

for the ionization loss. For  $\mu = 1$ , Eq. (25) gives the result of Eq. (16) in Ref. 6.

In conclusion we thank Professor A. A. Sokolov for suggesting this topic and for a discussion of our results.

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83

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## GLOW OF AIR DURING A STRONG EXPLOSION, AND THE MINIMUM BRIGHTNESS OF A FIREBALL \*

Iu. P. RAIZER

Academy of Sciences, U.S.S.R.

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The optical properties of air at temperatures below 6,000° are considered. It is shown that the radiation and absorption of visible light at temperatures between 6,000° and 2,000° is due to the nitrogen dioxide that is formed in the air at these temperatures. This affords an explanation for several optical phenomena observed in strong explosions: the glow of air in a shock wave at low temperatures (down to 2,000°), the separation of the shock-wave front from the boundary of the fireball when the temperature of the front is close to 2,000°, and the peculiar effect of minimum brightness of the fireball.

A general description of the optical effects observed during strong (atomic) explosions in air is given in an American survey.<sup>2</sup>

A shock wave propagates from the center of the explosion along a trajectory which was shown by Sedov<sup>3</sup> to satisfy, with good approximation, the self-similar law  $R \sim t^{2/5}$ .

So long as the amplitude of the wave is sufficiently large, the surface of the front of the shock wave (SWF) glows brightly, forming the so-called

fireball (FB). The brightness or the effective temperature of the FB, taken to mean the absolute temperature of a black body producing an identical radiation flux as the FB, diminishes with time as the true temperature behind the SWF decreases. At a certain instant of time,  $t_{\min}$ , which is on the order of  $10^{-2}$  sec for an explosion with energy  $E \sim 10^{21}$  ergs, the SWF stops glowing and the boundary of the glowing body separates from the wave front. The brightness of the FB now goes through a minimum, after which it increases again — the FB, so to speak, flares up again. Now the dimensions of the FB increase much slower, while

\*The work was performed in 1954. For a brief communication of the results see the review, Ref. 1.

the front of the shock wave moves far ahead. The brightness of the FB rises to a maximum at an instant  $T_{\max} \sim 10^{-1}$  sec, after which it dies down slowly, within approximately one second.

Figures 1 and 2 show schematically the dependence of the effective FB temperature on the time and on the trajectory of the SWF, and also the time dependences of the SWF trajectory,  $R_f(t)$ , and of the FB boundary trajectory,  $R_0(t)$ . The scales are based on an explosion energy  $E \sim 10^{21}$  ergs.

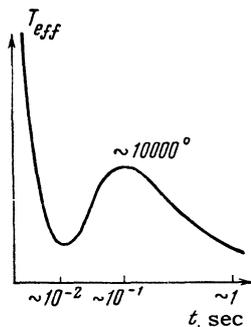


FIG. 1

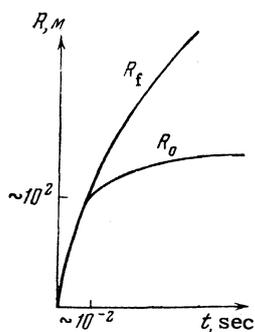


FIG. 2

The energy radiated during the explosion amounts to approximately one third of the explosion energy, and the fraction of the light radiated prior to the minimum, a time interval of one-hundredths of the total glow time, is on the order of 1%.

At temperatures above approximately  $10,000^\circ$ , the air absorbs a continuous spectrum in the visible region, principally by photoionization of the highly excited nitrogen and oxygen atoms (and molecules). The light is radiated as the result of the inverse process, photorecombination of free electrons with the ions.

Quanta of frequency  $\nu$  can be absorbed only by atoms excited to an energy  $I - h\nu$  ( $I$  is the ionization potential). The number of these atoms is proportional to the Boltzmann factor  $\exp[-(I - h\nu)/kT]$ , with  $I - h\nu \gg kT$  at  $T \sim 10,000^\circ$ . The coefficient of continuous absorption,  $\kappa_\nu$ , therefore diminishes very rapidly with decreasing temperature. Although the range of the light amounts to tens of centimeters at  $T \sim 9,000^\circ$ , it is on the order of meters at  $T \sim 8,000^\circ$ , and on the order of kilometers at approximately  $6,000^\circ$ .

At temperatures above  $\sim 9,000^\circ$ , the range of the light is less than the distances at which the temperature behind the SWF changes noticeably, on the order of meters. Therefore, when the SWF temperature is above  $9,000^\circ$ , the front radiates like an absolutely black body, and the effective

temperature coincides with the true temperature behind the SWF.\*

Cold air, as is known, is quite transparent to visible radiation, since the molecules of the nitrogen and oxygen absorb light only in the ultraviolet portion of the spectrum. Let us assume that the only light-absorption mechanism during heating is the photoionization process of the highly-excited nitrogen and oxygen atoms and molecules, a mechanism that is effective in practice above approximately  $9,000^\circ$ . This would, first, stop the SWF from glowing as soon as its temperature drops to  $\sim 9,000^\circ$ , for even at  $T \sim 5,000^\circ$  the light-emissionability would become negligible. Second, at SWF temperature below  $\sim 9,000^\circ$ , the layer of air between the front and the surface of  $\sim 9,000^\circ$  would be practically transparent to the visible light and the hotter region of air with  $T \sim 9,000^\circ$  would glow across this layer (the temperature in the explosion wave rises from the periphery to the center<sup>3</sup>). The effective temperature of the FB would therefore not fall below  $\sim 9,000^\circ$ .

Experience has shown that the air in the shock wave actually glows at temperatures down to  $\sim 2,000^\circ$ , for it is exactly at this temperature that the front becomes invisible and the boundary of the FB becomes separated from the SWF. In addition, the effective temperature of the FB diminishes to values below  $\sim 9,000^\circ$ . This is evidence that, in the temperature interval from  $\sim 9,000^\circ$  to  $2,000^\circ$ , another mechanism exists in the air for continuous absorption and radiation of visible light.

We shall discuss in this article the optical properties of the air at temperatures below  $\sim 9,000^\circ$ . It turns out that these properties are determined by the nitrogen oxides NO and NO<sub>2</sub> that are formed in the heated air.

This will lead to an explanation for the following experimentally-observed phenomena: glow of a shock wave at temperatures considerably below

\*This is true only up to  $T_f \approx 90,000^\circ$  behind the SWF. With further increase in the amplitude of the shock wave, the effective temperature diminishes rapidly to a limiting value  $T_{\text{eff}} \approx 18,000^\circ$  and is no longer dependent on the amplitude. The cause of this phenomenon, examined in detail in Ref. 4, lies in the self-screening of the SWF at high  $T_f$ , when the SWF expands through radiant heat exchange.

It must be noted that the maximum and limiting brightness temperatures observed experimentally may turn out to be lower than the values mentioned above, owing to partial absorption of light by the non-equilibrium nitrogen dioxide, which should appear in the cold air ahead of the SWF under the influence of the neutrons and the  $\gamma$  quanta.

9,000°, abrupt cessation of glow at  $T_f \sim 2,000^\circ$  and the separation of the SWF from the boundary of the FB, and the very peculiar effect of the minimum brightness and subsequent "flareup" of the FB. The kinetics of the formation of the oxides of nitrogen in the air during strong explosions, and the concentration of these oxides, were considered in an earlier work.<sup>5</sup>

## 1. METHOD OF COMPUTING THE EFFECTIVE RADIATION TEMPERATURE

We are interested in the region of minimum brightness, i.e., that stage of the explosion, in which the temperature of the SWF is still sufficiently high, above  $\sim 1,500^\circ$ , and the shock wave is strong. Only a small fraction of the total explosion energy is radiated at this stage, and therefore the hydrodynamics of the shock wave can be described with sufficient accuracy by the self-similar solution of Sedov<sup>3</sup> with a certain effective adiabatic exponent  $\gamma$  (Ref. 5).

In the center, when the temperatures are very high, on the order of 100,000°, the self-similar solution naturally no longer conforms to reality, for in this region the temperature profile becomes equalized by radiant heat exchange. Nevertheless, this does not affect in practice the distribution of the hydrodynamic quantities in the external layers of the wave, the only distribution of importance when considering the brightness of the FB.

The thickness of the radiating layer near the surface of the FB is considerably smaller than the radius of the FB, which is on the order of hundreds of meters, and the radiating layer can therefore be considered plane.

It is easy to derive a general formula for the radiation flux from the surface of a heated body, at a frequency  $\nu$ , by integrating the sources of light along the ray at a certain angle to the normal, with allowance for the absorption along the path, and then integrating the resultant expression over the angles. This gives the well-known expression for the spectral brightness<sup>6</sup>

$$S_\nu = 2 \int_0^\infty B_\nu(T) E_2(\tau_\nu) d\tau_\nu, \quad (1)$$

where

$$E_2(\tau_\nu) = \int_1^\infty e^{-\tau_\nu z} \frac{dz}{z^2}; \quad (2)$$

$B_\nu(T)$  is the Planck radiation flux at frequency  $\nu$ , emitted from the surface of an absolutely black body,

$$B_\nu(T) = \frac{2\pi h}{c^2} \frac{\nu^3}{e^{h\nu/kT} - 1}; \quad (3)$$

$\tau_\nu$  is the optical thickness for radiation at a frequency  $\nu$ , measured inward from the surface of the SWF

$$\tau_\nu = \int_0^x \kappa_\nu dx, \quad (4)$$

$x$  is the radial distance, also measured inward from the surface of the SWF, and  $\kappa_\nu$  is the absorption coefficient, corrected for the forced emission, and equal to the reciprocal of the range of the light,  $\kappa_\nu = 1/l_\nu$ . The effective temperature of radiation at a frequency  $\nu$  is determined from the obvious formula

$$B_\nu(T_{\text{eff}}) = 2 \int_0^\infty B_\nu(T) E_2(\tau_\nu) d\tau_\nu. \quad (5)$$

Knowing the temperature profile  $T(x)$  behind the SWF and the light absorption coefficient  $\kappa_\nu(x)$  at any point, it is possible to calculate the effective temperature of radiation from Eqs. (5), (3), and (4).

To be specific, all further calculations will be referred to the red line  $\lambda = 6500 \text{ \AA}$  ( $h\nu = 1.91 \text{ eV}$ ).

The temperature and density distributions behind the SWF will be taken from Sedov's self-similar solution with effective adiabatic exponents  $\gamma = 1.23$  at  $T_f > 3,000^\circ$  and  $\gamma = 1.27$  at  $T_f < 3,000^\circ$  (see Ref. 5). If the temperature changes little in the radiating layer behind the SWF, i.e., in the layer that gives the principal contribution to the integral (5) (its optical thickness is on the order of unity), then we can put in (5)  $B_\nu(T) \approx B_\nu(T_f) = \text{const.}$  This yields, as expected,  $T_{\text{eff}} \approx T_f$ .

## 2. TYPICAL PROPERTIES OF AIR ABOVE 6,000°

To calculate the coefficient of absorption of red light by photoionization of the highly-excited atoms and molecules, let us employ the well-known Kramers formula for hydrogenlike atoms.<sup>6</sup> This formula takes also into account the absorption by free electrons in the field of the ions (which is considerably less than the photoionization at  $\sim 10,000^\circ$ ). After inserting the constants, the Kramers formula becomes (for the red line)

$$\kappa_\nu = 1.48 T^\circ \eta (e^{h\nu/kT} - 1) \sum_i c_i e^{-I_i/kT} \text{ cm}^{-1}. \quad (6)$$

Here  $\eta$  is the compression, i.e., the ratio of the

air density  $\rho$  to the normal density  $\rho_0 = 1.25 \times 10^{-3} \text{ g/cm}^3$ ,  $c_i = n_i/n_0\eta$  is the concentration of particles of the  $i$ -th kind ( $n_i$  is the number of particles per  $\text{cm}^3$  and  $n_0 = 2.67 \times 10^{19} \text{ cm}^{-3}$  is the number of molecules per  $\text{cm}^3$  of air under standard conditions),  $I_i$  are the ionization potentials ( $I_O = 13.6 \text{ ev}$ ,  $I_N = 14.5 \text{ ev}$ ,  $I_{O_2} = 12.5 \text{ ev}$ ,  $I_{N_2} = 15.5 \text{ ev}$ ). The effective charge of the atomic remnant, which is proportional to  $\sqrt{\kappa_\nu}$ , is taken to be 2.5 (Ref. 6).

Some doubt may be raised by the application of the Kramers formula to nonhydrogenlike atoms, and particularly to molecules. One must bear in mind, however, that red light with  $h\nu = 1.91 \text{ ev}$  is absorbed only by electrons that are at very high levels, moving in a field close to the Coulomb field. In addition, as will be shown below, the quantities that are of interest from the point of view of calculating the effective temperature depend only logarithmically on the factor of the exponential in formula (6). On the other hand, the fundamental (Boltzmann) temperature dependence of the absorption is unconditionally correct also for nonhydrogenlike atoms and for molecules.

At temperatures below  $\sim 12,000^\circ$  and at high compressions, such as prevail near the SWF, the nitrous oxide NO, which is formed in heated air, makes a substantial contribution to the sum (6). In spite of its small concentration (on the order of several percent, see Ref. 5), the absorption of the oxide is large, for it has a considerably lower ionization potential,  $I_{NO} = 9.4 \text{ ev}$ .\*

Table I gives the values of  $\kappa_\nu$  for different temperatures and for two values of compression,  $\eta = 10$  and  $\eta = 1$ . The table lists also the partial absorption coefficient  $\kappa_\nu \text{ NO}$ . At temperatures below  $\sim 9,000^\circ$ , practically the entire absorption is due to the nitrous oxide.

The limiting temperature, for the mechanism of light absorption considered here, must be taken to mean that temperature at which the range becomes on the order of a meter, i.e., on the order of the characteristic dimensions, at which the temperature changes noticeably in the shock wave. The nitrous oxide reduces this limit from  $\sim 9,000^\circ$  to  $\sim 6,000^\circ$ . It is to this temperature,  $T_f \approx 6,000^\circ$ , that the SWF radiates as a black body,  $T_{\text{eff}} \approx T_f$ .

If, when calculating the effective temperature of the FB for the instants of time when the temperature of the SWF is considerably lower than  $6,000^\circ$ , we break up the integral (5) into two parts, one for outer colder layer of air,  $0 < \tau_\nu < \tau_\nu^*$  ( $0 < x < x^*$ ) with a temperature  $T_f < T < 6,000^\circ$ , and one for the inner, hotter region with  $T > 6,000^\circ$ , then the integral can be written

$$B_\nu(T_{\text{eff}}) = 2 \int_0^{\tau_\nu^*} B_\nu(T) E_2(\tau_\nu) d\tau_\nu + B_\nu(T^*) E_3(\tau_\nu^*), \quad (7)$$

where  $T^*$  is certain effective temperature of the radiation leaving the surface that bounds the inner, hotter region. This temperature, thanks to the exponential dependence of  $\kappa_\nu$  on  $T$ , depends only logarithmically on the density and on the value of the factor ahead of the exponent in the Kramers

TABLE I

| $T^\circ$ | $\eta = 1$                    |  | $\eta = 10$                   |  |
|-----------|-------------------------------|--|-------------------------------|--|
|           | $\kappa_\nu, \text{ cm}^{-1}$ | $\kappa_\nu \text{ NO}, \text{ cm}^{-1}$ | $\kappa_\nu, \text{ cm}^{-1}$ | $\kappa_\nu \text{ NO}, \text{ cm}^{-1}$ |
| 5000      |                               |  | $2.64 \cdot 10^{-4}$          | $2.64 \cdot 10^{-4}$                     |
| 6000      | $2.65 \cdot 10^{-4}$          | $2.65 \cdot 10^{-4}$                     | $5.74 \cdot 10^{-3}$          | $5.7 \cdot 10^{-3}$                      |
| 8000      | $6.5 \cdot 10^{-3}$           | $6 \cdot 10^{-3}$                        | 0.17                          | 0.17                                     |
| 10000     | $4.6 \cdot 10^{-2}$           | $2.7 \cdot 10^{-2}$                      | 1.19                          | 1.0                                      |
| 12000     | 0.31                          | $5 \cdot 10^{-2}$                        | 5.4                           | 2.6                                      |

\*The values of the coefficient of absorption of red light behind the SWF in air, measured by Model' (Ref. 7) at two values of  $T_f$ , can be viewed as experimental evidence that absorption of light is essentially due to precisely the nitrous oxide. The oxygen and the nitrogen would give a considerably greater difference in the values of  $\kappa_\nu$  than was obtained experimentally. A quantitative comparison of the experimental values of  $\kappa_\nu$  with the theoretical ones is difficult, owing to the fact that the temperature is not known accurately. Apparently, the value  $\kappa_\nu = 3.7 \text{ cm}^{-1}$  must pertain not to the temperature of  $10,900^\circ$  as measured by the brightness, but to the temperature  $T_f = 11,500^\circ$ , calculated from the wave velocity  $8.05 \text{ km/sec}$  with the aid of the shock adiabatic.

formula (as already noted above, this circumstance indeed makes possible the use of this formula).

The temperature  $T^*$  has a rather narrow range from  $\sim 7,000$  to  $\sim 9,000^\circ$ , increasing somewhat with decreasing density.

### 3. OPTICAL PROPERTIES OF THE AIR BELOW $6,000^\circ$

Let us formulate the fundamental requirements that must be satisfied by the sought mechanism of light absorption, in order that it be usable for the

explanation of the following experimental facts:

(1) The absorption (and radiation) spectrum should be practically continuous in the visible region.

(2) The absorption and radiation should cease abruptly at a temperature of  $\sim 2,000^\circ$ .

(3) In the temperature range from  $\sim 6,000$  to  $2,000^\circ$ , the absorption should lead to a range of light on the order of meters. In fact, if  $l_\nu$  is much less than a meter, then a layer with temperature  $\sim 6,000 - 2,000^\circ$  will not shield to a sufficient extent the low-temperature radiation  $T^*$ . If, on the other hand,  $l_\nu$  is much less than a meter, then the layer will be quite opaque, and the effective temperature, reaching a minimum, cannot increase noticeably.

(4) For the same reason, the temperature dependence of the absorption cannot be greater than the Boltzmann value  $\kappa_\nu \sim \exp(-W/kT)$  with  $W \gg kT$ , since the range would change very strongly in the above temperature range.

Let us consider the possible mechanisms for the absorption of light at temperatures below  $6,000^\circ$ .

At low temperatures, the negative oxygen ions formed are either atomic, with binding energy  $\epsilon \approx 2.2$  ev, or molecular, with  $\epsilon \approx 1$  ev. These ions are due essentially to the transfer of electrons from the NO molecules to the oxygen, since NO has the very lowest ionization potential. The oxygen ions absorb the visible light, causing detachment of an additional electron. Calculation of the ion concentration in accordance with the Sach formula from known<sup>5</sup> concentrations of O, O<sub>2</sub>, and NO shows that the ion concentration depends on the temperature in accordance with the Boltzmann equation, with the high energy  $W \approx 3.6$  ev.

In addition, an estimate of the absolute value of the absorption coefficient, with the aid of known data on the absorption cross-section<sup>8</sup>  $\sigma_0^- \approx 2.5 \times 10^{-18}$  cm<sup>2</sup>, shows that the ions can produce a noticeable effect only at high temperatures, above  $5,000^\circ$ .

Being transparent to the visible light, the oxygen, nitrogen, and nitrous-oxide molecules that remain in the electronic ground state at ordinary temperatures absorb, as is known, only the ultraviolet radiation. At high temperatures, the absorption spectra of the molecules shift towards the red side, since the smaller quanta can be absorbed by the molecules in which oscillations are excited.

A detailed investigation of the possible transitions, using the potential-curve schemes of various electronic states of the O<sub>2</sub>, N<sub>2</sub>, and NO mole-

cules of Refs. 9 and 10, shows noticeable absorption of the red light calls for high excitation, i.e., the coefficient of absorption is proportional to the Boltzmann factor with a high energy  $W$ .

An estimate of the absorption cross-section is evidence that, as in the case of negative oxygen ions, this mechanism gives a certain effect only at temperatures above  $\sim 5,000^\circ$ .\*

The most probable is the hypothesis that the light is absorbed by the nitrogen dioxide, which forms in air at temperatures  $\sim 6,000 - 2,000^\circ$  in quantities on the order of  $10^{-2}\%$  (Ref. 5).

Deferring the experimental confirmation of this hypothesis to the next section, let us consider the optical properties of nitrogen dioxide.

Cold nitrogen dioxide is an opaque gas, whose brownish-red color is due primarily to the absorption of light in the blue portion of the spectrum. The molecular bands, which form a complex system, are so closely adjacent, that they give a practically continuous absorption spectrum. The dependence of the absorption cross-section on the frequency in the visible portion of the spectrum was investigated by many authors; the most complete data were obtained by Dixon<sup>12</sup> who measured the absorption from  $\lambda \approx 4,000$  A ( $h\nu \approx 3.1$  ev) to  $\lambda \approx 7,000$  A ( $h\nu \approx 1.78$  ev).

The cross-section diminishes monotonically in this interval from  $\sigma \approx 6.5 \times 10^{-19}$  cm<sup>2</sup> to  $\sigma \approx 10^{-20}$  cm<sup>2</sup>. According to Harris and King,<sup>13</sup> the absorption in the infrared region is very small —  $\sigma < 4.5 \times 10^{-23}$  cm<sup>2</sup> at  $\lambda \approx 10^{-4}$  A. From the Dixon curve it is seen that the cross-section approaches a maximum at  $\lambda \sim 4,000$  A. This is also confirmed by the indication that the cross-section passes through a minimum at  $\lambda \approx 3020$  A (Ref. 14).

\*Note (November 25, 1957). A recently published article by Kivel, Mayer, and Bethe<sup>11</sup> contains a detailed examination of the molecular radiation (and absorption) of light by nitrous oxide at high temperatures. Upon substitution of numerical values, the approximate formula given by these authors for the coefficient of absorption becomes (for red light)

$$\kappa_\nu = \frac{8.4 \times 10^4 c_{\text{NO}} \eta}{T} e^{-43000/T} \text{ cm}^{-1}.$$

At  $T = 5,000^\circ$  and at standard density ( $\eta = 1$ ), we get  $\kappa_\nu = 2.3 \times 10^{-4}$  cm<sup>-1</sup> and  $l = 43$  m; at lower temperatures the range is even greater, this confirming that the above mechanism cannot give a substantial effect below  $\sim 5,000^\circ$ .

It must be noted that below  $6200^\circ$  the molecular absorption by the nitrous oxide becomes greater than the photoelectric absorption (each of these mechanisms yields  $\kappa_\nu = 6 \times 10^{-4}$  cm<sup>-1</sup> at  $\nu = 1$ ). As the temperature rises, the relative role of this mechanism diminishes: thus, if  $T = 8,000^\circ$  it amounts to 17% of the photoelectric one.

It is very important to have an idea of the temperature variation of the cross-section in the red portion of the spectrum (there are no reliable experimental data). For this purpose it would be necessary, at least, to know the potential-surface scheme of the  $\text{NO}_2$  molecule. There are no indications to this effect in the literature. We must therefore confine ourselves to semi-quantitative estimates.

It is natural to assume that the entire absorption spectrum in the visible region is due to a transition to the next nearest electron level. Judging from the fact that  $\sigma$  drops abruptly to a negligible value at  $h\nu \approx 1.7$  eV, one might think that the energy of the level amounts to  $\epsilon \approx 1.7$  eV. The maximum of the cross-section at  $h\nu \approx 3.1$  eV can be explained by the fact that the transition from such an energy satisfies the Frank-Condon law in the best manner. Starting from these considerations, one can imagine a certain section of potential surfaces in the form shown in Fig. 3. As the

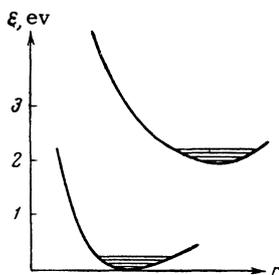


FIG. 3

temperature rises, vibrational levels are excited in the  $\text{NO}_2$  molecules and, as seen from Fig. 3, the maximum of the cross-section, corresponding to the transition that satisfies the Frank-Condon law in the best manner, shifts towards the red side together with the entire  $\sigma(\nu)$  curve. Since the electron level in the  $\text{NO}_2$  molecule lies very low, even a relatively small increase in temperature can excite to a sufficient degree vibrational levels whose energy (in eV) is  $\epsilon = 0.079\nu_1 + 0.169\nu_2 + 0.199\nu_3$  ( $\nu_1$ ,  $\nu_2$ , and  $\nu_3$  are the quantum numbers). Thus, for example, at a temperature on the order of  $2,500^\circ$ , 65% of the molecules are at levels not lower than  $\epsilon_{111} = 0.45$  eV, from which the transition with absorption of a red quantum  $h\nu = 1.91$  eV becomes quite probable.

Thus, we can assume that the cross-section for the absorption of red light by nitrogen dioxide increases monotonically (to a certain limit) with the temperature, and already at relatively small temperatures, on the order of several thousands of degrees, it reaches a value on the order of the maximum cross-section of the cold dioxide.

Unfortunately, there are no sufficient experimental information on the  $\text{NO}_2$  molecule,\* with which to carry out the very complicated temperature dependence of the absorption. Therefore, to calculate the effective temperature of the FB, we shall use the following likely values for the cross-section of absorption of red light:

|   |      |      |      |      |
|---|------|------|------|------|
| $T^\circ = 5000$  | 4000 | 3000 | 2600 | 2000 |
| $\sigma_{\text{NO}_2} \cdot 10^{19} \text{ cm}^2 = 3.6$ | 3.0  | 2.15 | 1.8  | 0.84 |

#### 4. MINIMUM BRIGHTNESS OF FIREBALL

The hypothesis concerning the absorption of light by nitrogen dioxide leads to an easy and natural explanation of the characteristic features of the observed phenomena. It becomes quite clear why at a SWF temperature  $T_f \approx 2,000^\circ$  the SWF stops glowing and detaches itself from the boundary of the FB.

As shown in Ref. 5, the exceedingly abrupt reduction in the rate of nitrogen oxidation with diminishing temperature, at the very temperature  $\approx 2,000^\circ$ , results in practice in a cessation of the formation of the oxide, and consequently, also of the dioxide of nitrogen in the layers of the air included in the SWF.

After the separation, at  $T_f \approx 2,000^\circ$ , the boundary of the glowing region is at first that layer of air behind the SWF, which was heated by the SWF to a temperature  $\approx 2,000^\circ$  and which bounds the region of the existence of the dioxide. This layer moves forward, and stops gradually as the pressure in it drops to atmospheric (see the trajectory of the FB on Fig. 2). In the case of adiabatic expansion, the temperature in the layer diminishes slowly from the initial value of  $\sim 2,000$  to  $\sim 800^\circ$ .† Probably, the boundary of the FB will penetrate with time somewhat deeper, into layers in which temperatures are closer to  $2,000^\circ$ , since the radiating ability, which is proportional to  $\exp(-h\nu/kT)$  ( $h\nu \gg kT$ ) diminishes very sharply with decreasing temperature. More accurately speaking, the boundary of the FB is determined by the sensitivity of the recording instrument. This naturally explains also the effect of the minimum brightness of the FB near the instant when the SWF breaks away from the FB.

Let us note first that the absorption of light by the nitrogen dioxide is of the required order of

\*The probabilities of transition between the various vibrational levels were calculated only for certain diatomic molecules.

†The initial pressure in the layer is  $p_f \approx 50$  atmos;  $T \sim p^{(\gamma-1)/\gamma} \sim p^{3/4}$ , for in this temperature region  $\gamma \approx 1.35$ .

magnitude. For example, at  $T = 3,000^\circ$  and a compression  $\eta = 5$ , the concentration of  $\text{NO}_2$ , according to calculations of Ref. 5, is  $1,58 \times 10^{-4}$ . With an absorption cross-section  $\sigma_{\text{NO}_2} = 2.15 \times 10^{-19} \text{ cm}^2$ , this gives a range  $l = 2.2 \text{ m}$ .

The temperature dependence of the concentration  $c_{\text{NO}_2}$  and of the cross-section  $\sigma_{\text{NO}_2}$ , and consequently, of the coefficient of absorption is quite weak in the interval from  $\sim 6,000$  to  $\sim 2,000^\circ$ .

Consider a layer of air behind the SWF at any one instant of time, say when the temperature of the SWF is  $T_f = 3,000^\circ$ . The temperature behind the SWF rises, and the density decreases. Accordingly, the concentration of the dioxide diminishes rather rapidly with the distance from the SWF. Using the method discussed in Ref. 5 to calculate the concentration  $c_{\text{NO}_2}(x)$  at each point  $x$ , with the known temperature and density known from the self-similar solution, and employing also the absorption cross-sections  $\sigma_{\text{NO}_2}(T)$  given above, it is possible to plot the distribution of the absorption coefficient behind the SWF,  $\kappa_\nu(x)$ .

At the point where the temperature reaches  $\sim 6,000 - 7,000^\circ$ , the concentration of the  $\text{NO}_2$  and the absorption becomes very small. However, starting with temperatures of the same order of magnitude, the absorption of light by the nitric oxide comes into play, as does also the absorption by the oxygen and nitrogen, considered in Sec. 2; this absorption increases very sharply with increasing temperature, i.e., with increasing distance from the SWF.

Figure 4 shows the distribution  $\kappa_\nu(x)$  for the instant  $t = 1.5 \times 10^{-2} \text{ sec}$  for a SWF radius  $R_f = 107 \text{ m}$  (explosion energy  $E = 10^{21} \text{ erg}$ ), at which the SWF temperature becomes  $T_f = 3,000^\circ$ . The same diagram shows the values of the temperatures and density at several points  $x$ . Another typical distribution of  $\kappa_\nu(x)$  is obtained when the SWF temperature is below  $\sim 2,000^\circ$  (see Fig.

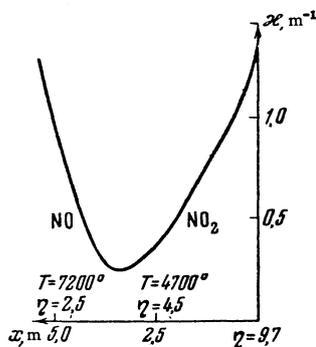


FIG. 4

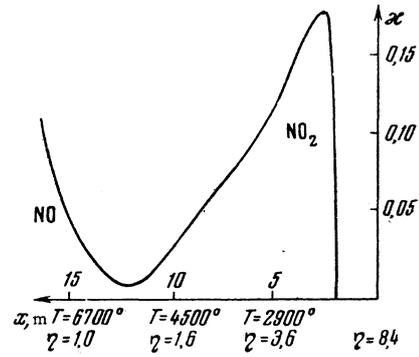


FIG. 5

5, which pertains to  $t = 2.64 \times 10^{-2} \text{ sec}$ ,  $R_f = 138 \text{ m}$ ,  $T_f = 1,600^\circ$ ). In this case the absorption begins not immediately behind the SWF, but somewhat away from its surface, in the particles that were heated by the passage of the SWF to a temperature  $\sim 2,000^\circ$ . No dioxide was formed in the outer layer, in which  $\kappa_\nu = 0$ .

The layer of air between the surface of the SWF and the surface where the temperature has an order of  $6,000^\circ$ , containing the nitrogen dioxide and having an optical thickness  $\tau_\nu^*$ , plays a double role. On the one hand, it absorbs the radiation of temperature  $T^* \sim 7,000 - 9,000^\circ$ , which is generated in the internal region with  $T > 6,000^\circ$  [the screening factor  $E_3(\tau^*)$  in the formula (7)]. On the other hand, it radiates light on its own [first term of (7)].

As the temperature of the SWF diminishes, starting with  $T_f \approx 6,000^\circ$ , the actual and optical thicknesses of the air layer containing the dioxide increase, and the effective temperature  $T_{\text{eff}}$  drops. Since the optical thickness  $\tau_\nu^*$  is on the order of unity, the effective temperature exceeds the temperature of the SWF substantially. The ratio of the first term to the second in formula (7) diminishes, and when  $T_f \approx 2,000^\circ$  it becomes very small: the role of the dioxide layer reduces, essentially, to screening the internal hot region, and the layer itself radiates little.

When the temperature of the SWF reaches  $\sim 2,000^\circ$  no more dioxide is formed in the layers of air newly captured by the front. Even if the total amount of the dioxide transformed by that instant of time were to remain constant, the optical thickness of the screening layer would diminish with time. In fact, as a consequence of the scattering of the air in the explosion wave, the same number of molecules  $\text{NNO}_2$  would be distributed over a spherical layer of an ever increasing radius

$$\tau_\nu^* = \int_0^{R_f} n_{\text{NO}_2} \sigma_{\text{NO}_2} dr$$

and diminishes with constant

$$N_{\text{NO}_2} = \int_0^{R_f} 4\pi r^2 n_{\text{NO}_2} dr,$$

roughly speaking in proportion to  $\sim R_f^{-2}$ .

Actually, the total amount of the dioxide, after it stops being produced in the air layers newly captured by the SWF, diminishes within a certain length of time,<sup>5</sup> which leads to an even faster reduction of  $\tau_v^*$ . Thus, at  $T_f < 2,000^\circ$ , the screening by the dioxide layer diminishes and the internal hot region gradually "becomes bare;" the effective temperature in this case increases — the FB, so to speak, flares up again.

The above qualitative considerations concerning the nature of the minimum brightness are illustrated in Table II, which lists the effective temperatures calculated in accordance with formula (5) for an explosion with energy  $E = 10^{21}$  erg. The effective temperature passes through a minimum, and the optical thickness  $\tau_v^*$  passes through a maximum, at  $T_f \approx 2,600^\circ$ , close to the break-away temperature  $T_f \approx 2,000^\circ$ .

TABLE II  
 $E = 10^{21}$  erg

| $t \cdot 10^8$ sec | $R_f, \mu$ | $T_f^\circ$ | $T_{\text{eff}}^\circ$ | $\tau_v^*$ |
|--------------------|------------|-------------|------------------------|------------|
| 0.75               | 82         | 5000        | 5930                   | 1.06       |
| 1.05               | 93         | 4000        | 4810                   | 1.96       |
| 1.50               | 107        | 3000        | 4110                   | 2.42       |
| 1.81               | 109        | 2600        | 3600                   | 3.23       |
| 1.95               | 112        | 2300        | 4150                   | 2.16       |
| 2.25               | 128        | 2000        | 4520                   | 1.80       |
| 2.39               | 132        | 1800        | 4810                   | 1.61       |
| 2.64               | 138        | 1600        | 5400                   | 1.15       |
| 2.94               | 143        | 1400        | 5600                   | 1.11       |

It is interesting to trace what happens to the minimum brightness of the FB with changing explosion energy. All the values of the time and all the dimensions remain proportional in a like manner to  $E^{1/3}$  (thanks to the approximate correctness of the self-similar hydrodynamic solution). The concentration of the dioxide in the principal region is in an equilibrium state, i.e., it depends only on the temperature and density of the particles, and not on its lifetime in the heated state, and therefore, roughly speaking, the optical thicknesses during the corresponding instants of time (for a definite SWF temperature) are proportional to the dimensions, i.e., also to  $\sim E^{1/3}$ . It follows therefore that the screening by the dioxide diminishes with diminishing explosion energy, and the excess of  $T_{\text{eff}}$  over  $T_f$  increases. By way of an

example, Table III lists the results of the calculations for an energy  $E = 10^{20}$  erg.

TABLE III  
 $E = 10^{20}$  erg

| $t \cdot 10^8$ sec | $R_f, \mu$ | $T_f^\circ$ | $T_{\text{eff}}^\circ$ | $\tau_v^*$ |
|--------------------|------------|-------------|------------------------|------------|
| 0.43               | 49         | 5000        | 6380                   | 0.61       |
| 0.61               | 53         | 4000        | 5560                   | 1.16       |
| 0.72               | 58         | 3000        | 5060                   | 1.42       |
| 0.82               | 60         | 2600        | 4800                   | 1.77       |
| 0.95               | 65         | 2300        | 5380                   | 1.18       |
| 1.01               | 66         | 2000        | 5850                   | 0.96       |
| 1.16               | 70         | 1800        | 6050                   | 0.88       |
| 1.38               | 73         | 1600        | 6510                   | 0.71       |
| 1.41               | 75         | 1400        | 6980                   | 0.54       |

The position of the minimum is practically unchanged ( $T_f \approx 2,600^\circ$ ), and  $T_{\text{eff}}$  at the minimum is higher. In the limiting case of very small energies, the screening by the dioxide tends to zero and the minimum brightness should degenerate.

In the case of very high energies, the excess of  $T_{\text{eff}}$  over  $T_f$  diminishes, the minimum becomes deeper (the dioxide layer, which is placed directly behind the SWF, radiates on its own).

The effective temperature at the minimum can never become less than the temperature limit for the formation of nitric oxide, which remains close to  $2,000^\circ$  for observable energies. Thus, at  $E = 10^{24}$  erg the characteristic times increase merely ten-fold compared with  $E = 10^{21}$  erg. This affects quite negligibly the temperature limit, owing to the exceedingly sharp temperature dependence of the reaction velocity for the oxidation of nitrogen.

Assuming that the brightness of the FB reaches a minimum during an instant when the temperature on the SWF has a definite value, and that the distribution of the  $\text{NO}_2$  concentration, together with the profiles of the temperature and the density, changes in a similar manner, we arrive at an approximation  $t_{\text{min}} \sim E^{1/3}$ . Inasmuch as all these conditions are satisfied only approximately, the dependence of  $t_{\text{min}}$  on  $E$  may be somewhat different. We restrict ourselves here to an examination of the stage of the minimum brightness of the FB. Other sections of the  $T_{\text{eff}}(t)$  curve (the maximum and the subsequent decrease), are more affected by radiation processes in which the nitrogen dioxide does not play such an important role.

We take advantage of the opportunity to express deep gratitude to D. I. Blokhintsev, M. A. El'iashevich, Ia. B. Zel'dovich, and A. S. Kompaneets for interest in the work and for valuable discussions.

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84

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### *SOME OPTICAL EFFECTS OF PLASMA OSCILLATIONS IN A SOLID*

I. I. SOBEL'MAN and E. L. FEINBERG

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

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Three optical effects involving "plasmons" (collective oscillations of electrons in a solid) are considered: (a) excitation of a plasmon by absorption of an x-ray quantum and its effect on the structure of the x-ray absorption edge, (b) Raman scattering by a plasmon, (c) absorption of light of the plasmon frequency. The cross sections for all three processes are large.

ALTHOUGH data on characteristic energy losses by fast electrons in a solid may be explained semi-quantitatively on the basis of the concept of collective electron oscillations,<sup>1,2</sup> the question of the reality of these oscillations cannot be considered to have been completely cleared up. It therefore seems useful to consider other effects, and in particular optical ones. Two types of collective oscillations are possible in a "plasma" of free electrons in a solid — optically active ones capable of absorbing and emitting light, and optically inactive ones. However, indirect interaction with light is possible for oscillations of both types. In this article we

shall consider the following processes:

1. Excitation of a plasmon by the absorption of an x-ray quantum (this process is important for the structure of the absorption edge).
2. Excitation of a plasmon by inelastic scattering of a photon (Raman scattering).
3. Absorption of light of frequency of an optically-inactive plasma oscillation due to the virtual excitation of one of the inner electrons.

All these processes are due to the Coulomb interaction of a plasmon with the inner electrons. As will be shown below their probabilities are quite appreciable.