DIAMAGNETIC MOMENT OF A STRONG SHOCK WAVE OF A HIGH-TEMPERATURE LIGHT EXPLOSION IN GASES

G. A. ASKAR'YAN, M. M. SAVCHENKO, and V. K. STEPANOV

P. N. Lebedev Physics Institute, U.S.S.R. Academy of Sciences

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Extensive experimental material is reported on diamagnetic perturbations of a strong shock wave due to a light spark in different gases at different pressures. A theoretical description of this phenomenon is given with the aid of the theory of strong shock waves. It is shown that the long lifetime of the diamagnetic moment offers evidence of the high-temperature character of the process in the light spark. Experiments are presented on the reflection and focusing of a shock wave and on its cumulative action on the fireball of the spark, for the purpose of repeated utilization of a dense hot plasma. New possible effects of interaction between the strong magnetic field and a shock-wave plasma are described. Practical applications of the results are noted.

INTRODUCTION

THE authors have recently reported,[1-5] using as an example the "light spark," or the explosive release of light energy in the focus of a laser in gas, on investigations of the diamagnetic perturbation of the external magnetic field of a high-temperature shock wave.

Characteristic singularities[2,3] in the variation of such a diamagnetic moment were observed, namely, after occurring abruptly, the moment exists for a time exceeding by hundreds of times the time of light-energy input. In the articles,[4,5] the prolonged diamagnetic perturbation was connected with the expansion of the so-called "fireball" (FB)—the high-temperature region that remains in the center of the weakening shock wave. Assuming that it is possible to introduce an average temperature in the FB (at a high temperature conductivity, small dimensions of the region) an attempt was made[5] to explain the long lifetime of the moment and estimates were made of the value of the adiabatic coefficient that should be assigned to the plasma in order to explain the weak variation of the moment. This model, however, is much too simple for cases when an important role is played by the sharp inhomogeneity of the radial temperature distribution, an inhomogeneity characteristic of a shock wave when processes equalizing the temperature gradient play a small role.

We report in this paper extensive experimental material on the investigation of the diamagnetism of a shock wave of a light spark in different gases and different pressures, and give a theoretical description of this phenomenon with the aid of the theory of strong shock waves. The process explaining the slow variation of the moment will be based on the motion of layers of matter with continuously increasing temperatures in the interior of the shock wave in a direction opposite to that of the magnetic field. This correspondence between the diamagnetism and the internal, most heated part of the shock wave is a further development of the treatment given in [4-6]. We note also that the treatment of the process given in [6], where diamagnetic perturbations are considered and are set in correspondence with the quantities on the front of the shock wave, has a limited application, since in the immediate region behind the shock wave the temperature may exceed by many times the temperature from the shock wave itself.

1. EXPERIMENTAL INVESTIGATION OF THE DIAMAGNETISM OF A LIGHT SPARK

The beam of a powerful Q-switched laser was focused by a lens of focal length $f = 4.5$ cm inside a thick-wall bomb, into which the different investigated gases were introduced under pressure. The bomb was made of stainless steel and had sealed windows for the entrance and exit of the beam, and also sealed-in leads for the transmission of the signal from the induction coil (pickup of radius $R = 6$ cm) surrounding the spark. The bomb was connected with a vacuum system, a manometer, and flasks with the compressed gases. When the gas was changed, the bomb was scrubbed many times and evacuated. When complicated gases were used, capable of being decomposed or reacting under the influence of the spark wave, the content of the bomb was changed after each spark.

The diagnostic external magnetic field (reaching 10^4 Oe) was produced in the focal region of the lens. Around this region, an induction coil was wound and used to measure the change of the magnetic flux after the occurrence of the spark. The pressure in the bomb ranged from 20 atm down to the minimum value at which the gas still broke down (in the case of argon, krypton, and xenon—on the order of 0.05 atm). We investigated all the noble gases, air, nitrogen, oxygen, hydrogen, deuterium, carbon dioxide, SF_6, etc.

The absorbed energy was determined as the difference between the incident and transmitted energies, by diverting parts of the energy to two calorimeters (the procedure is described in detail in [3], where a diagram of the setup without the bomb is given). The incident energy was varied by means of neutral filters, other conditions being equal.

The main experiment consisted of investigating the dependence of the amplitude, i.e., the maximum of the diamagnetic moment M, on the energy E absorbed by the spark in different gases at different pressures. It turned out that M(E, p) = M(e/p) for each gas. These relations are shown in Figs. 1–4 in a log-log scale. Plots of $M(E/\rho)$ are given, since E/ρ is an essential parameter in the theory of shock waves. Here ρ is the initial gas density, which depends on the pressure in the bomb, $\rho = \rho_0 p_{atm}$. It turned out that the $M(E/\rho)$ dependence is very close to linear (more accurately $M \sim (E/p)$[1, 2]), and for each gas the points can be fitted quite well by a single straight line, although the ranges of the values of E and ρ, the argument E/ρ and the function M are quite large, and the values of M were obtained both by changing the energy input and by changing the gas density.

It turned out also that at a given E/ρ the magnetic moment is the larger, the larger the mass of the ion of the atom. In particular, for hydrogen and deuterium, at the same energy and at the same pressure, the diamagnetic moments are close, i.e., $M_H \approx M_D$, $M \sim m_i(E/\rho)$. This relation is satisfied approximately for the gases H_2, D_2, He, Ne, O_2, and N_2, if m_i is taken to be the mass of the atomic ion (for these gases M/m = 49, 46, 51, 38, 46, and 32, respectively). For argon, krypton, and xenon

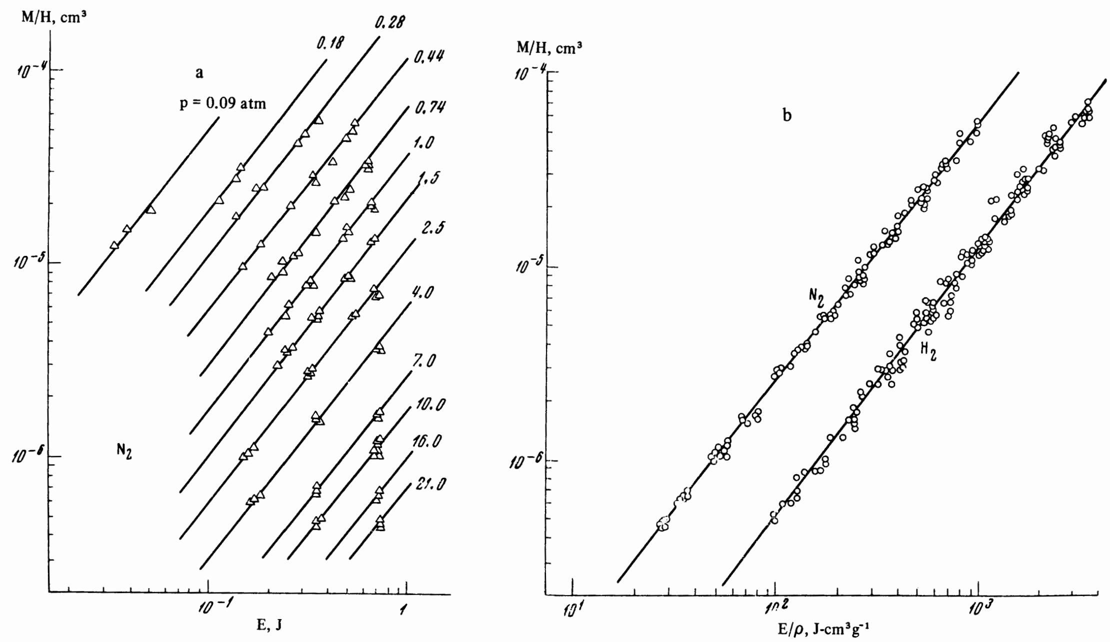

FIG. 1. Dependence of M/H on the energy input E in nitrogen for different pressures p (a) and on E/ρ in nitrogen and hydrogen (b).

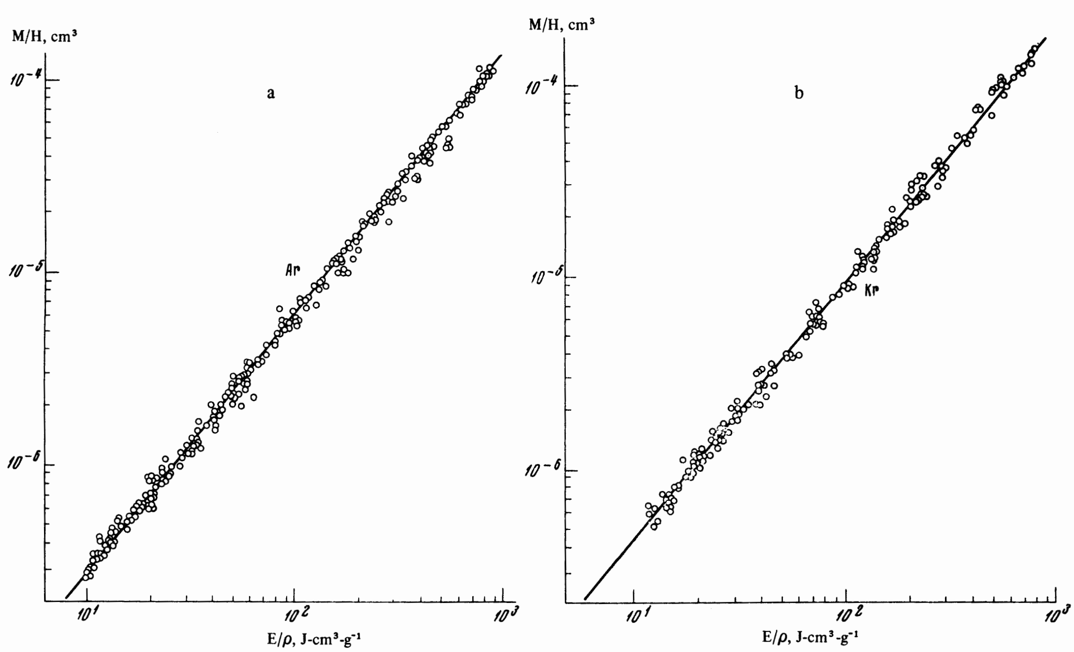

FIG. 2. Plot of M/H vs E/ρ: a—in argon, b—in krypton.

in the same units we have M/m = 10, 6.3, and 4.6, respectively.

Experiments were also performed in which the shock wave was returned by reflection from a solid surface (a dielectric shell of cylindrical or spherical form). Sharp kinks were observed in the oscillograms, reversal of the sign and large values of the inverse magnetic moment upon collision with a focused shock wave, thus indicating the possibility of using a reflected shock wave for a strong compression of the fireball of a light spark, in order to use the dense heated plasma again or in order to add energy again and employ the counter-pressure of the converging shock wave to prevent spreading of the plasma.

Secondary measurements were made in addition to the main ones. We investigated the longitudinal localization of the diamagnetic perturbation by moving the measuring diamagnetic coil (a similar experiment for air is described in [3]). In the present investigation, these experiments were performed for krypton, in which the spark was visually very large and bright, and in which the diamagnetic region was expected to be more elongated. The radius of the coil in these experiments was only 3 mm. This experiment also gave a lo-

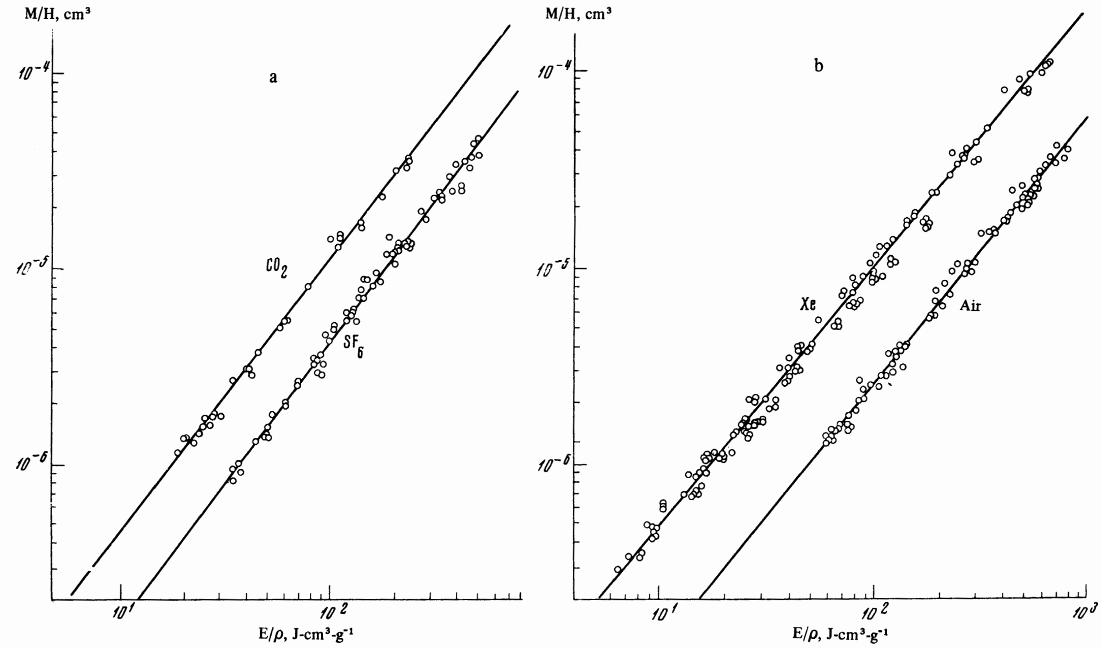

FIG. 3. Plot of M/H vs E/ρ: a—in carbon dioxide and SF_6, b—in xenon and in air.

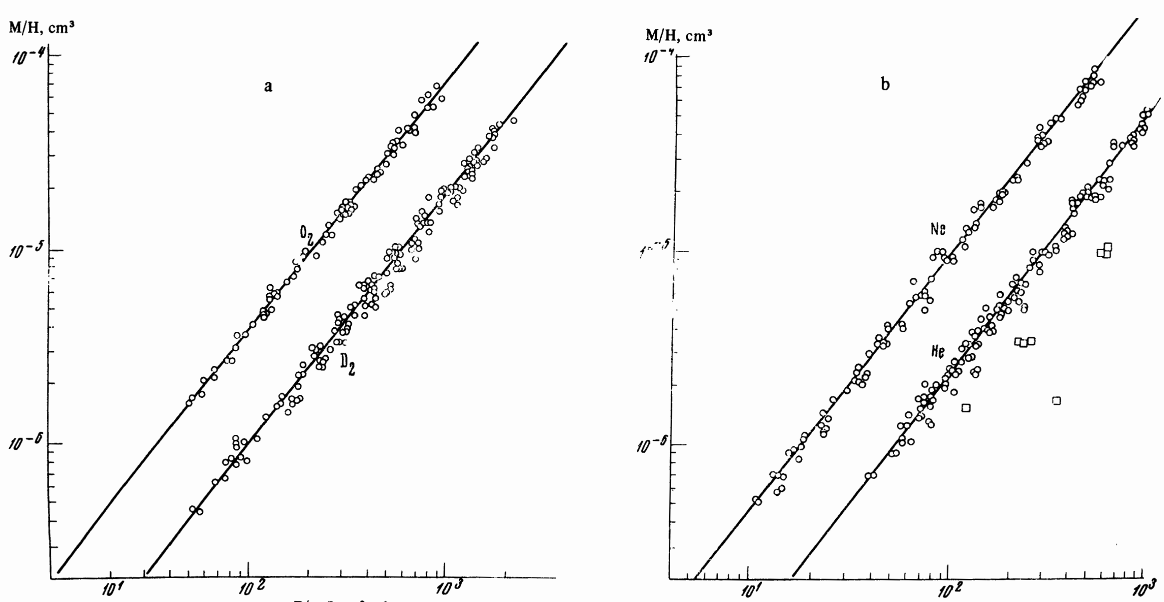

FIG. 4. Plot of M/H against E/ρ: a—in oxygen and deuterium, b—in neon and helium. The rectangles denote points for the lower pressures 0.4 and 0.7 atm, when the spark is "transparent." These points drop out.

calized region of perturbation of the magnetic field, since the measured $\Delta\Phi(z)$ agreed quite well with the known formula for the magnetic flux through an induction coil of radius R, due to a pointlike magnetic moment:

$$\Delta\Phi(z) \approx 2\pi MR^2 / (z^2 + R^2)^{3/2}$$

with a half width $\Delta z = 1.6\ R_m \approx 5$ mm in our case. We consider this result to be interesting, since it is evidence of a difference between the volume of the glowing zone and the volume of the most significant energy release.

In the main measurements we used large coils with $R \approx 6$ mm, i.e., it could be assumed with assurance that the dimensions of the diamagnetic region were small compared with the radius of the coil.

We performed also a series of experiments aimed at investigating the dependence of the diamagnetic signal on the dimensions of the energy-release region and on the method of the energy input: the energy was varied in different ways—with filters, by changing the pump, with the aid of shutters and diaphragms covering the side, central, or annular parts of the beam. In this case the volume of the focus and its shape also changed, but the diamagnetic moment was dependent only on the energy input, and all the points fell on a single straight line. We investigated also the dependence of the diamagnetic moment on the focal length of the lenses, which ranged from 2 to 15 cm. The volume of the focal region

$$V_f \approx \pi\rho_f^2 z_f = f^4\varphi^2 / d \sim f^4$$

changed in this case by a factor 3×10^3, whereas the diamagnetic moment decreased with increasing focal distance by only a factor of 1.3. The main measurements were performed with a single lens of focal length 4.5 cm.

These additional experiments have demonstrated the general character of the results of main series of experiments and simplified the explanation of the processes that lead to diamagnetism.

2. EXPLANATION OF THE DIAMAGNETISM OF A STRONG SHOCK WAVE

The diamagnetic perturbation of a strong shock wave is connected with the appearance of eddy currents when the conducting layers of the medium move behind the shock wave in the external magnetic field. At first, when the temperature and the conductivity on the front of the shock wave are sufficiently large, the dimensions of the perturbation region can be quite close to the dimensions of the shock wave. For example, for a spheroidal perturbation region

$$M = -\frac{V}{4\pi(1-n)} H_0,$$

where V is the volume of the region where the field is forced out, n is the so-called demagnetizing factor, $n \ll 1$ for an elongated spheroid and $n = 1/3$ for a spherical volume. In the latter case the radius of the shock wave, according to the simplified solution, which affords a good approximation (see, for example, [7]), is

$$r_{sh} = \left\{\frac{75}{16\pi}\frac{(\gamma-1)(\gamma+1)^2}{(3\gamma-1)}\right\}^{1/5}\left(\frac{E}{\rho}\right)^{1/5} t^{2/5}$$

and at the start of the process $M \approx -\frac{1}{2} r_{sh}^3 H_0$.

However, the growth of the magnetic moment slows down when the rate of the expansion $\dot{r}_{sh}$ becomes commensurate with the rate of diffusion of the magnetic field $v_H \approx c^2/4\pi\sigma\delta$, where $\delta = \alpha r_{sh}$ and $\alpha \sim 0.1$–0.3. We can estimate the value of this moment: putting $\sigma = AT^{3/2}$, where

$$A \approx 10^7/Z, \qquad T_{sh} = \frac{\gamma-1}{(\gamma+1)^2}\frac{m_i}{k}\dot{r}_{sh}^2,$$

we obtain

$$r_m \approx \left[\frac{10^8\alpha}{k^{3/2}4\pi c^2 Z}\right]^{1/5} m_i^{3/10}\left(\frac{E}{\rho}\right)^{2/5}\frac{(\gamma-1)^{7/10}}{(3\gamma-1)^{2/5}}$$

or

$$M_m/H = \frac{1}{2} r_m^3 = \frac{1}{2}\left[\frac{10^7\alpha}{k^{3/2}c^2 Z}\right]^{3/5} m_i^{9/10}\left(\frac{E}{\rho}\right)^{6/5}\frac{(\gamma-1)^{21/10}}{(3\gamma-1)^{6/5}},$$

i.e., for a spherical wave

$$M/H \sim m_i^{9/10}(E/\rho)^{6/5}.$$

It is easy to show that in the cylindrical case

$$M/H \sim m_i (E/\rho)^{4/3}.$$

As seen from the experimental results, in all gases the dependence of M on E/ρ is quite close to the dependence described by these formulas, namely, the slope is close to 1.2 (more accurately—slightly larger, 1.25, since the experiment apparently realizes the intermediate case, a quasispherical shock wave, with the shape of the perturbation region first elongated but soon becoming rapidly rounded out by expansion. This simplified formula also explains the comparison experiments with hydrogen and deuterium, from which it followed that at a given E/ρ we get $M \sim m_i^{9/10} = 1.86$.

It is interesting to note that gases with low excitation levels and ionization levels (for example argon, xenon, and krypton) give anomalously small M/m, a fact that can be attributed either to the closeness of γ to unity or to the large charges Z_{eff} of the ions.

As to the absolute value of M/H, the theory gives the correct order of magnitude, several times $10^{-5}\ cm^3$, in agreement with experiment. However, the simplified theory does not explain the cardinal properties of diamagnetic excitation, namely the small change of the diamagnetic moment in time after its occurrence. This model has not made it possible to analyze in detail the process of penetration of the magnetic field inside a shock wave with allowance for the sharp variation of the temperature and conductivity of the medium inside the shock wave.

We have therefore considered in greater detail the perturbation of the magnetic field by a strong shock wave accompanying a high-temperature explosive release of energy.

3. THEORY OF THE DIAMAGNETISM OF A STRONG SHOCK WAVE OF A POINTLIKE EXPLOSION

The diamagnetic perturbation from a shock wave is due to the motion of conducting layers of the medium. At first, at high temperatures, the radius of the region from which the field becomes forced out is very close to the radius of the shock wave:

$$r_{sh} \approx (Et^2/\rho)^{1/(\nu+2)},$$

and the diamagnetic moment is $M \sim r_{sh}^{\nu}$, where ν is the index of the geometry ($\nu = 3$ for spherical symmetry and $\nu = 2$ for cylindrical symmetry). With decreasing temperature on the front of the shock wave, the region of the eddy currents producing the diamagnetic moment penetrates deeper into the shock wave, so that the distributions of the temperature and of the conductivity inside the shock wave become important. It is known (see, for example, [7, 8]) that the temperature in a shock wave is minimal on its front and increases rapidly on moving from the front to the center (or line) where the energy is released. The ratio of the temperature at each point to the temperature T_{sh} on the front of the shock wave is given by

$$\Theta = \frac{T}{T_{sh}} = F^{2\nu/(\nu+2)}\left[\frac{2\gamma}{\gamma-1}\left(F-\frac{\gamma+1}{2\gamma}\right)\right]^{-\beta_3}\left[\frac{2}{(\gamma-1)}\left(\frac{\gamma+1}{2}-F\right)\right] \times\left\{\frac{2(\nu\gamma+\nu+2)}{3\nu-2-\gamma(\nu-2)}\left[\frac{(\nu+2)(\gamma+1)}{2(\nu\gamma-\nu+2)}-F\right]\right\}^{-2\beta_1},$$

where γ is the ratio of the specific heats of the gas and F is a parameter connected with the quantity r/r_{sh} by the relation

$$\frac{r}{r_{sh}} = F^{-2/(\nu+2)}\left[\frac{2\gamma}{(\gamma-1)}\left(F-\frac{\gamma+1}{2\gamma}\right)\right]^{\beta_2} \times\left\{\frac{2(\nu\gamma-\nu+2)}{3\nu-2-\gamma(\nu-2)}\left[\frac{(\nu+2)(\gamma+1)}{2(\nu\gamma-\nu+2)}-F\right]\right\}^{-\beta_1};$$

where

$$\beta_1 = \beta_2 + \frac{\gamma+1}{\nu\gamma-\nu+2} - \frac{2}{\nu+2},$$

$$\beta_2 = \frac{\gamma-1}{2\gamma-2+\nu}, \quad \beta_3 = \frac{\nu}{2\gamma-2+\nu} = 1-2\beta_2.$$

From these relations we readily obtain

$$\Theta = \left(\frac{r}{r_{sh}}\right)^2 F^2 \frac{2}{\gamma-1}\left(\frac{\gamma+1}{2}-F\right)\Big/\left[\frac{2\gamma}{\gamma-1}\left(F-\frac{\gamma+1}{2\gamma}\right)\right]$$

from which it follows that $\Theta \gg 1$ only when $F \simeq (\gamma+1)/2\gamma$. (We recall that the parameter F varies in the range $(\gamma+1)/2\gamma \le F \le 1$.) Therefore if we are interested in the interior regions with $T \gg T_{sh}$, we obtain $\Theta(r)$ in the form

$$\Theta = \left(\frac{r}{r_{sh}}\right)^{-\nu/(\gamma-1)}\Phi(\nu,\gamma) = \frac{T}{T_{sh}(t)}.$$

The rapid growth of the temperature away from the shock wave towards the interior causes the main diamagnetic perturbation to be produced by interior regions with high temperature, since the layer of shock wave is not only cooler and has a small conductivity, but also is thin, $\delta_{sh} \approx r_{sh}(\gamma-1)/3(\gamma+1)$, and this ensures a high rate of diffusion of the magnetic field through this layer and from it

$$v_H \approx c^2/4\pi\sigma(T_{sh})\delta_{sh}.$$

Let us estimate the radius r_H of the front of penetration of the magnetic field inside the hot layers, by equating the radial velocity $v_r = \dot{r}_{sh} r/r_{sh}$ to the rate of penetration of the magnetic field[1]:

$$v_H \approx c^2/4\pi\sigma(T)\delta_{eff}, \qquad \delta_{eff} \approx \sigma/\sigma_r' = 2T/3T_r' = Kr.$$

We shall assume that the substance is sufficiently heated so that the conductivity is given by $\sigma(T) \approx AT^{3/2}/Z_{eff}$, where $A = k^{3/2}/m_e^{1/2}\pi e^2 \ln\Lambda$ and Z_{eff} is the effective ion charge. Using the well known expression

$$T_{sh} = \frac{8m_i(\gamma-1)}{(Z+1)k(\nu+2)^2(\gamma+1)^2}\left(\frac{E}{\rho}\right)r_{sh}^{-\nu},$$

where m is the mass of the atom, we obtain for the radius of the front of the magnetic field

$$r_H \approx B(\nu,\gamma)\left\{\frac{m_i^3}{Z^2(Z+1)^3}\left(\frac{E}{\rho}\right)^4\right\}^{(\gamma-1)/a} r_{sh}^{-b/a},$$

$$a = 4+3\nu-4\gamma, \quad b = 4\gamma\nu+2\gamma-7\nu-2.$$

The effective magnetic moment is

$$M \approx -r_H^{\nu}H_0 \sim \left\{\frac{m^3}{Z^2(Z+1)^3}\left(\frac{E}{\rho}\right)^4\right\}^{\nu(\gamma-1)/a} r_{sh}^{-\nu b/a}.$$

Using the experimentally established long lifetime of the magnetic moment $\dot{M}(t) \approx 0$, we find, in view of the time variation of $r_{sh}(t)$, that the exponent of r_{sh} is close to zero, i.e., $4\nu\gamma + 2\gamma - 7\nu - 2 = 0$. For example, for $\nu = 3$ we obtain $\gamma = 23/14 = 1.64$ and for $\nu = 2$ we obtain $\gamma = 8/5 = 1.6$, which are quite close to the value of γ for an ideal gas, $\gamma = 5/3 = 1.66$. But this is precisely the exponent possessed by high-temperature gases. Consequently, in the case of high-temperature explosions, r_H and M depend extremely little on r_{sh}, i.e., on the time, since the exponent in the relation $M \sim M_0 r_{sh}^{s}(t)$ is very close to zero. This explains the experimentally observed long lifetime of the diamagnetic moment, confirming the high-temperature character of the light-spark process, as noted in [9].

We note that high-temperature values of γ can occur also in those cases when the temperature is lower than the energy of the next excitation level (at a large distance to the next level), or in those cases when there is no time for recombination of the plasma or for ionization of the upper levels of the atoms (rapid expansion).

Using the coefficient in front of r_{sh}^{s}, we can obtain the dependence of this diamagnetic moment on the properties of the medium and on the energy release:

$$M_0 = B(\nu,\gamma)\left\{\frac{m^3}{Z^2(Z+1)^3}\left(\frac{E}{\rho}\right)^4\right\}^{\nu(\gamma-1)/a}.$$

For example, for $\nu = 3$ we obtain

$$M_0 \approx \left\{\frac{m^3}{Z^2(Z+1)^3}\left(\frac{E}{\rho}\right)^4\right\}^{3(\gamma-1)/(13-4\gamma)} \sim \frac{m^{18/19}}{Z^{12/19}(Z+1)^{18/19}}\left(\frac{E}{\rho}\right)^{24/19} \sim m\left(\frac{E_0}{\rho}\right)^{1.26}$$

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1) It is easy to see that in the case of an abrupt temperature distribution behind the shock wave the main perturbation of the magnetic field is connected, in accordance with the theory of strong explosions, with the minimal radius on which the external magnetic field changes strongly (the main contribution to the magnetic moment is made by the small radius of the region of integration of the magnetic moments of the currents). For any other distribution of velocities and temperatures, this may not be satisfied and the main moment may be produced by the entire volume in which the current is distributed.

at $\gamma \approx {}^5/_3$ and $Z \approx 1$. This describes sufficiently well the experimental results of the first section of the article, in which a relation of the type $M_0 \sim (E/\rho)^{1.2}$ was obtained for most gases and data are given for M_0 of two isotopes—hydrogen and deuterium: at the same E/ρ ratios the result obtained was $M_D = 2M_H$ (in this case γ can be assumed to be the same and the ratio of the absolute magnitudes can be taken).

It follows also from the described picture of the process that at some instant of time the pressure of the plasma in the expulsion region becomes commensurate with the pressure of the magnetic field $p_H \approx H^2/8\pi$. This instant of time can be estimated in simple fashion in view of the independence of the pressure p of the coordinates inside the shock wave: $p = E/4r_{sh}^3(t) \sim p_H$, hence $r_{sh.cr}^3 \sim E_0/H^2$ or $t_{cr} \sim E^{1/3}\rho^{1/2}/H^{5/3}$. After this instant of time the magnetic field exerts a strong influence on a transverse motion of the central part of the plasma with $r < r_H$. (We note that this occurs when the internal pressure becomes commensurate with the magnetic pressure, since the pressure of the thrust of the plasma motion is much smaller than pressure inside the plasma: $\rho u^2 \ll p$. Indeed, $\rho u^2 \ll \rho_{sh}\dot{r}_{sh}^2 \approx p_{sh} \approx p$.)

The slowing down of the expansion and the stopping of the plasma can accelerate the penetration of the magnetic field, i.e., the time of vanishing of the diamagnetic moment may depend on the external magnetic field. Although the vanishing of the diamagnetic moment can be due to weakening of the shock wave (when the condition $p_{sh} \gg p_{atm}(\gamma + 1)/(\gamma - 1)$ is not satisfied, the shock wave ceases to be strong), or to losses (to radiation, heat conduction), it is always possible to choose the magnetic field strong enough to make its role in the vanishing of the magnetic moment decisive. For example, at $H \approx 3 \times 10^4$ Oe the magnetic pressure is $p_H \approx H^2/8\pi \sim 30$ atm and at such pressures the shock wave can still be regarded as strong (i.e., the magnetic pressure stops the transverse motion of the internal plasma before the wave ceases to be strong, and for extimates we can use the solution of the strong shock wave).

The other possible mechanism of suppressing the magnetic moment by a magnetic field, by magnetizing the conductivity at $\omega_H \sim \nu_s$, calls for much stronger fields or temperatures, for in this case the plasma phenomena occur at high concentrations and pressures (indeed, since $\omega_H = eH/mc$ and $\nu = n_i A/(kT)^{3/2}$, we obtain magnetization at $n_i \leq n_{i.cr} \approx 3 \times 10^{11}\, H/T^{3/2}[eV] \approx 10^{16}/T^{3/2}[eV]$, whereas $n_i > n_{i.isobar} \approx 3 \times 10^{19} \times 3 \times 10^{-2}/T\,[eV] \sim 10^{18}/T\,[eV]$. Thus, in the region of interest to us $n_i \gg n_{i.cr}$ and there is no magnetization.)

Knowledge of the time variation of the magnetic moment is important for knowledge of the inductive processes occurring near the perturbation region, for the investigation of the radio emission $E_{wave} \approx n \times \ddot{M}/c^2R_0$, of the strong action exerted on the plasma by inhomogeneous magnetic fields $F \approx M(t)\partial H/\partial z$, etc.

4. "FIREBALL" OF LIGHT SPARK

It was observed in [4, 10] that the glowing high-temperature region becomes detached from the shock wave, and the stage of the so-called "fireball" was investigated. We shall use the expression for the temperature distribution in the shock wave to determine the motion of the boundary of the region of the strong glow. Let us assume that this region is determined by the condition $T = T_{glow}$. Then the $r_{glow}(t)$ dependence is obtained from

$$r_{glow}/r_{sh} = (\Phi T_{sh}/T_{glow})^{(\gamma-1)/\nu}.$$

Substituting the expression for $T_{sh}(r_{sh})$, we obtain

$$r_{glow} = \left(\frac{\Phi m E}{T_{glow} k\rho}\right)^{(\gamma-1)/\nu} r_{sh}^{1-3(\gamma-1)/\nu} \sim \left(\frac{E}{\rho}\right)^{(2\gamma-2+\nu)/5\nu} t^{2(\nu-3\gamma+3)/5\nu},$$

For example, for $\nu = 3$ we have

$$r_{glow} \approx \left(\frac{E}{\rho}\right)^{(2\gamma+1)/15} t^{2(2-\gamma)/5}.$$

The instant at which the detachment of the boundary of the "fireball" from the shock wave is observed can be determined by putting $r_{glow}/r_{sh} = \alpha$ or by specifying a distinguishable jump $r_{sh} - r_{glow} = \Delta r_{det}$. For example, in the former case the temperature of the shock wave at the instant of detachment is given by

$$T_{sh}(t_{det}) \approx \alpha^{\nu/(\gamma-1)} T_{glow}/\Phi,$$

i.e., we can have $T_{sh}(t_{det}) \ll T_{glow}$. Thus, the time in which the detachment is registered exceeds by several times the time when $T_{sh} = T_{glow}$. This indeed was registered in [4, 10]. (This can be easily verified by comparing the time necessary to register the detachment with the time of cooling of the shock-wave front.)

It should be noted that in the employed shock-wave models it was assumed that the thermal conductivity processes play a minor role, i.e., it was assumed that the change of the temperature in each region of the medium behind the shock wave is determined mainly by the adiabatic expansion and not by the influx of heat from the hotter layers. However, for small dimensions and not too high temperatures (the initial stage, large energy inputs, small densities) the time of heat equalization r^2/κ_e may be commensurate with the time of the process, since at high temperatures the electronic temperature conductivity $\kappa_e \approx T_e^{5/2}/Zn_i$ can be sufficiently large even at high densities. In the case $r^2 \approx \kappa_e t$ we can use for the shock wave a solution with zero temperature gradient,[8] for which a region of gas at rest near the center up to $r_* = \sqrt{\theta_2} r_{sh}$ is characteristic and for $r > r_*$ the gas velocity changes in a nearly linear manner: $v(r) \approx v_{sh}(t)(r - r_*)/(r_{sh} - r_*)$ ($\theta_2 = 0.244$ for $\nu = 3$ and $\theta_2 = 0.240$ for $\nu = 2$). In this case, the estimate of the diamagnetic perturbation becomes simpler, since the conductivity $\sigma = AT^{3/2}$ depends only on the time and does not depend on the coordinates. The temperature is in this case

$$T(t) = \frac{4\theta_2 m_i}{k(\nu+2)^2}\left(\frac{E}{\rho}\right)^{2/(\nu+2)} t^{-2\nu/(\nu+2)}$$

and when the strong-perturbation condition $\dot{r}_{sh} > v_H$ is satisfied, we obtain

$$M \sim r_{sh}^{\nu} \sim (E/\rho)^{\nu/(\nu+2)} t^{2\nu/(\nu+2)}.$$

In the case when the magnetic field has time to penetrate to the interior

$$M \sim \sigma \int_{r_*}^{r_\gamma} r^{\nu} v\, dr \sim \sigma r_{sh}^{\nu+1} v_{\gamma},$$

i.e.,

$$M \sim \left(\frac{E}{\rho}\right)^{(5+\nu)/(\nu+2)} t^{-(2\nu-2)/(\nu+2)}.$$

In the intermediate case, when the temperature conductivity is significant only for a very hot zone whose dimensions are commensurate with or exceed r_H—the region of repulsion of the field in a model of a shock wave without thermal conductivity, the model considered in [5] is valid.

In the case of rapid expansion of the spark plasma, we can expect non-equilibrium or long-lived ionization to last for a prolonged time (the recombination regime was investigated for a light spark in hydrogen in [11]). Plasma trails due to light sparks and ionization aureoles were investigated in [12, 13]. We note that the effects considered above can become manifest also under geophysical conditions, such as lightning flashes, meteor explosions, and other high-temperature processes.

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