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Light Flash from a Stron Shock Wave of a Laser Spark. The Effect of a Strong External Magnetic Field

G. A. ASKAR'YAN, S. D. KAĬTMAZOV, AND A. A. MEDVEDEV

P. N. Lebedev Physics Institute, Academy of Sciences, USSR

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Experiments with a visible light flash from a laser spark are described. The time variation of the light intensity is investigated. It is shown that a strong magnetic field (up to 200 kOe) does not affect the leading edge of the light pulse but does affect the trailing edge, increasing the luminous energy by a factor of 1.4. A theory of visible emission of a strong shock wave from the light spark is given and it is demonstrated that a stage of the process exists in which the shock wave compression layer can be regarded as a black body for the observed visible light. The buildup dynamics and the duration of the emission are evaluated and the dependence on the emission of the strong magnetic field inducing the vortex fields that heat the shock wave plasma is also considered.

INTRODUCTION

THE laser spark, or the optical breakdown of a medium in the laser focus, has been the subject of numerous papers (see for example[1-4] or reviews[5,6]). The main laser-spark property that attracts many researchers is the opportunity to study and apply high-temperature phenomena[7,8,9] in concentrated explosive liberation of energy. The laser spark is accompanied by a blinding flash of light in the visible region of the spectrum as well as in other regions ranging from infrared to hard ultraviolet and x-ray[10], forming a gas ionization halo around the spark[11]. The high light intensity and the width of the spectrum are due to the high temperature of the process and the high plasma density in the shock wave.

The present work reports on experiments performed to study the time dependence of the light flash from the spark, the effect of a strong magnetic field (up to 200 kOe) on the spark luminescence, and provides an explanation of the luminescence and of the mechanism whereby the magnetic field affects the light flash from the spark (the first brief report on this effect was published in[12] and later in[13]).

1. THE EXPERIMENT

To obtain the light spark we used a neodymium laser Q-switched by a rotating prism. The laser produced a 1—1.5 J pulse 30—40 nsec at the half-width and 100 nsec at the base (duration of total energy input). The spark was formed by focusing the beam with a ~5.2 cm lens within a space filled with air or other gas under normal or reduced pressure. The light flash in the visible range was recorded with a coaxial photocell connected to an I2-7 interval timer (for time measurement of the light pulse), or via an integrating circuit to a DEO-1 oscilloscope (for measurement of total energy of luminescence). To evaluate the effect of a strong magnetic field on the spark light we used a magnetic field up to 200 kOe generated by Bitter coils receiving the discharge 3000 μF capacitor bank at 5 kV within 50 μsec. The diameter of the solenoid working cavity was 0.8 cm and its length was 1 cm, so that an angle up to 100° was subtended.

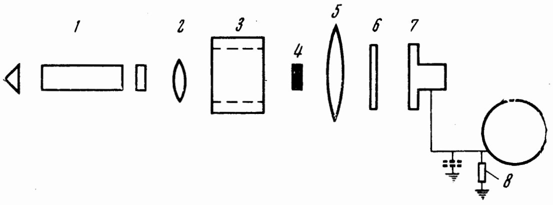

FIG. 1

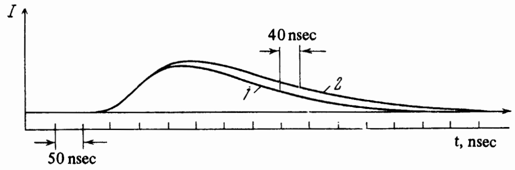

FIG. 2

Observations were performed along the solenoid axis, which coincided with that of the laser beam. Figure 1 shows the experimental setup. After laser beam (1) was focused with lens (2), the beam passed through solenoid (3) and was prevented by small disc (4) from reaching coaxial photocell (7). The light from the spark was collected by lens (5) with a focal length of ~13 cm. SZS optical filter (6) removed the scattered laser light. The signal was fed across input resistor (8) to oscilloscope((9).

We measured flashes from many sparks and averaged the resulting data, a measure necessitated by fluctuations in the spark geometry, absorbed energy, and location. The effect of the magnetic field on pulse amplitude was analyzed by statistical reduction of the results of repeated measurements (50 out of 100 sparks were produced in a magnetic field.) It turned out that a 200-kOe field affects significantly the light from the spark.

Figure 2 shows a time-averaged spark light pulse in time with (2) and without (1) the magnetic field. It is apparent that the luminescence rise time is comparable to the energy release time of 100 nsec and that the rise time is totally unaffected by a magnetic field of this intensity. The luminescence duration at one-half amplitude is about 320 nsec and increases to 360 nsec when the magnetic field is turned on. A comparison of the areas under both curves yielded a ratio $S_H/S_0 \approx 1.3$. Measurement of the integral of the light flash also reflected the effect of the magnetic field: the pulse proportional to the total light energy increased 1.4 times in the presence of magnetic field if the spark occurred in gas under atmospheric pressure, and 1.6 times if the gas pressure was ≈0.3 atm[12].

2. THEORY OF SPARK SHOCK WAVE LUMINESCENCE. EXPLANATION OF THE MAGNETIC FIELD EFFECT

The main initial light flash from a laser spark, whose power exceeds many times that of the subsequent afterglow is only of the order of several hundred nsec for a ≈ 1 J laser pulse and energy input duration of ~100 nsec. The luminescence has a continuous spectrum with superimposed lines of scattered laser emission of and ionic and atomic transitions[14]. We are mainly interested in the continuous emission spectrum bearing the bulk of the energy detected by a broadband energy receiver. The continuous spectrum may be due to various emission mechanisms. Our analysis showed that such emission in the visible region of $\hbar\omega = 1.3$ eV is due to the emission from the shock-wave compression layer, which can be regarded as a "black body" for this spectral region because of the very high concentrations of plasma in the compression layer and because the temperature is minimal on the shock front (the temperature increases rapidly and the plasma density falls off behind the compression layer within the shock wave, i.e., the quantum absorption length l_a sharply increases).

Indeed, the depth of absorption of a quantum with $\hbar\omega \ll kT$ in the plasma is $l_a \approx \omega^2 c/\omega_p^2 \nu_s$, when the frequency of the absorbed light is $\omega \gtrsim \nu_s$ where $\nu_s \approx 30Z^2 n_i/T^{3/2}$ is the collision frequency, i.e., $l_a \approx \omega^2 T^{3/2}/3Z^3 n_i^2$. But it is just in the compression layer at the shock front that the concentration is maximal, $n_{is} \approx n_{i0}(\gamma + 1)/(\gamma - 1)$, where γ is the effective adiabatic exponent[15] ($\gamma \approx 1.24$ under conditions of interest). This means that the quantum absorption length is minimal in the compression layer. For the values $\omega \lesssim 10^{16}\ \mathrm{sec}^{-1}$, $n_{is} \approx 2 \times 10^{20}$ ion/cm^3, $Z_{eff} \approx 3 - 10$, and $T_s \lesssim 3 - 30$ eV, we obtain $l_a \lesssim 10^{-3} - 10^{-4}$ cm, while the width of the compression layer $\Delta R_s \approx \frac{1}{2}(\gamma - 1)R_s/(\gamma + 1) \approx 0.1\ R_s$ is many times larger, i.e., the "black body" stage occurs within a broad time range, except for the initial stage itself. The time t of the beginning of the black-body stage is determined by the relation $l_a(t_1) \approx \Delta R(t_1)$. We note that the blackness of the compression layer increases still further in directions inclined to the normal to the shock wave surface.[1]

Thus the spark emission in the visible range is similar to the black body radiation at the shock wave temperature, i.e., in the spectral interval $\Delta\omega$

$$\Delta W_\omega \approx S_s \frac{\hbar\omega^3}{4\pi^3 c^2} \frac{\Delta\omega}{e^{\hbar\omega/kT} - 1},$$

where $S_s(t)$ is the surface of the shock wave. For example for $\hbar\omega/kT_s \ll 1$

$$\Delta W_\omega \approx S_s \omega^2 k T_s \Delta\omega / 4\pi^3 c^2 \sim S_s T_s.$$

The radius and temperature of the shock wave for non-instantaneous energy emission can be determined from the theory of Drabkina[16] for a specified effective specific plasma energy $u = A\rho^a T^b$, from which we determine the pressure $p = (\gamma - 1)u\rho$ and

$$T^b = \frac{p\rho^{-(a+1)}}{(\gamma - 1)A}, \quad \gamma = \frac{1 - a}{b - 1}$$

($b \approx 1.55$ and $a \approx -0.12$ for the temperatures of interest). The radius of a cylindrical shock wave then is

$$R \approx \left(\frac{\alpha}{\rho_0}\right)^{1/4} \left[\int_0^t Q_1^{1/2}\, dt\right]^{1/2}$$

and

$$p = \frac{(\alpha\rho_0)^{1/2}}{2(\gamma + 1)} Q_1 \Big/ \int_0^t Q_1^{1/2}\, dt \approx \frac{Q_1(t)}{R^2},$$

where $T \sim p^{1/b}$ and where $b \approx 3/2$, which corresponds in our case to $Z_{eff} \sim T^{0.5}$ (i.e., the condition determining Z_{eff} is $I_1 Z_{eff}^2 \sim kT$). In all cases

$$Q_1 = \int_0^t \dot{Q}_1\, dt$$

is the running energy release and ρ_0 is the initial gas density.

For example for small t, assuming a power $\dot{Q} \sim t^m$ (we recall the energy emission front can differ from the front of the light pulse), we obtain

$$W \sim R_s T \sim \frac{Q^{2/3}}{R^{1/3}} \sim Q^{2/3} \Big/ \left[\int Q^{1/2}\, dt\right]^{1/6} \sim t^{(7m+5)/12}.$$

However, it follows from Fig. 2 that the rising front of the luminescence is nearly linear, so that $m \approx 1$, i.e., the energy-release power increases nearly linearly. The function

$$\dot{Q} \approx \dot{Q}_0 (t/\tau) \exp\left[-(t/\tau)^2\right]$$

or

$$Q(t) \approx \dot{Q}_0 \tau \{1 - \exp\left[-(t/\tau)^2\right]\},$$

$$R_s \approx \left(\frac{\dot{Q}_0 \tau}{\rho_0 l}\right)^{1/4} \left[\int_0^t (1 - \exp[-(t/\tau)^2])^{1/2}\, dt\right]^{1/2},$$

where l is the length of energy emission region, seems adequate for extrapolation.

After energy emission is terminated, we have at first

$$\Delta W_\omega \sim R_s^{-1/3} \sim t^{-1/6}$$

or for $\hbar\omega \gtrsim kT$

$$\Delta W_\omega \sim t^{1/2} \exp\{-\hbar\omega / kT(t)\},$$

where $T(t) \sim t^{-2/3}$. At lower temperatures the emission decreases exponentially, the shock wave glow dimishes, and the shock wave breaks away[14] from the luminous fireball.

We estimate the order of magnitude of the critical instants of time. Assuming that

$$\dot{Q}_1 \approx \dot{Q}_{10} t / \tau \approx Q_m t / \tau^2 l,$$

we obtain

$$R_s(t) \approx (Q_m / \rho_0 l \tau^2)^{1/4} t, \quad \Delta R \approx 0{,}1R.$$

Whereas $Z(T) \approx (kT/I_1)^{1/2} \sim T^{1/2}$, the quantity $l_a \sim T^{3/2}/Z^3$, i.e., it does not depend on the temperature

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[1] The surface localization of the optical effects under consideration implies insensitivity of the above description to the thermal regime within the shock wave.

and consequently on the time. Therefore the condition $l_a \approx \Delta R$ yields

$$t_1 = \frac{3\omega^2}{n_i^2}\left(\frac{I_1}{k}\right)^{3/2}\left(\frac{\rho_0 l\tau^2}{Q_m}\right)^{1/4} \approx 10 \text{ nsec}$$

for $Q_m \sim 1$ J and $\tau \sim 50$ nsec, i.e., the "black body" stage begins early for the visible spectral region.

The time t_2 of the beginning of the exponential drop of the black-body emission is determined from the condition $\hbar\omega \approx kT_s(t_2)$. Since $kT_s \approx Q_m / V_s Z_{eff} n_{is}$, $Z_{eff}(kT \approx \hbar\omega) \approx 1$, and

$$V_s \approx \pi R_s^2 l \approx \pi l (Q_m / \rho_0)^{1/2} t,$$

it follows that

$$t_2 \approx (Q_m \rho_0)^{1/2} / \pi\hbar\omega l n_{iy} \approx 300 \text{ нсек}$$

in accordance with experiment.

The effect of strong magnetic field on the spark glow can be due to various processes. We evaluate the fields for which the heating of the shock wave compression layer by the skin current becomes observable. They are given by the condition $0.3 n_{es} kT_s / t_{eff} \approx \sigma E^2$, i.e., the cooling rate due to expansion is comparable to the energy emission from the currents induced in the interior. Assuming that the induction field

$$E \approx vH / c \quad \text{и} \quad \sigma / T \approx AT^{1/2} \approx 10^9, \quad t_{eff} \approx 100 \text{ nsec},$$

we obtain

$$H^2 \approx 0.3 n_{ey} k c^2 T / t_{eff} v^2 \sigma \approx 10^{11} \text{ э}^2,$$

i.e., H ≈ 300 kOe in accordance with experiment.

A strong magnetic field may also possibly affect the electronic thermal conductivity of the light-spark plasma, which changes the thermal regime within the shock wave. This quenching of thermal conductivity by a strong magnetic field can be utilized to obtain high temperatures in the light spark[17].

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