or $\sim c$, depending upon whether we are considering pair-wise recombination or adherence to inert molecules. When the density drop obeys the law $\rho \sim t^{-2/(\gamma+1)}$ the integral on the right converged, approaching a finite limit in infinite time. However the equation for radiative recombination contains the first power rather than the second power of the density. The integral (with the cross section $\sim 1/T$) diverges for any $\gamma > 1$. Consequently, $c \to 0$, the decrease of c being determined by photorecombination.

Even a brief enumeration of the phenomena that occur in unloading waves of solids heated by strong shock waves shows the broad possibilities of this method, which can be used to investigate diversified physical processes in the vapors of metals and other solids at high temperatures and in the broad range of densities which cannot be achieved by other laboratory methods.

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