Analysis of the nature of ball lightning

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The existing hypotheses that describe the nature of ball lightning are analyzed by an approach based on the elementary processes that occur in this lightning. It is shown that the internal energy stored in the ball lightning can be retained in it during the observed time only if this energy is chemical in nature. The chemical reactions and radiation processes that occur in excited air are investigated. It is shown that at reasonable values of the internal energy none of the hypotheses concerning ball lightning can explain the appearance of the surface forces that bring about the spherical shape of the ball lightning.

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ANALYSIS OF THE NATURE OF BALL LIGHTNING

1. Ball lightning is a puzzling natural phenomenon, which has been attracting researchers' attention for several centuries. During that time, considerable information has been accumulated concerning ball lightning, and many hypotheses were advanced for its explanation. However, since the very occurrence of ball lightning is accidental in nature, its detailed experimental study is difficult. For this reason, and also because ball lightning is a rather unusual phenomenon, it is impossible to draw at present any unequivocal conclusions concerning its nature. At the same time, we have abundant information concerning other phenomena that occur in excited gases. This information can be used also in the analysis of the hypotheses that describe the nature of ball lightning. The purpose of this article, which is methodological in character, is to analyze the nature of ball lightning from the point of view of the elementary processes that take place in it.

2. We present first the ball-lightning parameters which we shall use as a basis. We use here the data from Singer's book "Nature of Ball Lightning,"[1] in which is gathered the most information (about 600 papers) on ball lightning.[1)] Using the data of this book, we assume henceforth that the diameter of the ball lightning ranges from 10 to 40 cm and its lifetime is on the order of 10–100 sec. There are great discrepancies between estimates of the energy stored in the ball lightning. We shall assume that this lightning is similar in its optical characteristic to a gas-discharge lamp of 10–100 W power, so that the energy stored in it is 10^2–10^4 J.

3. Let us analyze the existing hypotheses aimed at explaining the nature of ball lightning. A ball lightning is a volume of excited gas produced after the action of an ordinary lightning. We start from the assumption that this gas is approximately at room temperature. If the temperature of the ball lightning were to be several thousands of degrees, then the lightning would float upwards[2)] and could not be observed for a prolonged time at low altitudes. At the considered temperatures, the nitrogen and oxygen are present, under thermodynamic equilibrium, in the form of molecules.

Further, in the analysis of the nature of ball lightning we shall not discuss the ball-lightning hypothesis when it is maintained by an external source (see, e.g.,[4]).[3)] In this case special attention must be paid to the external energy source itself, without an analysis of which we are unable to draw any reliable conclusions concerning the nature of the ball lightning solely on the basis of the elementary processes. In addition, we shall not dwell on the hypotheses that the ball lightning is an outer-space or nuclear phenomenon—these cannot withstand any serious criticism.

Table I is a summary of the results on the elementary processes that lead to the decay of the ball lightning under various assumptions concerning its nature. It includes hypotheses according to which the ball lightning is not a strongly heated excited gas. (The elementary-process parameters cited without references were taken from[2].) Let us comment briefly on Table I.

a) The plasma theory of ball lightning assumes that the gas contains a certain number of charged particles. The atomic ions enter in a reaction with the air molecule to produce molecular ions, e.g., $O^+ + O_2 \rightarrow O_2^+ + O$, $N^+ + O_2 \rightarrow NO^+ + O$. The constants of the first and second reactions are 10^{-11} and 6×10^{-10} cm^3/sec, i.e., during a time on the order of 10^{-8} sec the atomic ions are transformed in air into molecular ones and the decay of the ball lightning is due to the dissociative recombination of the electrons and the molecular ions. An estimate of the internal energy of the ball lightning for this mechanism and for the one that follows was obtained in the following manner: Starting with the recombination coefficient α and the lightning decay time τ, the density of the charged particles was estimated, equal to $(\alpha\tau)^{-1}$ or $(\alpha N\tau)^{-1}$, where N is the total density of the gas molecules. The internal energy of the ball lightning was estimated from the condition that the production of each pair of charged

[1)] We cite the description of ball lightning given in that book: "Luminous spheres are produced during the time of a storm, usually in some connection–although not necessarily at the same time or place–with ordinary lightning. They are more or less spherical objects with approximate diameter 25 cm and distinct color–red, yellow, and sometimes blinding white–and trace in the air a long and sometimes tortuous path near the earth, penetrate into buildings, crackle, are literally electric discharges, exist frequently for 5 seconds, and then suddenly vanish either with loud explosion or noiselessly. Reports on these properties, which are so different from the properties of ordinary linear lightnings, have encountered considerable mistrust, but very many detailed observations of ball lightning have been registered, and several photographs were taken" (see [2]).

[2)] According to the results of [3], a soap bubble of 20–35 cm diameter filled with helium floats upward at a speed of 1.2 cm/sec. The density of helium is approximately that of air at 220°K.

[3)] Kapitza [4] describes the production of a hovering poasma filament in a dense gas under the influence of microwave radiation. Under certain conditions (the type of gas, stabilization of the plasma filament by the circulation of the gas), this freely hovering gas discharge recalls ball lightning.

TABLE I

Nature of lightning	Character of internal energy	Character of decay	Examples of decay processes	Decay rate constant	Density of excited particle at a lightning decay time 10 sec	Internal energy at a decay time 10 sec and a diameter 20 cm
Plasma consisting of electrons and ions	Released upon recombination of charged particles	Dissociative recombination	$e + O_2^+ \rightarrow O + O$ $e + N_2^+ \rightarrow N + N$ $e + NO^+ \rightarrow N + O$	$2 \cdot 10^{-7}$ cm³/sec $2 \cdot 10^{-7}$ cm³/sec $4 \cdot 10^{-7}$ cm³/sec	$5 \cdot 10^5$ cm^{-3}	10^{-8} J
Plasma consisting of positive and negative ions	Ditto	Triple recombination of positive and negative ions	$O_2^- + O_4^+ + O_2 \rightarrow 4O_2$ $NO^+ + NO_2^- + N_2 \rightarrow$ $\rightarrow NO + NO_2 + N_2$	$1{,}6 \cdot 10^{-25}$ cm⁶/sec 10^{-25} cm⁶/sec	$3 \cdot 10^4$ cm^{-3}	10^{-9} J
Ions of one sort	Energy of electric field produced by charged particles	Spreading of ions under influence of electric field	Mobility of heavy ions higher than 0.1 cm²/V-sec		10^7 cm^{-3}	10^{-7} J
Excited gas containing electron-excited atoms or molecules	Electron excitation of atoms	Energy release upon quenching of electron excitation	$O_2(^1\Delta_g) + O_2 \rightarrow 2O_2$ $O_2(^1\Sigma_g^+) + N_2 \rightarrow O_2 + N_2$ $N_2(^3\Sigma^+) + O_2 \rightarrow N_2 + O_2$ $O(^1S) + O_2 \rightarrow O + O_2$ $O(^1D) + O_2 \rightarrow O + O_2$	$2 \cdot 10^{-18}$ cm³/sec $2 \cdot 10^{-17}$ cm³/sec $4 \cdot 10^{-12}$ cm³/sec $3 \cdot 10^{-13}$ cm³/sec $5 \cdot 10^{-11}$ cm³/sec	Lifetime under normal conditions < 0.1 sec	
Excited gas containing vibrationally-excited molecules	Vibrational excitation of molecules	Energy release upon quenching of vibrational excitation	$N_2^* + N_2 \rightarrow 2N_2$ $O_2^* + O_2 \rightarrow 2O_2$ $N_2^* + CO_2 \rightarrow CO_2^* + N_2$	$\sim 10^{-19}$ cm³/sec [5] 10^{-17} cm³/sec [5,6] $6 \cdot 10^{-15}$ cm³/sec [7]	Lifetime under normal conditions < 0.01 sec	
Chemical	Released in chemical reaction	Chemical reaction of components	$2O_3 \rightarrow 3O_2 + 69.4$ kcal/mole $2NO_2 \rightarrow N_2 + 2O_2 + 16$ kcal/mole	$4 \cdot 10^{-20}$ cm³/sec at 400 °K [8] —	$< 2 \cdot 10^{19}$ cm^{-3}	$3 \cdot 10^4 \eta$ J (η—ozon concentration) $6 \cdot 10^3 \eta$ J (η—NO_2 concentration)

particles consumes an energy on the order of the ionization potential of the initial atomic particles.

b) The process $e + 2O_2 \rightarrow O_2^- + O_2$ with a constant 3×10^{-30} cm⁶/sec takes place in air at 300° K, so that under normal conditions all the electrons are converted into negative ions in a time $\sim 10^{-8}$ sec. The binding energy of an electron in any negative ion is much less than the characteristic ionization potential of the molecule, so that recombination of the positive and negative ion in the gas phase proceeds with release of energy. For complex ions the rate constant of this process increases with the complexity of the ion. Therefore the condition for the existence of a ball lightning, which was proposed by I. P. Stakhanov, containing positive and negative ions, is likewise not satisfied.

c) For this ball-lightning mechanism[1,10] we took the smallest of the observed values of ion mobility.[11] The time of decay of the ball lightning was assumed to be the one in which the sphere radius doubles (see[12]).

d) The presented constants correspond to decay of metastable atoms and molecules of oxygen and nitrogen; they correspond to decay at room temperature and increase sharply with rising temperature. Resonantly-excited states of atoms and molecules decay in the molecular gas even more rapidly (photon emission accompanying their decay is not forbidden). For example, the quenching of the resonantly-excited state of the sodium atom (de-excitation of the atom in this state gives rise to the yellow line) by a nitrogen molecule is characterized by a rate constant on the order of 10^{-10} cm³/sec. Thus, the quenching of electron-excited states in molecular gas is quite rapid and the nature of ball lightning cannot be explained by the presence of electron-excited atoms in the molecular gas. We note that the foregoing analysis is incorrect if the gas is dissociated.

e) The cited constants correspond to room temperature and increase strongly with rising temperature. The vibrationally-excited nitrogen molecules transfer effectively their excitation to the oxygen molecules, to the carbon dioxide molecules etc., and these in turn give up this energy to translational degrees of freedom. Vibrational relaxation of molecular nitrogen in a mixture of gases is therefore faster than in pure nitrogen, and occurs in a time on the same order as the relaxation of the vibrationally-excited molecules of oxygen. As a result of the vibrational relaxation, the energy stored in the vibrational degrees of freedom is converted into heat within times that are short in comparison with the ball-lightning lifetime.

f) The ozone dissociation process proceeds in accordance with the scheme $O_3 + M \rightleftarrows O + O_2 + M$, $O + O_3 \rightarrow 2O_2$, where M is an oxygen or nitrogen molecule. Table I gives the effective constant of the ozene dissociation process $2O_3 \rightarrow 3O_2$, obtained at T = 400° K in air at 1 atm pressure, the constants of the individual processes being taken from Kondrat'ev's book.[8] The assumption that the ball lightning is of chemical origin implies that the ozone or some other thermodynamically-unstable chemical compound constitutes a small part of the main gas—air (say, several per cent), and the molecules of this compound are destroyed as a result of reactions with one another or with impurities.

4. It follows from the table that among the considered ball-lightning mechanisms, the only acceptable one is that of the chemical origin of this lightning. In this case the energy of the ball lightning can be released in chemical reactions that are accompanied by changes of the type of particles contained in the lightning. We do not have enough information on the elementary process to make the next step and determine the components that should serve as the basis of the ball lightning. It can be shown, however, that one of these components can be ozone. The air in the channel of an ordinary lightning is dissociated. Let us see what the relaxation of atomic oxygen in lightning can lead to.

Table II lists the constants of the processes that occur in this case, taken from the book of V. N. Kondrat'ev, and pertaining to a temperature 400° K. We insert these

TABLE II. Processes occurring during the relaxation of dissociated oxygen at 400°K

Process	Rate constant of process
$2O+O_2 \rightarrow 2O_2$	$K_1=3\cdot10^{-33}$ cm⁶/sec
$O+2O_2 \rightarrow O_3+O_2$	$K_2=6\cdot10^{-34}$ cm⁶/sec
$O+O_2+N_2 \rightarrow O_3+N_2$	$K_3=6\cdot10^{-34}$ cm⁶/sec
$O+O_2+O_3 \rightarrow 2O_3$	$K_4=9\cdot10^{-34}$ cm⁶/sec
$O_3+O \rightarrow 2O_2$	$K_5=6\cdot10^{-14}$ cm³/sec
$O_3+O_2 \rightarrow 2O_2+O$	$K_6=2\cdot10^{-22}$ cm³/sec
$O_3+N_2 \rightarrow O_2+O+N_2$	$K_7=2\cdot10^{-22}$ cm³/sec

processes into the balance equations for the densities of the atomic and molecular oxygen and ozen and determine the amount of azone produced as a result. We obtain approximately

$$[O_3]=\left\{\frac{1}{[O]}+\frac{K_1([O_2]+[N_2])}{2(K_2[O_2]+K_3[N_2])[O_2]}\right\}^{-1}=\left(\frac{1}{[O]}+4\cdot10^{-19}\ \text{cm}^{-3}\right)^{-1};$$

here [O] is the initial density of the atomic oxygen, $[O_3]$ is the final density of the ozone, and $[O_2]$ and $[N_2]$ are the densities of the molecular oxygen and nitrogen, which we assume to be unchanged and equal to their values under normal conditions. It follows therefore that under favorable conditions of ozone production its amount in air can reach several per cent and can contain by the same token sufficient energy.

5. Assuming the ball lightning to be of chemical origin origin, let us examine some of its properties. In a volume containing a chemical component there occur chemical reactions, the by-product of which is radiation. One of the possible cycles of this type for the air containing ozone and nitrogen dioxide as impurities, consists of the processes

$$\begin{aligned}
&O_3+\begin{Bmatrix}N_2\\O_2\end{Bmatrix}\rightleftarrows O+O_2+\begin{Bmatrix}N_2,\\O_2,\end{Bmatrix}\\
&O+O_3\rightarrow 2O_2,\\
&O+NO_2\rightarrow NO_2+O_2,\\
&O_3+NO\rightarrow NO_2+O_2,\\
&O_3+NO\rightarrow NO_2^*+O_2,\\
&NO_2^*\rightarrow NO_2+h\nu.
\end{aligned}$$

The excited NO_2 molecule produced in the next-to-last reaction emits in the wavelength range[13] 5200—8100 Å (if the entire reaction energy were carried away by the photon, then the photon wavelength would be 5000 Å).

The foregoing cycle of processes leads in final analysis to a conversion of the chemical energy stored in the ozone. The rate constants of the presented processes[8] make it possible to draw a general picture of this cycle. If the densities of the ozone and of the nitrogen dioxide are comparable, then the dissociation of the ozone is due to reactions in which nitrogen oxides participates. The probability of formation of a molecule in the excited state in the reaction of NO with O_3 (i.e., the probability of the appearance of a photon as a result of this reaction) increases with increasing temperature, from 0.08 at 300°K to 0.32 at 700°K.[4)] This ensures a coefficient of conversion of chemical energy into radiation energy on the order of several per cent. The time required to dissociate the ozone is itself dependent on the temperature, thus, at a nitrogen dioxide concentration 1%, this time is on the order of 2×10^4, 0.4, and 10^{-3} sec at 300°, 400°, and 500°K, respectively.

The presented cycle of processes is enticing in that it explains the chemical composition of the wake of the ball lightning. According to measurements of Dmitriev[1], only the content of the nitrogen dioxide and of the ozone increased in the air through which a ball lightning passed. In addition, the considered glow mechanism accounts well for the observed color of the ball lightning, explains the volume (rather than surface) character of the luminescence of the ball lightning, as reconstructed from ball-lightning photographs.[14] To present the complete physical picture of the ball lightning, it is important to account not only for the elementary process but also by the macroscopic processes that occur in it. In particular, owing to the strong temperature dependence of the rates of the considered processes, the burnup of the chemically-active medium may have an irregular character, and the intensity of the luminescence of the ball lightning may oscillate strongly during its lifetime. This is indeed observed on photographs of ball lightning.[14]

6. Let us estimate the lifetime of a ball lightning, assuming its chemical character. This time is determined by the convective motion of the gas under the influence of the force of gravity and of the temperature drop in it. The heat flux q of the gas is in this case of the order of[15]

$$q\sim wN\Delta T\sim G^{1/4}\frac{\varkappa\Delta T}{L},$$

whence

$$w\sim\frac{G^{1/4}\varkappa}{LN};$$

where w is the velocity of the translational motion of the gas jet, N is the gas density, T is the temperature drop, G is the Grasshof number, κ is the thermal conductivity of the gas, and L is the characteristic ball-lightning dimension over which the heat transport under consideration is effected.

Assuming L ~ 20 cm, a thermal power release on the order of 100 W, and all other parameters of air under normal conditions, we get $G\sim10^6$, $\Delta T\sim100$ deg, and w ~ 3 cm/sec. This yields for the lifetime of the ball lightning an order-of-magnitude value L/w ~ 10 sec, which does not disagree with the order of the observed values.

7. The ball lightning can go out of existence in two ways, either as a result of convective motion of the gas the chemically active medium is scattered in the air, causing the glow to terminate, or else because a substance that reacts effectively with the chemically-active medium of the ball lightning enters into the zone of the lightning. The result is a thermal explosion[16] that causes the conversion of a noticeable fraction of the chemical energy of the ball lightning.

8. Let us consider the problem of the spherical shape of the ball lightning, which is one of the most difficult to explain. It is usually assumed that this spherical shape is caused by the surface tension due to the interaction between the particles situated inside the ball lightning. The surface tension on the boundary of the ball lightning makes its spherical shape stable to various perturbations.

Let us estimate the surface energy U_{sur} produced as

[4)] We note that the air is not strongly heated by the conversion of the ozone into oxygen. Thus, if the initial concentration of the ozone is 1%, then its decomposition heats the air by 50°.

a result of the interaction of the active particles in the ball lightning. This energy is of the order of

$$U_{sur} \sim U(N^{-1/3})\, N^{-1/3} SN,$$

where U is the potential of the interaction of two particles at the average distance between them, N is the density of the interacting particles, and S is the surface area of the ball lightning. The surface energy is the energy of attraction between the particles in the surface layer. We estimate this energy for the case when the active molecules have dipole moment. Table III lists the dipole moments of a number of molecules that can be active in ball lightning. We assume that the directions of the dipole moments of the neighboring active molecules are such that they are attracted, and then the attraction energy of these molecules at a distance R between them is $U \sim d^2R^3$, where the dipole moment of the molecule is $d \sim 10^{-8}$ cgs esu. This yields an estimate for the surface energy of the ball lightning in this case (the surface area of the ball lightning is $S \sim 10^3$ cm^2):

$$U_{sur} \sim 10^{-33} N^{5/3} \text{ erg} \cdot \text{cm}^5,$$

where N is the density of the active molecules.

This quantity should be compared with the kinetic energy of the internal motion that is capable of distorting the shape of the ball lightning. According to an earlier estimate, the characteristic velocity of the convective motion of the gas is $w \sim 3$ cm/sec. The kinetic energy of the convective motion of the gas inside the ball lightning is therefore

$$\mathcal{E} \sim 10 \text{ erg}.$$

We see that the ball-lightning surface energy produced by the dipole interaction of the active particles exceeds the kinetic energy of the convective motion when the active-molecule density $N > 10^{21}$ cm^{-3}. This is much higher than the molecule density in air. Dipole-dipole interaction of molecules in a ball lightning can therefore not ensure a sufficient surface tension to make the lightning surface spherical. We note furthermore that we have overestimated the surface energy, having assumed that the dipole molecules always attract one another.

Let us estimate the surface energy in the case when the surface tension is produced by the Coulomb interaction of the charged particles. Since the potential of the interaction of the particles with a unit charge e at a distance R is equal to e^2/R, we obtain from the formula for the surface energy

$$U_{sur} \sim e^2 N_i S,$$

where N_i is the density of the charged particles. Under our condition this formula yields

$$U_{sur} \sim 10^{-16} N_i \text{ erg} \cdot \text{cm}^3,$$

and the surface energy exceeds the kinetic energy of the convective motion of the gas at an ion density N_i $> 10^{17}$ cm^{-3}, which is also unrealistic, although the estimate is too high.

We consider finally an intermediate case, when the active gas contains dipole molecules with density N and charged particles with density N_i, where $N \gg N_i$. The potential of the interaction between a charged particle and a dipole molecule at a distance R between them is $U(R) \sim ed/R^2$. We assume that this interaction corresponds to attraction. We then have for the surface energy produced by the interaction of this type

$$U_{sur} \sim U(N_i^{-1/3})\, N_i^{-1/3} SN \sim e\, dSNN_i^{1/3} \sim 10^{-24} NN_i^{1/3} \text{ erg} \cdot \text{cm}^4.$$

At realistic values of the active-molecule density $N \sim 10^{17}$–10^{18} cm^{-3} and a charged-particle density $N_i \sim 10^5$–10^6 cm^{-3}, the surface energy resulting from the interaction between the charged particles and the dipole molecules is lower by only one order of magnitude than the surface energy due to the interaction of the dipole molecules themselves.

These estimates show that the interaction of the particles inside the ball lightning, even under favorable conditions, cannot produce enough surface tension to make the lightning surface spherical. This is why the problem of the shape of the ball lightning is one of the most difficult ones. It is possible that the shape is not strictly spherical at all. The shape can then be explained without resorting to surface forces. It is possible that the lightning shape is stabilized by circulation of the gas. Such a possibility was demonstrated in Kapitza's experiments.[4] In addition, the sphericity of the ball lightning may be attributed to a spherically-symmetrical distribution of the temperature field. Indeed, the rate constant of the chemical reaction that results in the heat release increases sharply with increasing temperature. The stable temperature distribution itself, which is not very sensitive to the form of the distribution of the heat source, is spherically symmetrical. The rate constant of the chemical reaction that leads to the luminescence also depends strongly on the temperature. The profile of the glowing region of the ball lightning therefore duplicates the temperature-distribution profile.

Proof favoring this explanation of the spherical shape of the ball lightning is provided by experiments on ignition of a combustible mixture introduced in small amounts into air.[1] This mixture, the ignition of which in a large volume of air is initiated with the aid of a spark, burns in a small spherical volume that constitutes a small fraction of the entire volume filled with the combustible mixture.

The analysis presented in this note allows us to conclude that a chemical cause of ball lightning is the most plausible from among all those considered.[5)] There remain many problems to be solved. It is necessary to identify the chemical mixture of which the ball lightning

TABLE III. Dipole moment of molecules in Debye units (10^{-18} cgs esu)

Molecule	O_3	NO_2	N_2O	H_2O	HNO_3	H_2O_2
Dipole moment, D	0.54	0.32	0.16	1.84	2.16	2.13

[5)] We have considered the case when the glowing sphere is produced in unheated air and is maintained by the internal energy of the particles it contains. There are other ways of producing a glowing sphere. These include the production of glowing gas volumes by external microwave radiation. [4] These objects contain a weakly-ionized plasma with a gas temperature 2000–2500°K. Another type of glowing sphere is a cluster of evaporated metal, produced by lightning or by a strong discharge. Such fireballs are heavier than air, and therefore fall and roll over the earth. However, these types of glowing spheres do not correspond to many of the observed cases of ball lightning.

is made up, and to find out the state of this mixture (gas, aerosol), the processes and chain reactions that lead to the release of energy and the glow of the ball lightning, the conditions under which it exists, and how spherical is its shape. These problems cannot be solved without experiments. Without an experimental confirmation likewise no theoretical explanation of the nature of the ball lightning be convincing. To set up the experiments, on the other hand, it is necessary to narrow down the group of conditions under which it is to be performed. This is precisely the problem that the author had in mind when writing this note.

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