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ANALYSIS OF PARAMETERS OF ELECTRIC AND MAGNETIC PHENOMENA ACCOMPANYING EXPLOSION AND SHOCK PROCESSES

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Parameters of electric and magnetic fields generated by an explosion of chemical explosives and impact of metallic bodies are determined.

Upon detonation of condensed explosives (detonation rate $D \sim 8 \cdot 10^3$ m/sec) and impact of metallic bodies moving at a relative velocity of $\sim (1-2) \cdot 10^3$ m/sec, the state of matter is characterized by similar pressure values of ~(0.2–0.5) kbar, high density of particles ($(1-10) \cdot 10^{28}$ m^{-3}) and temperatures of 1000 K (metals) and 3000–4000 K (detonation products (DP)), which provides a variety of physical [1-5] and, in particular, electromagnetic (EM) phenomena [6-12] accompanying these processes. Despite a number of works devoted to investigation of EM phenomena accompanying detonation of chemical explosives and impact of metallic bodies at high impact velocities [4], only Alekseev et al. [11] have correctly derived expressions for quasistationary electric and magnetic fields created by the region of continuous variation of hydrodynamic parameters (the region behind the shock wave front) loaded with products of detonation of a metallic rod.

The theory developed by Zel'dovich and Raizer [3] describes explosion processes with superhigh temperatures ($T \sim 10^6$ K, when the matter is a completely ionized gas) and shock phenomena at superhigh velocities ($V >> 10^4$ m/sec) and immediately makes it possible to determine quantitative characteristics of the radiation energy transfer in the low-temperature region under consideration. As regards the analysis of characteristics of quasistationary electromagnetic perturbations [13, 14], it invites substantial improvements.

From the standpoint of thermodynamics [15, 16], magnetohydrodynamics [13], and physics of weakly ionized gas [6], we have determined possible limits of parameters of EM perturbations emerging upon detonation of chemical explosives and impact of metallic bodies moving at intermediate velocities.

The electromagnetic field of a medium subjected to an explosion load can be naturally divided into four components of the electric and magnetic fields, E_1, E_2, E_3, and E_4, and B_1, B_2, B_3, and B_4, respectively. $E_1(B_1)$ will be assumed to be connected with the wave front; $E_2(B_2)$ is the result of wave transfer inside the medium; $E_3(B_3)$ is the electromagnetic field emitted by atoms and molecules as a result of their resonant excitation; $E_4(B_4)$ is the bremsstrahlung of charged DP particles.

The formation of a space charge at the front and emergence of an electric field (E_1) (Fig. 1) take place due to diffusion of electrons with a mobility substantially higher than that of DP ions [3, 6], and are observed within the region of variation of the density of the medium r_f (for metals, $r_f \sim 10^{-8}$ m [2]). Assuming naturally that thermodynamic equilibrium between electrons and the DP gas [15, 16] takes place (hence, $j = 0$ follows immediately [3, 6, 11]), we obtain the condition of constancy of the electrochemical potential in the medium

$$\mu - e\varphi = \text{const}. \tag{1}$$

It follows from condition (1) that

$$\mu_0 - e\varphi|_{x \to +\infty} = \mu_1 - e\varphi|_{x \to -\infty}. \tag{2}$$

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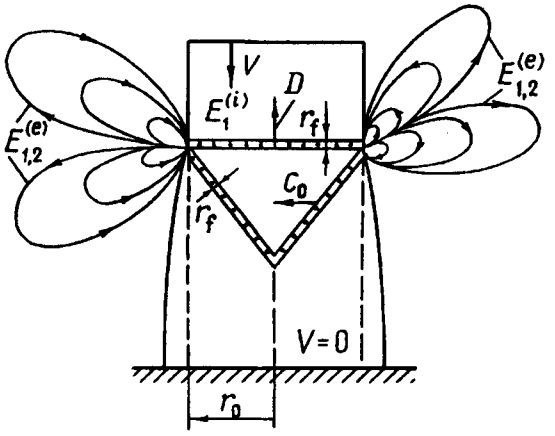

Fig. 1. Diagram of emergence of electric field upon collision of a metallic rod.

In metals, conduction electrons obey Fermi-Dirac statistics and have chemical potential $\mu = (\hbar^2/2m)(3\pi^2 n_e)^{2/3}$ [17]. Substituting the expression for the chemical potential into (2), we obtain the potential difference across the front

$$U_1 = \varphi|_{x\to-\infty} - \varphi|_{x\to+\infty} = \frac{\mu_1 - \mu_0}{e}. \tag{3}$$

Inasmuch as with explosion loading of a metal the relative change in the particle density is as follows [1]:

$$\frac{n_{e1} - n_{e0}}{n_{e0}} = \frac{P_f}{K},$$

(K has a value of about 0.2 at impact velocities $V = 2\cdot10^3$ m/sec for metals such as copper and steel [2]), to an accuracy of $\Delta n_e/n_{e0}$ (where $\Delta n_e = n_{e1} - n_{e0}$) Eq. (3) can be presented in the form

$$U_1 = \frac{2}{3e}\mu_0 \frac{\Delta n_e}{n_{e0}}. \tag{4}$$

Then the electric field strength at the front is $E_1^{(i)} \sim U_1/r_f$.

The characteristic parameters of EM perturbations at the front upon impact of metallic bodies are as follows: $U_1 = 1$ V and $E_1^{(i)} = 10^8$ V/m. In the region outside the medium at distances comparable with r_f, the electric field scales as U_1/r [14]. In the region $r >> r_0$, the field can be considered a dipole (here and in what follows, we will estimate an absolute value of the dipole moment d_q: the absolute value of the dipole moment in the region of charges $0 \le r \le r_f$ has an order of $\pi\varepsilon_0 E_1^{(i)} r_f r_0^2$) [14]

$$E^{(e)} \sim \frac{1}{4\pi\varepsilon_0}\frac{d_q}{r^3}, \tag{5}$$

hence

$$E_1^{(e)} \sim 0.25\, E_1^{(i)} \frac{r_f}{r}\left(\frac{r_0}{r}\right)^2 = 0.25\frac{U_1}{r}\left(\frac{r_0}{r}\right)^2.$$

With a characteristic body size $r_0 = 10^{-2}$ m we have $E_1^{(e)} \sim 1$ V/m ($r = 3r_0$) and $E_1^{(e)} \sim 10^{-3}$ V/m (in the case when $r = 0.3$ m).

The field created as a result of a perturbation in the density of the medium behind the front is as follows:

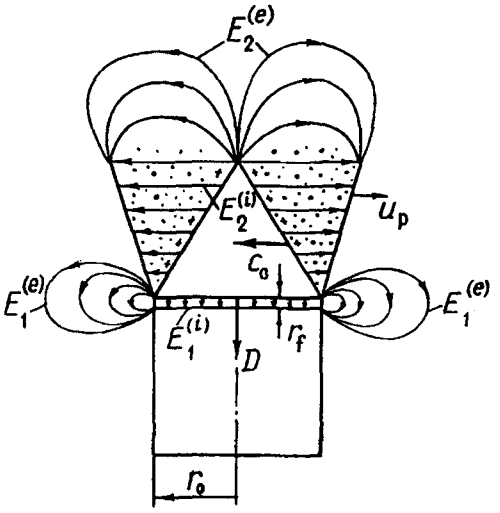

Fig. 2. Diagram of emergence of electric field upon detonation of a charge of a chemical explosive.

$$E_2^{(i)} = \frac{2}{3}\,\frac{\mu_0}{e r_f}\,\frac{n_{e1} - n_{e0}}{n_{e0}};\quad 0 \geq r \leq r_f;$$

$$E_2^{(i)} \approx 0,\quad r_f < r \leq r_0,$$

and at distances much greater than r_0:

$$E_2^{(e)} \sim \frac{1}{4\pi\varepsilon_0}\,\frac{d_q}{r^3}. \tag{6}$$

Since the surface area of the unloading wave (Fig. 1)

$$S = \pi r_0^2 \sqrt{\left(1 + \left(\frac{D}{c_0}\right)^2\right)},$$

and the density of the surface charge $\sigma \sim \varepsilon_0 E_2^{(i)}$, the dipole moment of the unloading region ($0 \leq r \leq r_0$)

$$d_q \sim \pi r_0^3 \sqrt{\left(1 + \left(\frac{D}{c_0}\right)^2\right)}\,\varepsilon_0 E^{(i)}.$$

Taking into account that $D = c_0 + \lambda u$, and $u \sim 0.5$ V [1], it is obvious that $D/c_0 \sim 2$. Then it follows from (6) that

$$E_2^{(e)} \sim 0.56\,\frac{U_1}{r}\left(\frac{r_0}{r}\right)^2, \tag{7}$$

hence $E_2^{(i)} = E_1^{(i)}$ and $E_2^{(e)} \approx 2E_1^{(e)}$. With increasing r_0, the value $E_2^{(e)}$ grows as $(r_{02}/r_{01})^2$.

Inasmuch as DPs (Fig. 2) are gaseous (the isoentrope exponent $\gamma = 2.5-3.5$) [1], their thermodynamic property consists in an exponential dependence of the concentration of free charged particles on the temperature. Let us estimate the number of free electrons n_e for a typical condensed explosive by assuming the products to be an ideal weakly ionized gas [5] (indeed, calculations show that the thermal energy equals $5.5 \cdot 10^{-20}$ J at $T = 4000$ K, and the energies of interaction of an electron with the water molecule and interaction between ions are $\sim 4.5 \cdot 10^{-21}$ J and 10^{-25} J, respectively, which is evidently much smaller). In this case we will assume that the main reactions that determine the concentration of free electrons in DP are DP ionization reactions

$$A \rightarrow A^+ + e$$

and electron capture by neutral DP particles

$$B + e \rightarrow B^- .$$

The detonation products of TNT (typical condensed explosive), in accordance with [18], have the following composition (mole/kg): C (15), CO_2 (5.3), CO (8.79), H_2O (7.05), H_2 (1.69), N_2 (5.2), HCN (1.4), and NH_3 (0.9). Then the DP particle concentration $n_0 \sim 10^{28}$ m^{-3}. The number of electrons n_e' formed as a result of ionization of atoms (molecules) A can be estimated from the Saha equation [5]:

$$\alpha^2 n_{0A} = 2\left(\frac{m_e kT}{2\pi\hbar^2}\right)^{3/2} \exp\left(-\frac{I}{2kT}\right), \quad \alpha << 1 . \tag{8}$$

When writing the Saha equation, we also assumed from natural considerations that $Z_e Z_A^+ / Z_A = 1$ (here Z_A, Z_A^+, and Z_e are statistical sums of atoms (molecules), ions, and electrons, respectively.

Finally we obtain

$$n_e' = \sqrt{2n_{0C}}\left(\frac{m_e kT}{2\pi\hbar^2}\right)^{3/4} \exp\left(-\frac{I}{2kT}\right). \tag{9}$$

The ionization potentials of C, CO_2, CO, N_2, and H_2O (main DP components) are 11.26, 13.8, 14.01, 15.6, and 12.6 eV, respectively [19]. Then it is evident from (9) that the main contribution to the electron density is made by carbon. Assuming that $n_{0A} = n_{0C} \sim 10^{27}$ m^{-3} in (9), we obtain $\alpha \sim 10^{-7}$, $n_e' \sim 10^{20}$ m^{-3}.

The density of electrons captured by neutral carbon atoms (here we also assumed the leading role of carbon as the element having the highest electron affinity [19] and a high density ($\sim 0.1 n_0$)), it follows from the balance equation for the electron capture reaction ($C + e \rightarrow C^-$) that

$$\frac{n_{0C} n_e'}{n_{C^-}} = 2\left(\frac{m_e kT}{2\pi\hbar^2}\right)^{3/2} \exp\left(-\frac{E}{kT}\right). \tag{10}$$

Inasmuch as $n_0 << n_{0C}$, assuming $\alpha_1 \leq 1$ we transform (10) to the form

$$\frac{n_{0C}(1-\alpha_1) n_e'}{\alpha_1 n_e'} = 2\left(\frac{m_e kT}{2\pi\hbar^2}\right)^{3/2} \exp\left(-\frac{E}{kT}\right),$$

hence

$$\alpha_1 = \frac{1}{1 + 2\dfrac{1}{n_{0C}}\left(\dfrac{m_e kT}{2\pi\hbar^2}\right)^{3/2} \exp\left(-\dfrac{E}{kT}\right)}. \tag{11}$$

Taking into account (9) and (11), we obtain the final expression for the electron density

$$n_e = 2\sqrt{\left(\frac{2}{n_{0C}}\right)}\left(\frac{m_e kT}{2\pi\hbar^2}\right)^{3/4} \exp\left(-\frac{\frac{1}{2}I + E}{kT}\right).$$

Assuming that electrons are captured by carbon atoms with $E = 1.27$ eV (^4S state) [19], it follows from (11) (assuming that $n_{0C} \sim 10^{27}$ m^{-3}) that $\alpha_1 \sim 0.988$, $n'' = 0.988 n_e'$, and $n_e = 10^{18}$ m^{-3}.

The Fermi energy μ_f of free electrons of DP (n_e) equals 10^{-24} J. The chemical potential calculated under the assumption that the electron gas is ideal ($\mu = kT \ln (0.5 n_e (2\pi\hbar^2/m_e kT)^{3/2})$), is $\sim 10^{-17}$ J. The obvious inequality $\mu >> \mu_f$ makes it possible to consider the gas of free electrons of DP to be ideal [17]. On the basis of (2) and (3), we obtain expressions for the potential differences and quasistationary electric fields emerging upon detonation of a condensed explosive (here, from physical considerations, we assumed the thickness of the front to be zero):

$$\ln \frac{eU}{kT} + \frac{eU}{kT} = 0,$$

hence

$$U_1 \approx 0.57 \frac{kT}{e}, \tag{12}$$

$$E_1^{(i)} \sim \nabla\varphi, \tag{13}$$

where φ is the solution of the Laplace equation satisfying the conditions

$$\varphi = U_1, \quad x \to -\infty; \quad \varphi = 0, \quad x \to +\infty;$$

$$U_2 = U_1; \tag{14}$$

$$E_2^{(i)} = E_1^{(i)}; \tag{15}$$

$$E_2^{(e)} \sim \frac{1}{4\pi\varepsilon_0} \frac{d_q}{r^3}. \tag{16}$$

When evaluating r_q (the characteristic dimension of the region of free electrons) we make use of the fact that the electron concentration n_e is primarily determined by the exponential factor $\exp(-(I/2 + E)/kT)$. Then, assuming the dependence of the temperature on the DP concentration to be a quadratic function ($T = T_0(n/n_0)^2$, where n_0 and n are the particle densities of the explosive and DP, respectively, [1]) we represent the electron density as follows:

$$n_e = n_{e0} \exp\left(2 \frac{\frac{1}{2} I + E}{kT_0} \frac{\partial n}{n_0 \partial r} r\right).$$

By assuming the zero electron density to be e times smaller than its value on the Chapman–Juge surface (n_{e0}), we obtain an estimate for r_q:

$$r_q \sim 0.5 \frac{kT}{\frac{1}{2} I + E} \left(1 + \frac{u_p}{c_0}\right) r_0,$$

hence, taking into account the relationship $u_p \sim c_0$ [1], we obtain

$$r_q \sim \frac{kT}{\frac{1}{2} I + E} r_0,$$

According to [20], the dielectric permeability of a gas mixture ε is determined by the expression

$$\frac{\Sigma_{(i)} x_i M_i}{\rho} \frac{\varepsilon - 1}{\varepsilon + 1} = \Sigma_{(i)} x_i P_i , \tag{17}$$

The components of TNT DP have the following polarizabilities (in Debyes) [20]: CO (0.1), CO_2 (0), N_2 (0), and H_2 (1.84). Taking into account (17) and the fact that the contribution of the orientational polarizability is substantially larger than the elastic polarizability [20], we find that the dielectric susceptibility of DP will be determined by H_20 molecules. The expression for the dielectric susceptibility of DP will be as follows [20]:

$$\chi = \frac{n_{H_2O} p^2_{H_2O}}{3\varepsilon_0 kT} . \tag{18}$$

For TNT, $n_{H_2O} \sim 10^{27}$ m^{-3}; hence $\chi \sim 0.1$ and $\varepsilon \sim 1$.

The area of the side surface of the front of the unloading wave $S = \pi\sqrt{1 + (D/c_0)^2} r_0$. By assuming that the density of the surface charge $\sigma \sim \varepsilon_0 E_2^{(i)}$, and the total charge Q on the surface S is a quantity of order of σS, and estimating the dipole moment of the region of product unloading as $d_q \sim Q/r_q$, we obtain

$$d_q \sim 6\pi\varepsilon_0 \sqrt{\left(1 + \left(\frac{D}{c_0}\right)^2\right)} \left(1 + \frac{u_p}{c_0}\right) r_0^3 E_2^{(i)} . \tag{19}$$

Taking into account that $c_0 \approx 0.6D$ and $u_p = c_0$ [1], we transform (19) to the form

$$d_q \sim 6\pi r_0^3 E_2^{(i)} . \tag{20}$$

By differentiating (13) and using (20), we finally obtain expressions for estimating the quasistable fields emerging upon detonation of condensed explosives:

$$E_1^{(i)} \sim \frac{\frac{1}{2} I + E}{e r_f}, \quad E_1^{(e)} \sim 0.35 \left(\frac{r_f}{r}\right) \left(\frac{r_0}{r}\right)^2 E_1^{(i)}, \quad E_2^{(i)} \sim \frac{\frac{1}{2} I + E}{e r_0}, \quad 0 \le r \le r_0 .$$

If the detonation wave has cylindrical or spherical symmetry (initiation along the axis or from the center of the charge), the external electric field $\sim \exp(-r/r_d)$ (r_d is the Debye radius [6]) vanishes at macroscopic distances:

$$E_2^{(e)} \sim 1.5 \left(\frac{r_f}{r}\right) \left(\frac{r_0}{r}\right)^3 E_2^{(i)} .$$

For condensed explosives, $r_f \in [0.5, 2] \cdot 10^{-3}$ m [21]. Therefore, at $r_0 = 10^{-2}$ m we obtain $E_1^{(i)} \in [1, 10] \cdot 10^4$ V/m, $E_1^{(i)} \sim 10$ V/m ($r = 3r_0$), $E_1^{(e)} \sim 10^{-4}$ V/m ($r = 0.3$ m), $E_2^{(e)} \sim 10^3$ V/m, $E_2^{(i)} \sim 10$ V/m ($r = 3r_0$), $E_2^{(e)} \sim 10^{-2}$ V/m ($r = 0.3$ m). In this case $U_1 = U_2 = 0.1$ V.

Since the thermal energy of DP ions equals kT, i.e., is equal to the thermal energy of electrons, the possible electric fields created as a result of diffusion of ions cannot exceed the electric fields created by electron diffusion. However, during the process of DP scatter, the emergence of a second electric field maximum created by ions is generally possible.

The presence of highly ionizable additives in the explosive (alkali metals, aluminum) leads to a sharp increase in the quasistationary electric fields accompanying detonation [9]. We detected electric field signals with an amplitude of ~ 2 V/m and a duration of $\sim (5-10) \cdot 10^{-6}$ sec at distances of ~ 0.3 m from the charge with a diameter of $2 \cdot 10^{-2}$ m. In this case, the signal amplitude had a cubic dependence on the distance. The charge was initiated at the end.

The expressions for electric fields obtained in the preceding section of the paper do not depend on the concentration of free electrons in DP, which is a consequence of satisfying the gas condition. Therefore, it is natural to reason in the following manner. Since aluminum particles behind the wave front have a velocity substantially

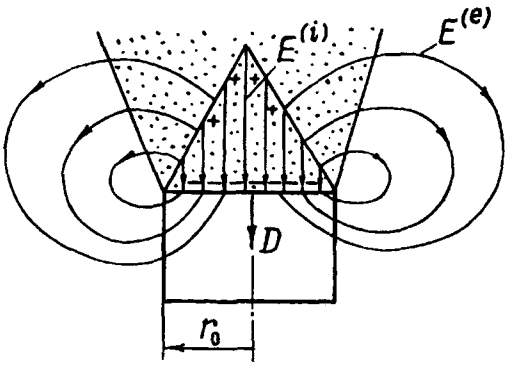

Fig. 3. Diagram of emergence of electric field upon detonation of a charge of a chemical explosive containing ionizable additives.

smaller than the DP mass velocity [22], in particular, the velocity of C^- ions, it is natural to assume that the formation of the spatial dipole (Fig. 3) takes place as a result of the fact that ions of Al combustion products (AlO, Al_2O_3) are overtaken by C^- ions (the regions appear to be shifted by distance x).

Let us estimate the parameters of the electric fields energing in this case.

From the energy conservation law we have

$$\frac{mu^2}{2} = \frac{e^2}{\varepsilon_0} n_{C^-} x^2 ,$$

where m is the mass of a C^- ion, and u is its mass velocity. Hence,

$$x \sim \frac{u}{e} \sqrt{\left(\frac{m}{2} \frac{\varepsilon_0}{n_{C^-}}\right)} .$$

Correspondingly:

$$E^{(i)} \sim u \sqrt{\left(\frac{m n_{C^-}}{2\varepsilon_0}\right)} , \quad Q \sim \sigma \pi r_0^2 = \pi r_0^2 u \sqrt{\left(\frac{m \varepsilon_0 n_{C^-}}{2}\right)} ,$$

$$d_q \sim \pi r_0^3 u \sqrt{\left(\frac{m \varepsilon_0 n_{C^-}}{2}\right)} , \quad E^{(e)} \sim 0.25 u \sqrt{\left(\frac{m n_{C^-}}{2\varepsilon_0}\right)} \left(\frac{r_0}{r}\right)^3 .$$

With $r_0 = 10^{-2}$ m, $r = 0.3$ m, $n_{C^-} \sim 10^{20}$ m^{-3}, and $I = 9.5$ eV (AlO) we obtain $E^{(i)} \sim 10^9$ V/m and $E^{(e)} \sim 1$ V/m.

In accordance with [23], in the wavelength region [0.02, 7] μm, the emissivity a ($a = 1 - \exp(kl)$, $k = \sigma n$, where σ is the collision cross-section, l is the thickness of the absorbing layer, and k is the absorption coefficient) of a CO_2 layer of a thickness 10^{-2} m at $p = 1$ bar ($n = 10^{24}$ m^{-3}) and $T = 3000$ K equals $5.7 \cdot 10^{-2}$. The concentration of CO_2 in DP is $\sim 10^{27}$ m^{-3}. Then the emissivity of a gas sphere of CO_2 of radius 10^{-2} m at $n = 10^{27}$ m^{-3} will be ~ 0.997. This makes it possible to assume that a DP layer of thickness $> 10^{-2}$ m emits as an absolutely black body. An energy flux emitted by the surface of an absolutely black body is

$$J = \sigma T^4 ,$$

which at temperature $T \sim 4000$ K equals 10^7 W/m^2. In this case the energy density of the electric (magnetic) field (J/c, c being the velocity of light) is $\sim 10^{-1}$ J/m^3, which, compared with the density of the kinetic energy $\rho u^2/2$ (10^9 J/m^3), is 10^{-11} of this amount. In this case $B_3 \sim 10^{-4}$ T and $E_3 \sim 10^5$ V/m. It is natural that in this case the EM radiation does not affect the detonation parameters; it only carries information. It should be noted that the presence of air-filled pores in pressurized explosives should lead, due to a higher, compared to the DP, compressibility, to a sharp (approximately tenfold) increase in the radiation intensity.

The spectral density of the energy V_ω in this case is distributed according to the Planck law

$$U_\omega = \frac{\hbar \omega^3}{\pi^2 c^3 \left(\exp\left(\frac{\hbar\omega}{kT}\right) - 1\right)}$$

and has a maximum at wavelength $\lambda_{max} = 0.7 \cdot 10^{-6}$ m (IR region).

For metals, the electron density is $\sim 10^{29}$ m^{-3} [24]. The absorption coefficient is $\sim 2\omega n_I/c$. In this case $n_p^2 = 1 - (\omega_p/\omega)^2$ ($\omega_p = \sqrt{n_e e^2/\varepsilon m_e}$ being the critical frequency) [24]. For $\omega << \omega_p$ (10^{16} Hz, i.e., up to the ultraviolet region) the metal radiates as an absolutely black body. The radiation maximum takes place at $\lambda = 3 \cdot 10^{-6}$ m.

The maximum frequencies of bremsstrahlung $\omega \sim m_e u_0^2/\hbar$, where u_0 is the thermal velocity of an electron. At $T = 3000-4000$ K we obtain $\omega \sim 10^{15}$ Hz (IR region). As has been shown earlier, DP absorb completely the radiation from this region. Therefore, the estimate holds:

$$B_4 < B_3, \quad E_4 < E_3.$$

Similar considerations are also applicable to the radiation resulting from recombination of charged particles.

NOTATION

μ, chemical potential of medium; φ, electric potential of the electric field; e, electron charge; x, coordinate system with the origin at the front and directed towards the unperturbed medium; μ_1 and μ_0, chemical potential of perturbed and unperturbed medium, respectively; n_e, concentration of conduction electrons; P_f, pressure at the front of the shock wave; n_{e1} and n_{e0}, conduction electron density upon shock compression and in unperturbed medium; K, modulus of dilatation of medium; U_1, potential difference created by the front; D, shock wave velocity; c_0, velocity of sound in unperturbed material; u, mass velocity behind the front; V_0, velocity of body; α, ionization degree; I, ionization potential of atom (molecule); E, affinity energy of carbon to electron; n_0 and n, original and final particle densities of explosive and DP; u_p, scattering velocity of products in vacuum; i, index of the i-th DP component; M_i, molecular weight of the i-th DP component; x_i, molar fraction of the i-th DP component; P_i, polarization of the i-th component of mixture; ρ, mixture density; α_1, fraction of electrons captured by carbons; n_{0A}, density of component A in DP; n_{0C}, density of carbon in DP; n^*, density of electrons captured by DP; n_{H_2O}, density of H_2O molecules in DP; m, mass of C^- ion; σ, collision cross-section; l, thickness of emitting layer; k, absorption coefficient; c, velocity of light; n_p, refractive index; r_0, body radius; r_f, width of front; p_{H_2O}, pressure of water vapor; λ, semiempirical coefficient; $\hbar$, Planck's constant. Indices: (e) and (i), parameters of electromagnetic fields outside and inside the body, respectively; q, Coulomb charge, denotes electrodynamic parameters of the DP ionization region; p, resonance parameter.

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