Physics of ball lightning

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The present state of the ball-lightning problem is analyzed. Observational data on ball lightning are reviewed and analyzed. Analogs of ball lightning in terms of properties are discussed. Basic characteristics of ball lightning are identified. They include a rigid framework, a chemical method of internal energy storage, and a spotty emission structure. The spottiness results from the existence of a large number of small hot zones which are responsible for the emission. Problems to be resolved are pointed out. Some models which might be of assistance here are described.

1. INTRODUCTION

Ball lightning is an interesting physical phenomenon. It would seem to be based on known physical principles, but the efforts of several generations of scientists to determine its physical nature have been rewarded with only a sketchy understanding. Fundamental questions regarding the nature of this phenomenon still lack completely definite, universally accepted answers. Research on ball lightning has become much more active in recent years; scientific centers to study it have been established in several countries, and an international symposium has been held. All this activity reflects the significant progress which has recently been achieved in this research. Specifically, a wealth of observational information on ball lightning has been accumulated in recent decades. Analysis of the observational data has resulted in the construction of models for individual properties of ball lightning which have analogs in other natural and technological entities and phenomena and which explain certain aspects of the nature of ball lightning.

The data available on ball lightning and the increasing interest in this problem guarantee further progress in research in this field. It is useful at this point to analyze the existing data on ball lightning and to identify what is known conclusively about its nature. These are the goals of the present paper. We summarize the observational data on ball lightning. We analyze this information and formulate some reliable conclusions about the nature of ball lightning. We also show relationships between ball lightning and other physical entities and phenomena which are similar in nature. We analyze possible versions of several processes which occur in ball lightning and ways to study them. It is my opinion that this approach may be useful to further research on ball lightning.

2. OBSERVATIONAL DATA ON BALL LIGHTNING

2.1. Collections of cases of observations

The research on ball lightning has a rich history. This phenomenon has been discussed and analyzed in the scientific world for essentially two millennia.[1] The present understanding of ball lightning is based on reviews and analysis of observational data. Today we have a wealth of observational data on ball lightning, which can be attributed to two factors: First, people have been collecting cases of the observation of ball lightning for a fairly long time, more than a hundred years (Table I). Second, ball lightning can be clearly defined and distinguished from other atmospheric phenomena. According to this definition, ball lightning is a glowing formation in the atmosphere, usually spherical, which moves freely through the air and exists both outdoors and in enclosures, for a matter of seconds or (rarely) minutes.

Extensive observational data on ball lightning have now been collected and analyzed. From these observations it is possible to extract reliable information on the quantitative properties of ball lightning. Table I shows the existing collections of cases of observation of ball lightning. It is important to note that the collections of data listed in Table I are independent. Each collection has its own method for analyzing

TABLE I. Collections of observational data on ball lightning.

Authors	Year	Country	Number of cases analyzed	Reference
Aragó	1859	France	30	[2]
Brand	1923	Germany	215	[3]
Humphreys	1936	US	280	[4]
McNally	1966	US	513	[5]
Rayle	1966	US	112	[6]
Dmitriev	1969	USSR	45	[7]
Arabadji	1976	Holland	250	[8]
Grigor'ev, Dmitriev	1978, 1979	USSR	327	[9]
Charman	1979	England	76	[10]
Stakhanov	1979, 1985	USSR	1022	[11, 12]
Keul	1981	Austria	80	[13, 14]
Grigor'ev, Grigor'eva*	1986	USSR	2082	[15—17]
Ohtsuki, Ofuruton	1987	Japan	2060	[18—20]
Egely	1987	Hungary	300	[21—24]

*We will be referring frequently to this collection of data, which we will call simply "Grigor'ev's data" for brevity.

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TABLE II. Average diameter of observed ball lightning.

Data collection	McNally[5]	Rayle[6]	Charman[10]	Stakhanov[11,12]	Keul[13,14]	Grigor'ev[16]	Egely[21]
Number of cases	446	98	64	1005	150	1796	204
$\bar{d}$, cm	30	32	26	22	30	19	35

the observational data. The eyewitness reports come from a number of regions around the world. The data in the various collections of observations thus complement each other, and together they constitute reliable information on the properties of ball lightning.

Note also the large statistical base of the observational data, which makes it possible to avoid dealing with distorted information.[1)] The development of methodological approaches for analyzing the cases of observations is also of value. A major contribution has been made here by Stakhanov,[11,12] who has worked from the data gathered and the analysis methods developed to raise our understanding of observed ball lightning to a qualitatively higher level. The development of Stakhanov's methods is presently being pursued successfully by Grigor'ev and his colleagues[15-17] on a larger statistical base. Let us discuss the basic properties of observational ball lightning.

2.2. Size and lifetime

In analyzing numerical values of the properties of observed ball lightning we should bear in mind that all the data are results of visual observation of ball lightning at a time at which the observer was in a state of some emotional shock. For this reason, there are errors in the information which cannot be eliminated by virtue of a large statistical base. This point should be kept in mind in the analysis of the observational data which follows. Table II shows the average diameters of ball lightning according to various sets of observations. The average value is $\bar{d} = 23 \pm 5$ cm. Earlier studies by a similar method, without the new data sets, resulted in an average diameter $\bar{d} = 28 \pm 4$ cm (Refs. 19 and 20). We see that the increase in the number of observational cases does not result in a reduction of the error. We should add that the distribution with respect to diameter of the cases of ball lightning has different shapes according to different collections of observational cases. Experience in the analysis of observational data tells us that the quantitative data obtained from observations are of limited accuracy and that this accuracy improves only slowly with increasing number of cases analyzed. Nevertheless, with a large statistical base one can expect a common size distribution for the cases of ball lightning. According to Stakhanov's analysis,[12] the distribution function for his set of observational data can be approximated well by the function

$$f(D) = \frac{D}{D_0^2} \exp\left(-\frac{D}{D_0}\right), \tag{1}$$

where D is the diameter of the ball lightning, and D_0 is the average diameter. This distribution is normalized by the condition

$$\int_0^\infty f_*(D)\, \mathrm{d}D = 1.$$

The lifetime distribution of cases of ball lightning has a complex shape. We introduce $P(t)$: the probability that the ball lightning has not decayed by the time t. We would naturally expect this function to be exponential. According to observational data, however, it can be approximated conveniently as a combination of several exponential functions:

$$P(t) = \sum_i A_i \exp\left(-\frac{t}{\tau_i}\right). \tag{2}$$

The values of the parameters of expression (2) according to various sets of observations are listed in Table III. This table includes those data from Grigor'ev's collection[16] which came from cases in which the appearance and decay of ball liqhtning were observed, or the decay of ball lightning was observed when it appeared just after linear lightning. In the other data sets, the lifetime of the ball lightning was taken to be the time over which it was observed.

We also introduce some average times to characterize the lifetime of the ball lightning. One is the average lifetime of the ball lightning,

$$\tau_1 = \int_0^\infty t \frac{\mathrm{d}P}{\mathrm{d}t}\, \mathrm{d}t; \tag{3a}$$

a second is a time which characterizes the initial decay rate,

$$\tau_2 = -\left.\frac{\mathrm{d}P}{\mathrm{d}t}\right|_{t=0}; \tag{3b}$$

and a third and a fourth are the times over which certain fractions of the ball lightning persist,

$$P(\tau_3) = \frac{1}{e}, \tag{3c}$$

$$P(\tau_4) = \frac{1}{2}. \tag{3d}$$

The values of these average times found from the data in Table III are shown in Table IV.

TABLE III. Values of the parameters in expression (2).

Parameter	Number of cases	A_1	τ_1, s	A_2	τ_2, s	A_3	τ_3, s
McNally[5]	445	0.86	3.5	0.14	44	0	—
Rayle[6]	95	0	—	1.00	14	0	—
Stakhanov[11,12]	982	0.57	11	0.43	54	0	—
Grigor'ev[16]	437	0.59	3.0	0.27	30	0.14	215

TABLE IV. Average lifetime (seconds) of ball lightning.

	Number of cases	τ_1	τ_2	τ_3	τ_4
McNally[5]	445	12	4	4,5	3
Rayle[6]	95	14	14	14	10
Stakhanov[11,12]	982	30	17	22	14
Grigor'ev[16]	437	40	5	9	4,5
Egely[21]	152	38	9	18	7,5

If the decay of ball lightning were exponential, we would have $\tau_1 = \tau_2 = \tau_3$ and $\tau_4 = 0.69\tau_3$, as in Rayle's case.[6] In other data sets which contain long-lived and short-lived cases, these average times are quite different. The lifetime of ball lightning is usually taken to be the quantity τ_4, which is, according to the data in Table IV, $\tau_4 = 8 \cdot 10^{\pm 0.3}$ s. In addition, the quantity τ_2, which characterizes the initial decay rate, is used. Taking an average of the data in Table IV, we find $\tau_2 = 9 \cdot 10^{\pm 0.3}$ s. We see that the values of these parameters agree within their errors. We will accordingly use them below as the average lifetime of ball lightning.

2.3. Shape and structure

Its name (both in Russian and in other languages) implies that ball lightning should be spherical. This expectation is supported by the observational data. Table V shows information on the shape of ball lightning according to the data of Stakhanov and Grigor'ev. The statistical error shown here applies to the sum of observations. We see that ball lightning is spherical in about 90% of the observations.

An important point is that the ball lightning retains its shape as it evolves in most cases. For example, according to Grigor'ev's data,[16] in only 134 cases of the 2082 analyzed was the shape of the ball lightning observed to change. In 25 cases, a sphere became a tape; in 15, a tape became a sphere; in 4, a sphere was deformed as it jumped around; and in 12 the ball lightning stretched out toward a conductor. We should add that in 226 cases (11%) the ball lightning was observed to have a translucent shell, in 119 cases (6%) it had a tail, and in 143 cases (7%) it was reported to have an internal structure, associated with a random motion of glowing spots or bright filaments in it. We see that standing behind this simple shape of ball lightning is a picture of internal processes which is by no means simple.

2.4. Nature of the motion

Among the other properties of ball lightning we note that its motion is usually smooth and horizontal. A horizontal motion was mentioned in 53% of the 110 observational cases of Rayle,[6] in 68% of the 1006 cases of Stakhanov,[11,12] and in 75% of the 1743 cases of Grigor'ev.[16] According to Rayle,[6] the ball lightning moved vertically (up or down) in 18% of the cases, and in 18% it traced out a complicated path. According to Stakhanov's data,[11,12] a downward motion was observed in 18% of the cases (183), and an upward motion in 5% (47). It follows from an analysis of Grigor'ev's data that the ball lightning moved upward toward clouds in 0.4% of the cases (7 observations), while in 5% of the cases (84) it moved downward from clouds. Despite the different methods used to analyze the results, it can be seen that the ball lightning usually executes a smooth horizontal motion. Other types of motion (including no motion at all) are possible.

Ball lightning frequently moves along a conductor. This event was observed in 20% of the cases in McNally's collection,[5] 16% of the cases in Rayle's collection,[6] and 4% of the cases in Grigor'ev's collection.[16]

A surprising aspect of the motion of ball lightning is its ability to find apertures and go through them or to pass through slits. According to Grigor'ev's data,[16] in 104 cases out of 2082 the ball lightning passed through a slit smaller than the diameter of the ball lightning itself. In 30 of these cases, the shape of the ball lightning changed, while in 12 it did not. Moreover, ball lightning can easily move around obstacles that it finds in its path. In Grigor'ev's collection,[16] this event was noted in 45 cases out of the 1743 in which a motion of the ball lightning was described.

An effect of wind on the motion of the ball lightning was reported in 52 cases in Grigor'ev's data set.[16] In 42 of these

TABLE V. Distribution of cases of ball lightning with respect to shape.

Shape	Number of cases		Sum, %
	Stakhanov[12] 878 cases	Grigor'ev *et al.*,[16] 2013 cases	
Sphere	788	1836	90.8±0.6
Ellipsoid	52	54	3.7±0.4
Tape	—	52	1.8±0.3
Shapeless	14	29	1.5±0.2
Pear	20	7	0.9±0.2
Disk	1	16	0.6±0.1
Ring	2	9	0.4±0.1
Cylinder	1	4	0.2±0.1
Spindle	—	5	0.2±0.1

TABLE VI. Probability for the appearance of ball lightning in various types of weather according to Ref. 16 (1924 cases).

Weather	Thunder storm	Over half an hour		Rain	Cloudy	Clear
		Before the storm	After the storm			
Probability, %	61,6	6,6	8,8	7,2	6,0	9,8

cases, the ball lightning was entrained by the wind, while in 4 cases it moved against the wind.

The velocity at which ball lightning moves lies in the range 0.1–10 m/s. The distribution of cases with respect to velocity has been found by Rayle,[6] Stakhanov,[11,12] and Grigor'ev.[16] The average velocity has been estimated to be a few meters per second.

2.5. Observation conditions

A definite role in our understanding of the nature of ball lightning is played by the conditions under which it is observed. These conditions give us an idea of the factors which influence the formation of ball lightning. There is usually a correlation between stormy weather and the observation of ball lightning. According to McNally's data[5] (513 observational cases), for example, 73% of the cases were observed during stormy weather. According to Rayle's data[6] (112 cases), this figure is 62%, according to Stakhanov's data[12] (1006 cases) it is 70%, and according to Grigor'ev's data[16] (1924 cases) it is 77%. According to Barry's data,[25] ball lightning was observed during a thunderstorm in 90% of the cases which he analyzed. Although each author understands "stormy weather" in his own way, we do see the correlation between the occurrence of ball lightning and storms. Table VI shows Grigor'ev's data[16] on the relationship between the appearance of ball lightning and the weather in more detail.

Indirect proof of a correlation between the appearance of ball lightning and stormy weather comes from the distribution of cases of ball lightning among the various months of the year. It follows from Table VII and Fig. 1 that more than 80% of the cases of ball lightning occur in the summer months (June–August), when most storms are observed. According to Egely's data,[21-24] 86 of 133 cases of the observation of ball lightning in Hungary fell in summer months.

This information, which refers to the USSR, the US, and several European countries, is thus directly and indirectly related to stormy weather. It might appear that this question is completely settled. However, some new data on Japanese ball lightning,[18-20] with a large statistical base (2060 cases), yield a different result: 89% of the observations occurred in clear weather, 7.6% occurred in rain, and only 2.5% during storms. In addition, there is a strong correlation between the seasonal distributions of ball lightning and ordinary lightning and also between their distributions over the area of Japan. Ohtsuki and Ofuruton[18-20] assert that the possible discrepancy between these results on Japan and the results for the "continent" might stem from particular features of Japanese weather. In summer months, on clear days, the relative humidity of the air in Japan is above 80%. At any rate, the discrepancy here requires a special analysis.

Despite this discrepancy, in both the Soviet and Japanese observations there is a good correlation between the seasonal distribution of ball lightning and that of ordinary lightning; in the Japanese observations, there is also a correlation in terms of the place of observation. Let us introduce a correlation coefficient in the usual way:[26]

$$k=\frac{\sum_i (X_i-\overline{X})(Y_i-\overline{Y})}{\left(\sum_i (X_i-\overline{X})\right)^2\left(\sum_i (Y_i-Y)^2\right)^{1/2}},$$

where X_i refers to the distribution of cases of ordinary lightning, Y_i refers to the distribution of cases of ball lightning, the index i specifies the nature of the distribution, and $\overline{X}$ and $\overline{Y}$ are the mean values of these quantities. In particular, for the seasonal distribution, X_i and Y are the probabilities for the observation of ordinary lightning and ball lightning, respectively, in the given month, and we have $\overline{X}=\overline{Y}=1/12$.

TABLE VII. Seasonal distribution of cases of ball lightning in the USSR.

Month		May	June	July	August	September	October-April	Sum
Data of Stakhanov[11,12]	Number of cases of ball lightning	48	158	355	225	35	63	884
	Fraction, %	5,4	17,9	40,2	25,4	4,0	7,1	100
Data of Grigor'ev[16]	Number of cases of ball lightning	117	296	823	296	69	112	1713
	Fraction, %	6,8	17,3	48,0	17,3	4,0	6,5	100
Overall data	Number of cases of ball lightning	165	454	1178	521	104	175	2597
	Fraction, %	6,4	17,5	45,4	20,0	4,0	6,7	100

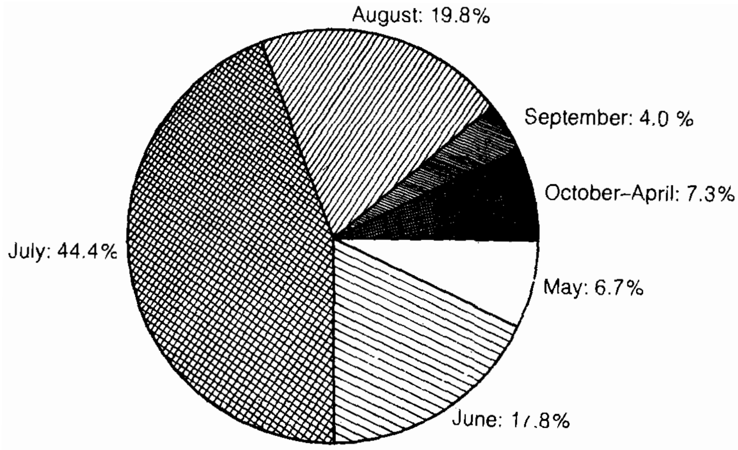

FIG. 1. Seasonal distribution of cases of ball lightning in the USSR and Hungary (2730 observational cases).

If the phenomena in question have a common origin, their probabilities would be related; i.e., we would have $X_i = AY_i + B$, where A and B are numbers. The correlation coefficient would then be unity. In the other limit, X_i and Y_i would be random quantities. In that case we would have

$$\sum_i (X_i - \bar{X})(Y_i - \bar{Y}) = \sum_i (X_i - \bar{X}) \sum_i (Y_i - \bar{Y}) = 0,$$

i.e., a zero correlation coefficient. Table VIII shows values of the correlation coefficient expressing the correlation between the probabilities for the appearance of ordinary lightning and ball lightning. We see that the data from different observations agree approximately, and the average correlation coefficient is

$k = 0{,}84 \pm 0.04.$

The places where ball lightning is observed are interesting. In roughly half the cases, the ball lightning is observed indoors. According to Rayle's data,[6] this fraction is 48%. Charman[10] analyzed 71 observations and reported that in 45 cases the ball lightning was observed outdoors, in 15 cases it was observed indoors, and in 11 the ball lightning penetrated into a building from the exterior. Table IX shows the corresponding data of Grigor'ev,[15] and Fig. 2 shows the overall data. In several cases, ball lightning has been observed in airplanes, and there are several reports of collisions of ball lightning with airplanes. These reports are evidence that it is possible for ball lightning to form at substantial heights. We will add that according to Grigor'ev's data[15] the ball lightning was observed in cities in 35% of the cases and in rural areas in 64%.

The distribution of cases with respect to the smallest distance to the observer is interesting. This information also gives us an idea of the brightness of ball lightning, since the brightness affects the distance over which an observer can detect the ball lightning. Table X and Fig. 3 show the distribution of cases of ball lightning with respect to distance from the observer. At large distances R the probability for the observation of ball lightning in an interval dR is described by a weak function of R: $dP \sim dR/R^{\alpha}$, where $\alpha \approx 1.5$. At small distances this probability cannot be described by a simple function. The typical optimum distance from the observer is a few meters.

2.6. Observation probability

A curious aspect of the ball-lightning problem concerns the probability for observing it. Ball lightning is regarded as a rare phenomenon, but the average probability for observing it can still be estimated. Rayle reports[6] that he asked 4400 of his coworkers at NASA and was told that 180 had observed ball lightning. Stakhanov[12] estimates the probability that a person will observe ball lightning over his lifetime as $P = 10^{-3}$. The most reliable information on this point comes from Egely's data.[21,23] Egely appealed to ball lightning eyewitnesses through Hungarian newspapers which had $1.5 \cdot 10^6$ subscribers and received descriptions of 520 cases of ball lightning, which had been observed by about 1500 people.[21] If we assume that the people who observe ball lightning

TABLE VIII. Correlation coefficient expressing the relationship between the probabilities for the observation of ordinary lightning and ball lightning.

Nature of distribution	Month of observation	Time of day of observation
Correlation coefficient	0,83 [12] 0,79 [16] 0,86 [18, 19]	— 0.88 [16] —

TABLE IX. Place where ball lightning has been observed[15,16] (1984 cases).

Place	Fraction, %	Place	Fraction, %
Indoors	50,2	At bank of river or lake	4,0
On street	24,5	In mountains	2,3
In field	9,5	In the sky, from the ground	4,1
In forest	4.4	In clouds, from an airplane	1,0

have lived half their life, on the average, and if we assume that all the subscribers report their observations, then we find an upper limit $P=2\cdot 10^{-3}$ on the probability that a person will observe ball lightning during his lifetime.

After Egely's communications with the newspaper subscribers were firmly established, he received, over the course of 1987, reports of 39 observations of ball lightning.[23] We can thus make another upper estimate of the probability for the observation of ball lightning over the lifetime of a person: $P=2\cdot 10^{-3}$. Putting all these data together, we find the following result for this probability:

$$P=10^{-2,2\pm 0,5}. \tag{4}$$

We can now move on to the areal density of the frequency of appearance of ball lightning. Referring this distribution to the earth's surface, we have the following expression for this density:

$$W=\frac{P}{\tau}p(0), \tag{5}$$

where τ is the lifetime of a person, and $p(R)$ is the distribution of cases of ball lightning with respect to distance from the observer. According to the data in Table X we have $p(0)=10^{-0.6\pm 0.5}\ \mathrm{m}^{-2}$, so the areal density of the frequency of appearance of ball lightning is

$$W=10^{1,3\pm 1,0}\ \mathrm{km}^{-2}\ \mathrm{yr}^{-1} \tag{6}$$

This figure is several orders of magnitude higher than an estimate offered by Barry.[25,27,28]

It is convenient to compare this figure with the density of the frequency of appearance of ordinary lightning, which is[29] $5.4\pm 2.1\ \mathrm{km}^{-2}\cdot\mathrm{yr}^{-1}$. Taking the ratio of these figures, we find

$$n=4\cdot 10^{\pm 1,2}. \tag{7}$$

cases of ball lightning per case of ordinary lightning.

We see that ball lightning is not a rare phenomenon. However, since it is usually observed at short range, the probability for observing it is a small quantity, although the probability for its occurrence is not.

2.7. Appearance and decay

Electrical phenomena in the atmosphere promote the formation of ball lightning. In his collection of observational data, Stakhanov[11,12] analyzed cases in which the stage in which the ball lightning appeared was detected. Of 67 such cases, in 31 it appeared directly in or near the channel of linear lightning, while in 29 it appeared from various metal objects and apparatus: electric sockets, radio receivers, heat-supply batteries, and so forth. In 7 cases it flared up "from nothing" in air. Table XI shows corresponding data from Grigor'ev,[16] which include 286 cases in which the ball lightning was observed to appear. The data are combined in Fig. 4.

Ball lightning may terminate either quietly or in an explosion. According to McNally's data,[5] the ball lightning decayed quietly in 112 cases and ended in an explosion in 309

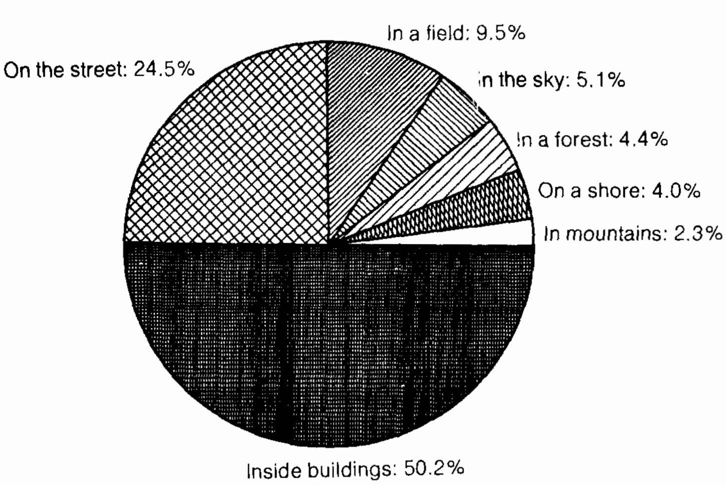

FIG. 2. Places where ball lightning is observed[15] (1984 observed cases).

TABLE X. Distribution of cases of ball lightning with respect to smallest distance from observer.

Distance range, m	Number of cases				Fraction, %
	Stakhanov[11,12]	Grigor'ev[16]	Egely[21]	Sum	
0—1	158	505	25	688	26
1—5	331	476	119	926	34
5—10	104	87	22	213	8
10—20	102	95	21	218	8
20—50	103	92	21	216	8
50—100	107	62	5	174	7
Greater than 100	80	137	31	248	9
Sum	985	1454	244	2683	100

cases. According to Rayle's data,[6] a quiet fading occurred in 54 cases, while an explosion was observed in 24. According to Charman, there was a quiet fading in 25 cases, while there was an explosion in 26. According to Egely's data,[21-23] the evolution of the ball lightning terminated in an explosion in 84 cases, while in 43 cases it faded away quietly. Table XII shows the data of Stakhanov[11,12] and Grigor'ev[14] for cases in which the termination of the ball lightning was observed. If we sum all these data, and if we lump in with the slow fades the cases in which the ball lightning broke up into parts, we conclude that explosions account for roughly half the terminations of ball lightning. Figure 5 shows a distribution with respect to the particular way in which the ball lightning decays for the sum of the observed cases.

In most of the observed cases, the ball lightning decayed without leaving any trace of itself. In some cases there were effects and damage which can be used to estimate the corresponding expenditure of energy. Such cases were analyzed by Barry,[25] Stakhanov,[12] and Egely.[24] On the basis of those estimates and Ref. 30, an energy distribution of cases of ball lightning has been constructed. It is shown in Fig. 6. Let us outline the general approach used to construct this distribution.[31-33] The distribution is written in the form $dP = CdE/E$, where C is a constant, and dP is the probability that the energy of the ball lightning lies in the energy interval dE. The energy of the ball lightning, E, has upper and lower bounds ($E_{\min} < E < E_{\max}$). From these results we find $30\cdot 10^{\pm 0.2}$ kJ as the most probable energy of ball lightning.

The observational cases for which the energy was estimated can be put somewhat arbitrarily into two categories. The first is that of cases in which the corresponding effect of the ball lightning could have resulted from internal energy of the ball lightning. The second category is that of cases in which energy from some external electrical source was utilized. In the first category, the most probable energy of the ball lightning is $7\cdot 10^{\pm 0.2}$ kJ. The limits on the energy range here are $E_{\min} = 0.1\cdot 10^{\pm 0.2}$ kJ and $E_{\max} = 400\cdot 10^{\pm 0.2}$ kJ. In cases in which the energy released as a result of the ball lightning was determined by an external electrical source, the most probable release of energy was $200\cdot 10^{\pm 0.2}$ kJ, and the range of energies was from $E_{\min} = 10\cdot 10^{\pm 0.2}$ kJ to $E_{\max} = 5\cdot 10^{\pm 0.2}$ MJ.

From these results we can find an estimate to satisfy our

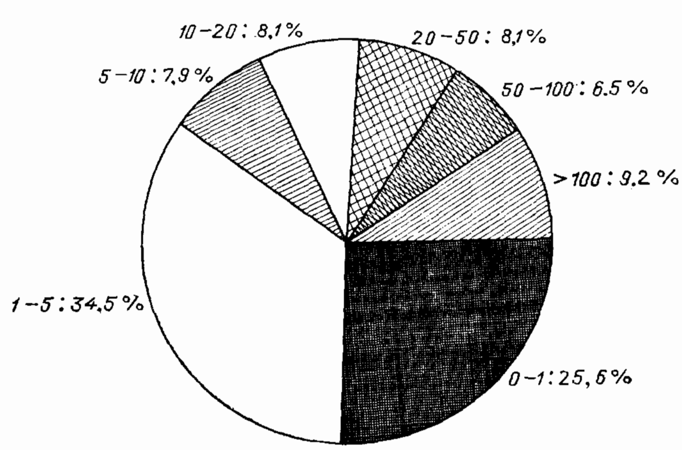

FIG. 3. Distribution of cases of ball lightning with respect to the smallest distance from the observer (2683 observed cases).

TABLE XI. Probability for the occurrence of ball lightning.[16]

Nature of occurrence	Number of cases	Probability, %
On metal conductor	154	54
At place where linear lightning has struck	32	11
In discharge channel of linear lightning	29	10
On metal conductor during a lightning stroke	21	7
On metal conductor from spark	20	7
In air "from nothing"	17	6
In clouds	13	5
Sum	286	100

curiosity on another point: How much power is dissipated in ball lightning? The average internal energy of ball lightning is

$$\bar{E} = \int_{E_{\min}}^{E_{\max}} E\,dP = E_{\max}\left(\ln\frac{E_{\max}}{E_{\min}}\right)^{-1} = 200\cdot 10^{\pm 0.2}\ \mathrm{kJ} \qquad (8)$$

Working from (6) and (8), we then find the average power of all ball-lightning activity:

$$\mathcal{P} = \bar{E} W S = 10^{4.1\pm 1.2}\ \mathrm{kW}$$

where $S = 5.1\cdot 10^8\ \mathrm{km}^2$ is the surface area of the earth. It is interesting to compare this figure with the average power of ordinary lightning. We take the latter to be of the order of[34-36] $5\cdot 10^7$ kW. If we treat ball lightning as a secondary effect of ordinary lightning, we then conclude that $10^{-3.6\pm 1.2}$ of the energy of ordinary lightning is expended on the production of ball lightning.

2.8. Emission properties

The emission by ball lightning occupies a central position among its properties. The emission results from processes which are important in the existence of this phenomenon, so reaching an understanding of the nature of the emission processes will also shed light on the nature of ball lightning. One characteristic of the emission is the color. Table XIII summarizes data on the color of ball lightning according to various sets of observational data. In this and the following table, we are using the simplified scheme for the distribution of ball lightning by color which was proposed by Stakhanov.[11] The last column of this table shows the probability for the given color found from the sum of the data; shown in parentheses is the value of this quantity according to Stakhanov's data. These results agree within the statistical error except for the case in which there is a mixture of colors. This case has apparently been discussed in different ways in different sets of observational cases.

It might seem that contradictions would arise in the agreed-upon picture of the distribution of observed cases of ball lightning by color as the number of observations increased. Table XIV compares the overall data from Table XIII with Grigor'ev's data.[16] Here Stakhanov's method for the distribution of observed cases of ball lightning by color has been used. The statistical error is given for the relative probability for the given color. It follows from Table XIV that the discrepancies in these data go well beyond the statis-

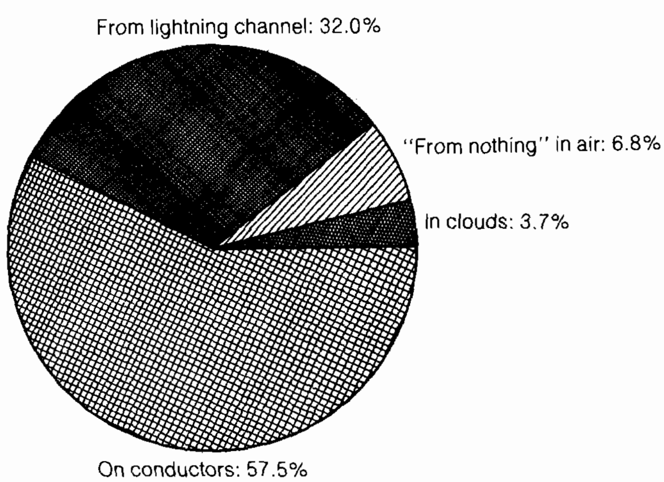

FIG. 4. Nature of the formation of ball lightning (353 observed cases).

TABLE XII. Mechanisms for the decay of ball lightning.

Nature of decay	Stakhanov[12]		Grigor'ev[16]	
	Number of cases	Fraction, %	Number of cases	Fraction, %
Explosion	335	55	493	43
Went into ground			157	14
Went into conductor			100	9
Quiet fading	197	32	258	23
Breakup into parts	78	13	123	11
Sum	610	100	1131	100

tical error. Further research will be necessary in order to determine the reason for these discrepancies. Figure 7 shows the distribution by color for the sum of observations of ball lightning.

The observed diversity in the color of ball lightning is evidence that this is a complex phenomenon. It follows that the emission of ball lightning may come from different substances. A more definite understanding of ball lightning as a source of light follows from an analysis of its brightness. A crude analysis[6] shows that ball lightning is a light source of intermediate intensity. Substantial progress in this area has been achieved by Stakhanov,[12] who collected data on the brightness of ball lightning as a source of light. Because of the imperfections of the eye as an instrument for measuring the brightness of a light source, and also because of the unusual conditions under which the brightness of ball lightning is perceived, one can estimate that the brightness of the ball lightning is determined within a factor of two or three in each case. To some extent, the large statistical base of observations reduces this error. Despite this large error, this information is of major importance. A good scale for expressing the brightness of ball lightning has been developed: The brightness is compared with that of an electric light bulb. Stakhanov's method was subsequently used by Grigor'ev.[16] These results are shown in Table XV.

In analyzing the data in Table XV, we assume that the brightness distribution of the cases of ball lightning is of the form

$$f(J) = \frac{nJ^{n-1}}{J_0^n} \exp\left[-\left(\frac{J}{J_0}\right)^n\right], \tag{9}$$

where $f(J)$ is the probability that the brightness of the ball lightning is J, and J_0 and n are parameters. The normalization condition on the probability is

$$\int_0^\infty f(J)\,dJ = 1.$$

We then have the following expression for $W(J_i, J_k)$,the probability that the brightness of the ball lightning lies in the interval from J_i to J_k:

$$W(J_i, J_k) = \exp\left[-\left(\frac{J_i}{J_0}\right)^n\right] - \exp\left[-\left(\frac{J_k}{J_0}\right)^n\right]. \tag{10}$$

Let us construct the functional

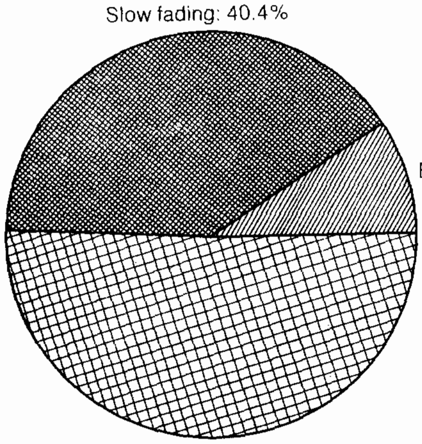

FIG. 5. Nature of the decay of ball lightning (2418 observed cases).

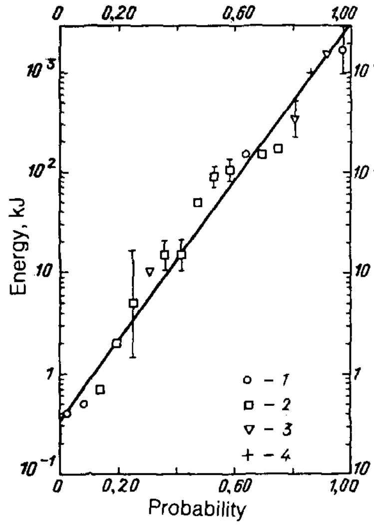

FIG. 6. Energy distribution of ball lightning. 1—Data of Ref. 25; 2—Ref. 12; 3—Ref. 23; 4—Ref. 30.

$$\varepsilon(n, J_0) = \sum_i (W(J_i, J_k) - W_{\text{obs}}(J_i, J_k))^2, \qquad (11)$$

where the probability $W(J_i, J_k)$ is given by (10), and $W_{\text{obs}}(J_i, J_k)$ corresponds to the observational data and is given in Table XV. The values of this functional are shown in Fig. 8 for certain values of the parameters as constructed from the sum of Stakhanov's data[12] and Grigor'ev's.[16]

The best parameter values clearly correspond to the minimum of functional (11). On this basis we can select from the class of distribution functions of the type in (9) that which gives the best description of the observational data. This function is characterized by the parameter values $n = 1.1$ and $J_0 = 116 \pm 12$ W (Fig. 8). The results found by this algorithm on the basis of Stakhanov's data[12] alone or Grigor'ev's data[16] alone (Table XV) agree within the indicated error with these results. We thus find the average brightness of ball lightning, in units of the power of an equivalent electric light bulb, to be

$$\bar{J} = \int_0^\infty J f(J)\, dJ = 110 \pm 10 \text{ W}.$$

Switching to the units used in illumination engineering, we find

$$\bar{J} = 1500 \text{ lm} (\pm 10\%).$$

The error indicated here reflects only the statistical scatter of the data. The actual error is considerably larger, since the method used to construct each value of the observed brightness is quite crude.

We might note another fact. Grigor'ev[16] estimates the dependence of the brightness of ball lightning on its diameter by the expression $J(D) \sim D^{2.4}$. If the diameter and brightness are correlated, this would be a reasonable expression, since with $J(D) \sim D^2$ we would have a surface source, and with $J(D) \sim D^3$ we would have a volume source, so this expression would describe an intermediate case. However, when we adopt this expression we find from expression (1) that the optimum value of the parameter n in (9) is close to 0.4. With that value, expression (9) does not agree well with the data in Table XV. In order to resolve this contradiction, we need to assume that the brightness of ball lightning is not correlated with its diameter. This assertion leads to the conclusion that ball lightning radiates from its surface. The analysis below of observational data makes it possible to test the validity of this conclusion.

2.9. Other properties

Looking at the other properties, we note that ball lightning is capable of acting as a source of heat. According to Rayle's data,[6] a perception of heat was reported in 4 cases of the collection, while such a perception was denied in 100 cases. In Stakhanov's collection,[11,12] 25 people of 294 who had observed ball lightning from a distance of less than 1 m reported a perception of heat; 8 people of 131 who were from 1 to 2 m away from the ball lightning reported heat; 20 of 379 people for which the smallest distance to the ball lightning was 2–5 m reported heat; and 9 of 676 people who observed the ball lightning from a distance greater than 5 m reported heat. According to Grigor'ev's data,[16] of the 383 cases in which the observers of ball lightning reported a perception of heat 64 answered this question in the affirmative. It follows from the entire set of data that only a few percent of the

TABLE XIII. Distribution of observed cases of ball lightning by color.

Observed color	Number of observations					Sum of observations	Probability of given color, %
	McNally[5]	Rayle[6]	Charman[10]	Egely[21]	Stakhanov[12]		
White	44	27	15	55	244	385	23 (26)
Red	48	7	5	56	180	296	18 (19)
Orange	50	46	12	7	113	228	14 (12)
Yellow	40	37	20	43	246	386	23 (26)
Green	3	10	2	—	12	27	2 (1)
Pale and deep blue through violet	42	25	5	18	111	201	12 (12)
Mixture of colors	84	—	9	26	30	149	9 (3)
Total number of cases	311	152	68	205	936	1672	100

TABLE XIV. Comparison of data on the distribution by color of observations of ball lightning.

Observed color	Sum of data in Table XIII		Grigor'ev[16]	
	Number of observations	Probability of given color, %	Number of observations	Probability of given color, %
White	385	23±1	247	14±1
Red and rose	296	18±1	297	16±1
Orange	228	14±1	633	35±1
Yellow	386	23±1	307	17±1
Green	27	1,6±0,3	22	1,2±0,3
Pale and deep blue through violet	201	12±1	230	13±1
Mixture of colors	149	9±1	67	3,7±0,5
Sum	1672	100	1803	100

observers report the perception of heat. There is no strong relationship between the probability for the perception of heat and the distance to the ball lightning, although we would expect such a relationship in the case of an isotropic heat source.

There may be an odor associated with the appearance of ball lightning. We do not have clear statistics on this point, but a variety of odors have been mentioned: sulfur, ozone, and nitrogen oxides. The appearance of ball lightning is frequently accompanied by a moderate sound: a crackle, hiss, or whistle. Ball lightning causes distortions in radio receivers. Dmitriev[7] has pointed out that in 6 of the 45 cases of the observation of ball lightning which he collected an effect of the ball lightning on radio communication was observed.

Ball lightning has electrical properties. We do not have clear statistics on this question. Several cases of this type have been described by Stakhanov.[12] The effect of ball lightning on a person is generally similar to the effect of an electric current. It can cause temporary numbness or paralysis of part of the body. According to Grigor'ev,[16] in three cases of his collection there were reports of burns from ball lightning similar to those from ultraviolet light.

Ball lightning sometimes leads to fatalities. In Stakhanov's collection,[11,12] for example, 5 fatal outcomes were mentioned in about 1000 cases of the observation of ball lightning. An analysis by Grigor'ev[16] shows that such reports should be treated with caution, because—if for no other reason—the information is coming from someone who is not a direct observer of the events. Indeed, the experience gained in our newspaper communications on this matter points to a low reliability of such publications. At any rate, the probability that people die as a result of ball lightning is extremely low, except in cases in which there is an electrical explosion with severe damage.

2.10. Authenticity and accuracy of the observational data

The authenticity and reliability of the observational data warrant a separate discussion. The authenticity of an individual observer is low, so it is not surprising that ball lightning was widely regarded as an optical illusion a few decades back (Refs. 37–39, for example). According to that interpretation, an intense flash of ordinary lightning would leave a trace on the retina of the observer's eye as a result of

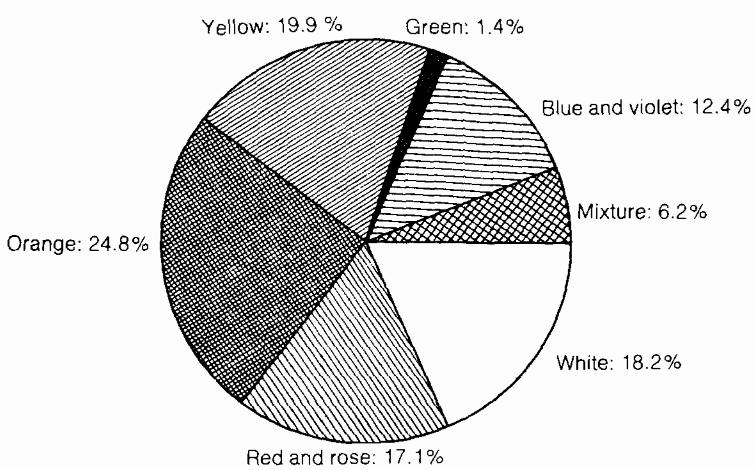

FIG. 7. Distribution of cases of ball lightning by color (2730 observed cases).

TABLE XV. Comparison of the brightness of ball lightning with the brightness of an electric light bulb.

Power of equivalent electric light bulb, W	Data of Stakhanov[12]		Data of Grigor'ev[16]	
	Number of cases	Fraction of total number, %	Number of cases	Fraction of total number, %
Less than 10	55	9,2	89	6,7
10—20	83	13,9	103	7,8
20—50	109	18,3	209	15,8
50—100	140	23,4	314	23,8
100—200	150	25,1	376	28,5
200—500	39	6,5	230	17,4
More than 500	21	3,5		
Sum	597	100	1321	100

several photochemical processes, and this trace would persist on the retina as a spot for 2–10 s. This spot would be perceived as ball lightning. As observational data accumulated, however, this hypothesis lost its adherents. Each observation includes a set of details which is difficult to accept as a fantasy of the observer. Consequently, essentially all the authors of books and reviews on ball lightning, as well as collectors of cases of observations, regard ball lightning as a real phenomenon.

However, the reliability of each individual case can still be questioned. In the first place, the observation of ball lightning is an unexpected event. The observer is not prepared. Moreover, the observer is in an excited state, so errors may be made in describing the observed phenomenon. Second, the observer tries to fit what he has seen into some pattern, with the result that proportions are distorted in the picture

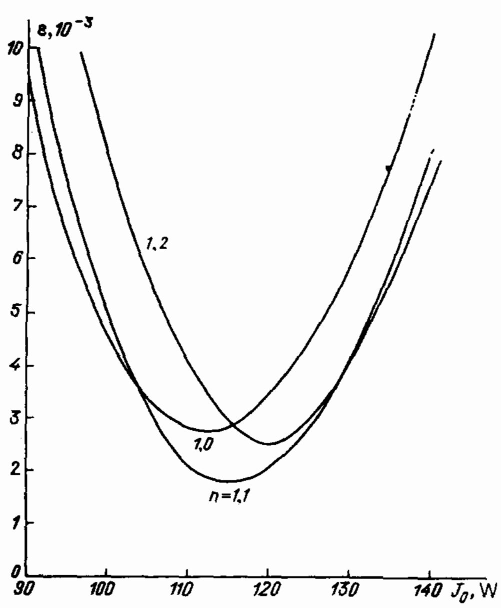

FIG. 8. The functional $\varepsilon(J_0,n)$ in (11) for various values of the parameters of distribution (9) of cases of ball lightning with respect to the radiant power emitted. The radiant power of the equivalent flux is expressed in the units of an electric light bulb.

which is seen, and the reliability of the details may be affected. Third, the way in which the properties of the phenomenon are determined leaves room for serious errors in the results. Fourth, this infomation frequently makes the press, where time pressure and the sensationalism of the report may result in serious distortions.

As a curious example in this direction we offer the following.[40] The newspaper *Komsomol'skaya pravda* published a note entitled "Fiery Visitor" on 5 July 1965 which describes the behavior of ball lightning with a diameter of about 30 cm which had been observed shortly earlier in Armenia. In particular, the following was stated in this article:

> Roaming around the room, the fiery ball passed through an open door into the kitchen and then flew out a window. The ball lightning hit the ground at the door and blew up. The force of this explosion was so great that a little wattle-and-daub house about fifty meters away collapsed. Fortunately, no one was killed.

An inquiry was submitted to the main office of the Hydrological and Meteorological Surface of the Armenian SSR regarding the behavior of this ball lightning. It was stated in response that ball lightning had indeed been observed. The behavior of the ball lightning in the apartment was described, and the description bore no resemblance to the words in *Komsomol'skaya pravda*. The response closed with the following words: "As for this wattle-and-daub house, the semicollapse was totally unrelated to the ball lightning."

Unfortunately, this was not the end of the matter. The report by the correspondent of *Komsomol'skaya pravda* served as the basis for an estimate of the energy of the ball lightning:[41] of the order of 10^9 kcal (this is the energy of a ton of explosives!). This estimate has been used in many publications on the energy of ball lightning, including some books.[25,42] Since the number of observations which permit estimates of the energy of the ball lightning is not very large (Fig. 6), a report of this sort is annoying disinformation.

The accuracy of the values of individual properties of ball lightning can be tested. Charman[10] reported on observations of meteors in the US after which witnesses were interviewed. The time of observation of the meteors in the sky was reported within an error of about 30%, while reports of other properties (color and sound) were less reliable.

The Grigor'evs[17] tested the accuracy in a large group of

TABLE XVI. Average properties of ball lightning.

Property, units of measure	Value of property
1 Probability of spherical shape, %	90 ± 1
2. Diameter, cm	23 ± 5
3. Lifetime, s	$8 \cdot 10^{\pm 0.3}$
4. Energy, kJ	$10^{1,3 \pm 0,2}$
5. Color	White, red, orange, yellow ($80 \pm 2\%$) Pale or deep blue, violet, green ($13 \pm 1\%$)
6. Light flux, lm	1500 ($\pm 10\%$)
7. Luminous efficiency, lm/W	$0,6 \cdot 10^{\pm 0,5}$
8. Correlation with atmospheric electricity	$70 \pm 10\%$ of cases of ball lightning in continental countries are observed in stormy weather
9. Season of year	More than 80% of cases of ball lightning are observed during summer months
10. Decay	In $50 \pm 10\%$ of the cases, the existence of the ball lightning terminates in an explosion
11. Probability for observation of ball lightning over a person's lifetime	$10^{-2.2 \pm 0.3}$

students and reached the conclusion that they determined the size of a ball with an accuracy of $10^{\pm 0.06}$, a time interval with an accuracy of $10^{\pm 0.2}$, and the brightness of a light source with an accuracy of $10^{\pm 0.2}$. These numbers are clearly upper boundaries on the accuracy for the properties of ball lightning reported by its observers.

It should be kept in mind that the reliability of certain reports is low, and they may distort the information about the ball lightning which is observed. A natural way to reduce the effect of unreliable information is to gather a large number of data points. Even in this case, of course, we cannot avoid errors, but with a large statistical base the errors should be at the scale of the values presented earlier.

2.11. Observational model of ball lightning

It is convenient to work from these sets of observations of ball lightning and the analysis of the observational data within these sets to construct an observational model of ball lightning which would have the average ball-lightning properties found from observations. This model would be of value from the collection standpoint and might serve as a basis for analyzing the nature of ball lightning. Table XVI shows the properties of this ball lightning. It is important to note that these values were found from an average of a large data file, so they are highly reliable within the error with which the corresponding property was found. We will not discuss the errors which stem from the primitive "eyeball" method by which the observational data were determined. Clearly, the error of this method of obtaining a result persists to a large degree when a large data file is averaged. Even within these errors, however, the collection and analysis of observational data which have been carried out (Table XVI) are of huge scientific value.

A convenience of the observational model of ball lightning is that it contains only facts which have been manifested in many cases of the observation of ball lightning. It should be noted, however, that a large fraction of the information which follows from the large data file is lost in the construction of a model of this sort. This loss is unavoidable because we have taken from the distribution with respect to a given property only its average characteristic. This replacement may result in the omission of qualitative characteristics present in the distribution function. For example, in analysis of the lifetime of ball lightning it was mentioned that there are two types of ball lightning (according to Stakhanov)[12] or three types (according to Grigor'ev)[16], which differ substantially in lifetime. Another important element which is not incorporated in the model of average ball lightning concerns the correlation between individual properties. These correlations have been established on the basis of a large data file (see Refs. 11, 12, and 15–17), and they reflect certain internal relationships between processes in ball lightning. Despite these shortcomings, an observational model of ball lightning is quite valuable. It is simple, and it provides an opportunity for simple tests of various hypotheses about what happens inside ball lightning.

3. ANALYSIS OF OBSERVATIONAL DATA

3.1. Interaction with the surrounding air

Analysis of the observational data on ball lightning makes it possible to draw a picture of this phenomenon. This analysis leans on known physical laws and makes it possible to work from the observational data to obtain new information concerning the nature of ball lightning. This approach has been taken, to varying degrees, in all the scientific books and reviews[10–12,25,32,33,42,43] and also some books[40,44,45] on ball lightning which are popularizations. The analysis makes use of certain assumptions, and the reliability of the conclusions depends on the validity of these assumptions. In this section of our review we include an analysis of the nature of ball lightning which stands on a solid foundation and which makes it possible to make reliable assertions regarding the nature of ball lightning. These assertions then become the foundation for further ideas about this phenomenon.

In our analysis we start from the position that ball lightning is some material formation in air in which certain processes occur, resulting in the release of energy and electromagnetic radiation. These processes also determine the observed properties of this luminous formation. We begin by considering the interaction of ball lightning with the sur-

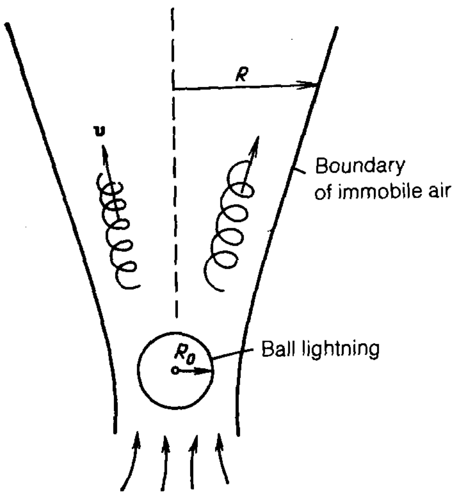

FIG. 9. Motion of the heated air near ball lightning.

rounding air. We assume that the ball lightning survives this interaction as a material formation and that the energy evolved by the ball lightning as heat goes into the air. These assumptions agree with observational data. We then analyze the nature of the motion of the surrounding air. Figure 9 shows a general picture of this motion. As it is heated near the ball lightning, the air rises, and cool air is drawn in to take its place. Far above the ball lightning, the motion of the air is similar to the motion of smoke emerging from a chimney. We will take this circumstance into account in estimating the properties of the moving air far from the ball lightning on the basis of the theory of Zel'dovich.[46]

We start with the Navier-Stokes equation for moving air:

$$(\mathbf{v}\nabla)\,\mathbf{v} = \nu\Delta\mathbf{v} + \mathbf{g}\,\frac{\Delta T}{T}, \tag{12}$$

where $\mathbf{v}$ is the velocity of the air, $\mathbf{g}$ is the acceleration due to gravity, ΔT is the difference between the temperatures of the air at the given spatial point and of the initial unheated air, and ν is the kinematic viscosity of air, which can be approximated well in the range of temperatures T of interest here by the function $\nu = \nu_0 (T/300)^{1.76}$, where $\nu_0 = 0.159$ cm^2/s (Ref. 47) These conditions, we might note, correspond to a slight heating of the air, $\Delta T \lesssim T$. Furthermore, the Reynolds number is large[2)] for motion of air under these conditions, $\mathrm{Re} = vR/\nu$ (R is the cross-sectional radius of the moving stream of air).

We see that the first term on the right side of the equation is small in comparison with the left side:

$$\nu\Delta v \sim \frac{\nu v}{R^2}\frac{1}{\mathrm{Re}} \ll \frac{v^2}{R}.$$

On this basis we find the following estimate of the typical velocity of the air where the cross-sectional radius of the moving air is R:

$$v \sim \left(gR\,\frac{\Delta T(R)}{T}\right)^{1/2}. \tag{13}$$

The power which is carried by the heated air is thus

$$Q \sim c_p\rho\Delta T \cdot vR^2 \propto c_p\rho g^{1/2}R^{5/2}\Delta T^{3/2}\cdot T^{-1/2}, \tag{14}$$

where c_p is the specific heat of the air and, ρ is its mass density. Since the power carried by the air does not depend on the cross-sectional area, we have $R^{5/2}\Delta T^{3/2}(R) = \mathrm{const}$, i.e.,

$$\Delta T(R) \sim R^{-5/3}. \tag{15}$$

As a geometric object, ball lightning exerts a drag on the moving air flow, so the air flowing around the ball lightning exerts an upward force on the lightning. Thermal processes associated with a transfer of heat from the ball lightning to the surrounding air thus give rise to a lifting force which acts on the ball lightning. This force is

$$F \sim \rho v^2R^2 \propto g\rho R^3\,\frac{\Delta T}{T}. \tag{16}$$

Introducing the numerical coefficient a, we rewrite this relation as

$$F = ag\rho R_0\,\frac{\Delta T(R_0)}{T}\,\pi R_0^2, \tag{17}$$

where R_0 is the radius of the ball lightning. In the model experiments carried out in Ref. 48, the numerical coefficient in (17) was found to be $a = 11 \pm 5$.

On the basis of these relations we can determine some properties of ball lightning. First, working from relation (14), and making use of the numerical parameter, we find that the heating of the air near an average ball-lightning formation is

$$T = 60\,\mathrm{K}\cdot 10^{\pm 0,6}. \tag{18}$$

This result is seen to be of the same order as that for an electric iron (flatiron), which is a good model for the heat exchange between ball lightning and the surrounding air. Second, we can determine the characteristic density of the ball-lightning material from the condition that it is capable of flying through the air. Equating the lifting force in (17), which is acting on an average ball lightning formation, to its weight, we find that the ratio of the weight of the ball lightning to the weight of the air which would occupy its volume under standard conditions is

$$Z = 1\cdot 10^{\pm 0,8}. \tag{19}$$

In other words, the average specific gravity of the ball-lightning material is of the order of that of air.[3)]

Two conclusions have thus been drawn from this analysis of the interaction of ball lightning with the surrounding air. First, the temperature in the boundary region is of the order of 100 K higher than the temperature of the air far from the lightning. Second, the specific gravity of the ball lightning material is of the order of that of air. No assumptions have been made here regarding the structure of the ball lightning, but in addition to the observational properties of ball lightning we have assumed that its properties remain the same over its lifetime.

3.2. Ball lightning as a source of light

The emission from ball lightning is one of its basic properties, so an analysis of the emission properties of ball lightning can provide useful information about it. For this purpose we compare ball lightning with other light sources, starting from the optical properties of an average ball-lightning formation (Table XVI), for which the light flux is

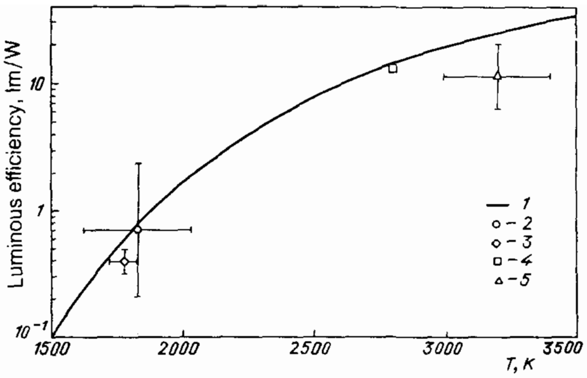

FIG. 10. Luminous efficiency of several light sources. 1—Blackbody; 2—ball lightning; 3—candle flame; 4—electric light buib; 5—pyrotechnic composition.

1500 ± 200 lm, and the luminous efficiency $0.6 \cdot 10^{\pm 0.5}$ lm/W. Figure 10 shows the luminous efficiency of ball lightning and that of some other light sources.

Let us compare ball lightning as a light source with a heated ball whose radius is equal to the radius of an average ball-lightning formation and whose surface is emitting as a blackbody. We can calculate the temperature that the ball surface would have if the light flux from it were the same as that from ball lightning. We find $T = 1360 \pm 30$ K. We can then calculate the temperature of a ball which would have the same luminous efficiency as an average ball-lightning formation. We find $T = 1800 \pm 200$ K. Finally, to reconcile the properties of the average ball-lightning formation which we are using, we assume that the heated ball has the same light flux and the same luminous efficiency as an average ball-lightning formation, but only part of the overall surface of the ball is emitting. We find that the fraction of the surface of the ball which is emitting is $10^{-1.7 \pm 0.8}$. From this simple analysis we can draw two important conclusions: First, the temperature of the emitting elements of ball lightning is about 2000 K. Here we must allow for the circumstance that in ball lightning there are energy-loss mechanisms beyond those characteristic of a blackbody. For this reason, the actual temperature of the emitting elements of ball lightning cannot be lower than that found from a comparison with a blackbody. Second, ball lightning is an optically thin system. By this we mean that either the lightning contains many seats of emission which together occupy only a small fraction of its volume, or—if the emission comes from all points of the volume—this is an optically transparent system in the visible part of the spectrum.

According to these estimates, the temperature of the emitting particles or emitting regions is of the order of 2000 K, while the temperature of the air bordering the ball lightning is substantially lower, according to the figures in the preceding paragraph. This discrepancy might be attributed to nonequilibrium conditions in the system in terms of the excited atoms or molecules which are emitting. In this case, the deviation from equilibrium results from the short lifetime of an excited atom, and situations of this sort are quite common in various problems in atomic physics, plasma physics, and high-temperature processes. At atmospheric pressure, however, the primary mechanism for the decay of excited atoms or molecules in air involves their collisions with molecules of air, not radiative processes. According to some calculations which have been carried out,[32,33,49] for example, the probability for the emission of a photon by a resonantly excited alkali metal atom in air at atmospheric pressure at a temperature of 2000 K is of the order of 0.01. This figure means that there is a nearly unit probability that an excited atom will decay as the result of a collision with air molecules, so the excited atoms will be at thermodynamic equilibrium with the air molecules. This conclusion, derived for resonantly excited atoms, is even more applicable to other excited atoms or molecules, which have shorter radiative lifetimes. Consequently, the density of excited atoms or molecules is determined exclusively by the temperature of this heated region; it does not depend on the particular method by which the excited particles are produced. Accordingly, the radiation temperature found above is the temperature of those regions of the ball lightning which are responsible for its emission.

As a result of this analysis we can draw the following conclusions. First, the temperature at the boundary of ball lightning [expression (18)] is relatively low. Second, the temperature of the emitting regions of ball lightning is about 2000 K. Third, these hot regions occupy only a small fraction of the volume of ball lightning. Putting these conclusions together, we can assert that ball lightning has a spotty structure and consists of many hot zones which together occupy only a small fraction of the volume.

The emission from these zones is perceived by the eye as an emission from the entire volume of the ball lightning. These conclusions are based on the observational properties of ball lightning and do not rest on additional assumptions regarding its structure or the processes which occur in it.

3.3. Nature of the energy storage

The answer to this question depends on whether we assume that the ball lightning is an autonomous source of energy or is maintained by an external energy source acting through electric or electromagnetic fields. This question has been debated for a long time now, and experience shows that either case is possible. For the time being we will restrict the discussion to the ball lightning which is observed near buildings into which external fields do not penetrate. According to Grigor'ev's data,[15,16] for example, of 1984 cases which were analyzed half the observations occurred in buildings (Table IX). In these cases the ball lightning is sustained by an internal energy source.

Taking into account the internal nature of the energy storage in ball lightning, and analyzing the processes which occur in it,[32,33,50,51] we reach the conclusion that only a chemical energy-storage method would be consistent with the ball-lightning lifetimes which are observed. This analysis runs as follows: We assume that the internal energy is stored in a plasma or in excited particles. We have concrete data for analyzing possible reaction mechanisms and for determining how the internal energy is converted into heat in each specific case. We introduce the internal-energy density ε and the lifetime of the system, τ, i.e., the time over which the system decays, and the internal energy converts into heat. In most cases we would have $\tau \sim 1/\varepsilon$; in particular, for all specific plasma models of ball lightning the product $\varepsilon\tau$ lies in the interval[32,50,51] $5 \cdot 10^{-13}$–$1 \cdot 10^{-11}$ J·s/cm^3. For the ball light-

TABLE XVII. The chemically active substance in an average ball-lightning formation.

Active substance	Specific energy evolution, kJ/g	Weight, g	Specific gravity,* g/liter
Pyrotechnic composition	6	1	0.2
Coal	30	0.2	0.04
Stearin	40	0.2	0.03
Ozone	3	2	0.4
SiO_2 aerogel	3	2	0.4

*The accuracy is $10^{\pm 1.0}$

ning which is observed (Table I), this quantity is $10^{1.2 \pm 0.6}$ $J \cdot s/cm^3$. This dramatic discrepancy is evidence that a plasma is incapable of storing the energy corresponding to observed ball lightning, over the lifetime of the lightning. We are thus forced to discard the plasma hypothesis and related hypotheses for ball lightning. This assertion can easily be understood from other standpoints. The lifetime of ball lightning is huge in comparison with the characteristic times of the kinetics of gases. For example, the time scale for collisions of molecules in atmospheric air is $\sim 10^{-10}$ s. Such a long relaxation time is suitable only for strongly forbidden processes, as which only chemical processes qualify. Processes involving charged particles, excited atoms, and excited molecules are vastly more efficient, so a storage of energy in such a form for a relatively long time would not be possible.

Chemical energy has yet another advantage over other types of energy: its high capacity. For example, the energy of an average ball-lightning formation could be provided by about ten matches. We imagine a sphere with a radius equal to that of an average ball-lightning formation, and we charge it to the limit, i.e., to the point that the electric field is at the breakdown level, $E = 30$ kV/cm. In this case the charge of the sphere is $10^{-5.2 \pm 0.1}$ C, and its energy is $10^{1.1 \pm 0.2}$ J, or smaller than the energy of an average ball-lightning formation by three orders of magnitude.

Comparing the chemical and electrical forms of energy, we note that chemical energy has a greater capacity, while electrical energy is characterized by much shorter times of conversion into other forms of energy. Once we assume that ball lightning has an internal energy source, we reach the unambiguous conclusion that this source is maintained by chemical energy. There is a certain amount of a chemically active substance inside ball lightning. Table XVII shows the weight of this substance for ball lightning with the most probable energy ($7 \cdot 10^{\pm 0.2}$ kJ), along with the specific gravity of the chemically active substance. We see that the specific gravity of the chemically active substance is lower than that of the ball lightning as a whole [expression (19)], although the difference does not go beyond the error of their determination.

Let us examine the latter case, in which the energy evolution in a porous system occurs at the expense of a loss of internal surface area; i.e., the substance becomes denser, losing its porosity. In the derivation of this quantity it was assumed that silicon dioxide molecules are spheres and that the interaction between them is a short-range interaction. With[52] $\Delta H = 133 \pm 7$ kcal/mole as the enthalpy per molecule of the solid-gas transition, there would be an energy evolution of $\Delta H/2$ per molecule initially on the internal surface upon a loss of internal surface area. We then find the energy evolution during the compaction of an aerogel to be $3.5 \pm 0.2\ J/m^2$. For an aerogel with a typical internal surface area ($S = 960\ m^2/g$), this result would correspond to a value of 3 kJ/g.

In many of the observed cases, an effect of ball lightning has been attributed to a release of electrical energy from an external source.[21,22] Indeed, in several cases it has been observed that electric power and telephone lines, various pieces of electrical equipment, and even buildings in rural areas are destroyed. If the damage is considerable, the charge flowing through the circuit is estimated to be 1 C. Since this charge is several orders of magnitude higher than that which ball lightning could carry in principle, we conclude that in these cases the electrical energy is drawn from an external source (a storm cloud or dust cloud) and that the ball lightning is a conducting body which causes an initial ionization in the air and transports energy of the external source.

There is, on the other hand, a list of observational cases which contradict a chemical source of energy for ball lightning. On this list are cases involving a rapid transfer of energy, e.g., a fusing of holes and metal objects, a splitting of trees and logs, etc. For example, the splitting of logs is represented as the result of a rapid evaporation of internal water, which creates a high pressure and ruptures the log.[12,15] These events would be possible only in the case of a rapid transfer of energy, in particular, during the flow of an electric current through a log. It would be difficult to imagine this to be the result of an effect of chemical energy.

These contradictions reflect the complexity of ball lightning as a real atmospheric phenomenon. Outdoors, ball lightning can evidently cause electric breakdown by virtue of an external energy source, so one could explain the circumstance that the energy released during the explosion is electrical. In cases in which the ball lightning is indoors, it is maintained by an internal, chemical energy source. These comments should evidently also be applied to ball lightning outdoors if it is in a free state.

With regard to the energetics of ball lightning, we thus reach the following conclusion. In most cases, ball lightning is maintained by an internal chemical source. Ball lightning interacts actively with electric and electromagnetic fields and can be the cause of an electric breakdown in air which results in the release of an energy significantly greater than that contained in the ball lightning. We have no basis for asserting that ball lightning indoors differs in nature from the ball lightning which causes the electric breakdown of air.

3.4. Structure and general conclusions

One of the primary questions regarding the nature of ball lightning is its structure. In analyzing this problem we need to allow for the circumstance that in most of the cases observed (Table V) the ball lightning has been spherical and has been capable of retaining its size and shape as it evolved. According to Ref. 16, in only about 4% of the observations has the ball lightning changed shape or broken up into parts. It follows that the substance of ball lightning (on the one hand) is tightly bound and (on the other) has a small specific gravity on the average.

These conclusions, combined with the observational properties presented earlier, impose some substantial requirements on the state of the substance of ball lightning. It follows in particular that the substance cannot be in a gaseous or dusty state. Estimates show that such formations, with the size and surface temperatures corresponding to the average ball-lightning formation, would lose their shape and would mix with the surrounding air over a time of the order of 0.1 s (Ref. 53).

Again we note that our discussion is based on the assumption that the processes which play out inside ball lightning are controlled by known physical laws. On this basis we are justified in rejecting ideas which have no analogs in the world around us. This is our attitude, for example, toward the hypothesis of Refs. 54–56, according to which the substance of ball lightning is in a state of a "strongly coupled" (or "nonideal") plasma. There is not enough information available to refute this hypothesis or even to make much progress toward analyzing it. However, there are no known cases of the prolonged existence of a strongly coupled plasma at a high temperature without an external energy source, and experience in the development of this problem shows that such an event would be difficult to expect. Consequently, despite the attractiveness of this hypothesis, it cannot compete with the ideas discussed below, which are based on definite analogs in nature or technology.

Ball lightning thus has a rigid framework. Since the average specific gravity of this framework is low, it is extremely porous. This outline of the structure of ball lightning has evidently been proposed before. For example, back in 1972 Zaĭtsev[57] asserted the following: "The appearance of ball lightning begins with the formation of three-dimensional cellular structures." In a 1982 paper by Aleksandrov *et al.*,[58] however, this concept was formulated on a fairly solid basis. Aleksandrov *et al.* worked from their own research on the explosion of metal wires by a current passing through them.[5] They observed that under certain conditions concerning the relaxation of the metal in the vacuum chamber some web-shaped structures formed, attached themselves to the walls of the chamber, and could persist in this state for 1–2 days. Measurements of the filaments making up these webs yielded an estimate of 0.01 μm. Extending these properties to ball lightning, Aleksandrov *et al.*[58] said that ball lightning had the structure of a filamentary aerosol, and they analyzed certain properties of ball lightning from this standpoint. In particular, they explained the stability of the structure of ball lightning in terms of an effect of electric charge which the lightning carries.

This picture of the structure of ball lightning was developed further in Refs. 32, 49, and 60. Earlier experimental work[61] had shown that the entities formed during the explosion of a metal wire under these excitation and relaxation conditions are of a fractal nature. They are called a "fractal aggregate" or "fractal cluster." This structure was extended to the framework of ball lightning,[49] so the framework of ball lightning has the structure of a fractal cluster. This refinement provides additional information. For example, it allows us to estimate the size of the structural elements of the framework of ball lightning, which turns out to be a few nanometers. However, at this point the very conclusion that ball lightning has a rigid framework is important for our purposes. This conclusion not only agrees with the observational data but also has analogs in the world around us.

From this analysis follow some general positions which should serve as the basis for models of ball lightning and which provide a general picture of the nature of this phenomenon. These positions reduce to the following: Ball lightning has a rigid framework with a specific gravity of the order of that of air. Chemical processes occur within this framework, and as a result of these processes chemical energy stored in ball lightning is converted into heat and the energy of radiation. This conversion occurs in many small-volume zones whose temperature is about 2000 K. The total volume of these seats of chemical reaction is small in comparison with the volume of the ball lightning. The average heating of the air at the boundary with ball lightning is some tens of degrees.

4. MODELING OF BALL LIGHTNING

4.1. Experimental modeling of ball lightning as a whole

If we are able to reach an understanding of the nature of ball lightning, we would in principle be in a position to reproduce this phenomenon. The development of a laboratory model of ball lightning would make it possible to study this phenomenon more thoroughly. For this reason, the history of research on ball lightning reveals numerous attempts to reproduce ball lightning as a whole under laboratory conditions. Some of these many attempts have been successful, resulting in the formation of glowing formations in air. Ultimately, however, even these successful attempts have failed to lead to a deeper understanding of ball lightning. These experiments have not turned out to be a step which would make possible more-detailed experiments and the determination of answers to new questions about the nature of this phenomenon. The reason for this lack of success lies in the complexity of the phenonenon, which rules out establishing the relationship between observational facts and experimental modeling of ball lightning as whole in any simple way.

In summary, the laboratory modeling of ball lightning with the goal of reproducing this phenomenon as a whole have been isolated episodes in the overall research on this topic. They have provided us with some useful experience. Many of these attempts are discussed in detail in Barry's monograph.[25] We will be discussing some of them below, in order to illustrate the general trends in the modeling of ball lightning and to take a look at them from the modern standpoint.

In all the early experiments the source of energy for the ball lightning has been an electric discharge in a gas, because this is a convenient method for supplying energy and because existing discharge devices have had an appropriate energy capability. Most cases of the modeling of ball lightning by this method were based on the assumption that ball lightning was of a plasma nature. For this reason, the goal in most of the studies was to produce a spherical discharge at atmospheric pressure which could exist even after the external source was turned off in certain formulations of the problem.

One of the primary conditions here is that the discharge region, which is a glowing plasma of spherical shape, must not touch the walls of the vessel in which the discharge is initiated. This condition was successfully arranged in 1942 by Babat (Ref. 62; see also Ref. 25). He used a microwave discharge with a frequency from 1 to 100 MHz and a power up to 100 kW. At pressures of the order of 10 torr, a fire ball appeared in the tube, without touching the walls. For many years thereafter, Babat's studies were continued and expanded by many investigators. Difficulties in the production of an rf discharge at atmospheric pressure were overcome by Kapitsa.[63,64] He was ultimately able to produce a microwave discharge in helium at pressures of several atmospheres. The glowing part of the discharge did not touch the walls and was spherical in shape. When organic impurities were added to the atmosphere, the emission intensified sharply.

Kapitsa's studies constituted the most systematic work on the modeling of ball lightning from the standpoint that ball lightning was of a plasma nature. Verifying that the plasma modeling ball lightning should decay rapidly, Kapitsa reached the conclusion that energy must be delivered to the plasma from the exterior. His experiments demonstrate such a possibility. Kapitsa's idea and his experiments are thus logically closed. The circumstance that (as subsequent research has shown)[65–67] the occurrence of ball lightning of this type is improbable is another matter.

Powell and Finkelstein[68] implemented a different method for producing a glowing ball in a microwave discharge at atmospheric pressure. Air at atmospheric pressure was ignited by an arc, and then a microwave discharge with a frequency of 75 MHz and a source power of 30 kW was used. This discharge occurred in an open glass tube. By moving the electrodes, one could change the size of the region occupied by the discharge. After the discharge ended, the glowing region became spherical and decayed in a fraction of a second. Powell and Finkelstein made a detailed study of the plasma emission spectrum. Although the lifetime of the glowing formations which were observed was substantially shorter than the lifetime of ball lightning, it was significantly longer than the typical plasma decay time at pressures near atmospheric. The authors attributed this anomaly to the presence of a large number of metastable molecules.

These experiments prove that it is possible to produce a gaseous plasma in the form of a glowing formation reminiscent of ball lightning, although not completely analogous. In formulating their experiments, Andrianov and Sinitsyn[69] started from the assumption that ball lightning arises as a secondary effect of linear lightning, from material which has evaporated after the linear lightning has occurred. To model this phenomenon, they used a so-called erosion discharge: a pulsed discharge which produces a plasma from evaporated material. The stored energy under their experimental conditions was 5 kJ, and the potential difference was 12 kV. The discharge was directed toward an insulator; the maximum discharge current was 12 kA.

The discharge region was initially separated from the normal atmosphere by a thin membrane. The membrane was ruptured when the discharge occurred, so the erosion plasma was ejected into the atmosphere. The moving bright region assumed a spherical or toroidal shape. Visible emission from the plasma was observed for about 0.01 s, while no emission of any type from the plasma was detected for longer than 0.4 s. This time is much shorter than the observed lifetime of ball lightning.

In another direction toward the production of glowing formations in air, a high-energy ($\sim$1-MJ) battery is short-circuited, and the resulting electric arc is blown out of the region in which it formed. This research originated from cases of short-circuiting in the electrical systems of American submarines. Silberg[70,71] estimated the energy expended on the formation of these fire balls to be 0.4–4 MJ. Their diameter was 10–15 cm, and their lifetime 1 s. In some later experiments, the electrical system of the submarine was modified, and the short-circuiting sometimes resulted in the appearance of fire balls. In terms of their content, however, these experiments were preliminary, and they seem to have been poorly reproducible.

For several years, experiments of this sort were carried out at Los Alamos National Laboratory by Took. Since their results were not disseminated beyond an internal report of the Laboratory, it appears that the investigator did not achieve what he expected. According to a report by Golka,[72] by 1971, after 2.5 years of experiments, Took had 30 000 photographs, on 4 of which ball lightning was reproduced. Golka carried out some similar experiments, using a short-circuiting in the electrical system of a moving locomotive. He obtained some glowing formations. Dijkhuis[73,74] modified the electrical system of a submarine, using copper film and capacitors with an energy capability of 0.5 MJ as electrodes. He obtained some bright balls 10 cm in diameter with a lifetime of 1.3 s. We will repeat that this series of experiments was conducted in such a way that it was of a preliminary nature, and the reproducibility was apparently poor. On the other hand, it *is* possible to produce glowing formations through the short-circuiting of high-energy electric circuits.

Among the experiments carried out to model the chemical nature of ball lightning, the most interesting and systematic were those carried out by Barry in 1966.[25,75–77] Air at atmospheric pressure with a propane admixture was ignited by a spark in a plexiglass box with dimensions of $50\times50\times100$ cm^3. The distance between the electrodes was 0.5 cm, the voltage was 10 kV, the duration of the discharge was 10^{-3} s, and the energy released was 250 J. At a propane concentration of 1.4–1.8%, a yellowish-green ball a few centimeters in diameter formed in the chamber immediately after the spark. The ball moved rapidly around the chamber in a disordered way and faded away in 1–2 s. This phenomenon has properties reminiscent of ball lightning, and at any rate it can be thought of as an analog of ball lightning.

Further studies showed that more-complex organic compounds form in the experiment. Barry reports other information which supports this possibility. The more-complex compounds, including hydrocarbons, condense at room temperature. Under the experimental conditions, they form aerosols and concentrate in a small spatial region. The initial spark creates the complex compounds in the amount required, and the small range of propane concentrations in which it is possible to produce the glowing balls is evidence that different chemical processes are competing in this system.

Barry's experiments were continued by some Japanese physicists,[19,78] who used the same arrangement to excite a chemical mixture, but who used a wider variety of compounds and some modern diagnostic apparatus. In particular, they videotaped the process. These experiments were carried out in a glass vessel with dimensions of $73\times37\times43$ cm. The electrodes were made of copper wire. The electrical energy supplied to the spark did not exceed 350 J. These experiments were carried out in methane-air and ethane-air mixtures at room temperature and atmospheric pressure. In addition, cotton fibers were added to the air and to the ethane-air mixture.

The best conditions for the formation of glowing balls were found near the threshold for inflammation. The glowing ball was green in the first stage of the process and later changed color. The diameter of the ball did not exceed 6 cm. The lifetime was about 0.3 s in a methane-air mixture with a methane concentration of 2%. In air to which cotton had been added, this lifetime increased to 0.6 s; when cotton was added to an ethane-air mixture, it increased to 2 s. The authors point out that the reproducibility of their results was low. Consequently, glowing formations which arise as the result of an electric spark and which are sustained by chemical energy can exist in air with the various chemical admixtures. However, the processes which lead to the appearance of these glowing formations have yet to be explained, and the actual experiments (carried out to produce glowing formations in air) have a poor reproducibility.

Among experiments carried out to reproduce ball lightning as a whole, the work by the Corums[79] deserves particular attention. That work was essentially a repetition of Tesla's experiments with modern apparatus. Since Tesla's work had not been published completely, the details of his experiments were not clear, and the results themselves were clouded with much uncertainty. For this reason, the work carried out by the Corums was not simply a matter of reproducing Tesla's experiments of 90 years earlier; they instead were obliged to come up with creative solutions for several intermediate problems. They used Tesla's rf generator, operating at a frequency of 67 kHz. That generator includes a helical waveguide, which is inductively coupled with a spark chopper. It provides a maximum voltage of 2.4 MV for the radio signal at a frequency of 67 kHz. The power which was supplied to the system was 70 kW, and the power of the signal at the electrodes was 3.2 kW. This power resulted in the breakdown of air over a distance of 7.5 m. The results of these experiments were recorded by photography and on videotape.

In that study, spherical glowing formations of millimeter dimensions were sometimes observed in the emission from the rf discharge. These formations grew to a diameter of a few centimeters and had a lifetime ranging from half a second to several seconds.

In analyzing the experiments on the modeling of ball lightning as a whole, we need to bear in mind that these experiments also reflect a general attitude toward the problem. On the one hand, this method is sometimes successful in producing glowing formations reminiscent of ball lightning. This success proves that this phenomenon is associated with natural processes in excited air. On the other hand, the poor reproducibility of the experiments on the production of glowing formations and the difficulties in controlling the experiments have made it impossible to extract additional information about ball lightning from these experiments. The experience gained in these studies demonstrates the complexity of the ball-lightning phenomena; it is so complex that even isolated successes in modeling it as a whole do not bring us closer to an understanding of the nature of this phenomenon. Consequently, over the past decade it has become more common to model individual aspects of this phenomenon and to analyze its individual properties with the help of physical entities and phenomena for which these properties of ball lightning are reproduced. We turn now to some analogs of ball lightning in terms of individual properties.

4.2. Analogs of ball lightning

The analysis above (Subsection 3.4) shows that ball lightning must have a rigid framework. This assertion[49] is based on an analysis of the relaxation of metal vapor. In the first stage of this process, some solid particles of nanometer size form. They then combine to form a porous cluster. This cluster has fractal properties.[77] One of these properties can be formulated as follows. If a sphere of radius r is drawn around one particle of a cluster, and if the radius of this sphere is significantly greater than the radius of an individual particle but smaller than the radius of the cluster, then the mass of the part of the cluster within the sphere, m, will depend on the radius of this sphere in accordance with[80,81]

$$m=m_0\left(\frac{R}{r_0}\right)^D. \tag{20}$$

Here m_0 and r_0 are the mass and radius of an individual particle of the cluster, and D is the fractal dimensionality of the cluster. The value of D depends on the conditions under which the cluster forms; when it forms from a relaxing vapor, the value is in the interval 1.8–2.1 (Ref. 49, for example).

As the cluster increases in size, the average density of the material in it decreases, and the cluster may break up into parts at certain sizes. Analysis of the mechanisms for the instability of such a cluster[82] shows that in practice its size can exceed the size of the constituent particles by three or four orders of magnitude. If many such clusters are combined, the result is a porous solid which has fractal properties at small scales, while being homogeneous at large scales. For our purposes, the most interesting cases of such porous systems are aerogels (Refs. 60, 83, and 84, for example).

An aerogel consists of tightly bound solid particles with a size of the order of a nanometer. Slightly more than ten types of aerogels have been produced at this point. All are oxides of various elements; apparently only in such cases does a strong chemical bond form between solid particles. All the basic research has been carried out with a silicon dioxide aerogel, and all applications of aerogels also involve this substance. Because of the complex procedure required to produce an aerogel, it is an expensive product. Its use has accordingly been limited. The highest density of the material in the aerogel samples which have been produced has been[85] 15 g/liter. This aerogel has a high thermal stability: Thermal destruction of an aerogel begins at temperatures above 1400 K (Ref. 85). We see that an aerogel is an analog of ball lightning in terms of its structure and that it could be utilized to model processes which occur in ball lightning.

A few comments are in order here. First, the density of the existing aerogels is an order of magnitude higher than that of the framework of ball lightning as given by (19). The reason for the difference lies in the particular technological procedure by which an aerogel is produced. The procedure makes use of supercritical properties of a gel solvent, i.e., high temperatures and high pressures.

If it proves possible to carry out this process successfully at normal pressures, it will become possible to produce a product of lower density, although also less stable. Second, the framework of ball lightning forms in the atmosphere, under nonequilibrium conditions, and the time over which the framework forms cannot be long. At most, it could not exceed the lifetime of ball lightning. Analysis shows that the time over which a framework forms depends sharply on the size of the particles in it.[32,60] The size of the particles in the framework of ball lightning thus has an upper bound, of the order of a nanometer. We see that in terms of this property an aerogel is a good model of the framework of ball lightning.

An aerogel is thus a convenient model for the framework of ball lightning. Chemical processes which occur inside this framework lead to a heating of isolated zones within the ball lightning, to a temperature of about 2000 K. These zones are responsible for the emission of ball lightning. One of the possibilities in this process stems from the condensation of the aerosol, i.e., the combining of the particles making up its framework into larger particles. The specific internal surface area then decreases, so associated energy is evolved. This energy evolution may sustain a high temperature inside the aerogel.

Figure 11 shows the condensation times of a silicon dioxide aerogel found from the data of Mulder and van Lierop[85] on the basis of the equation

$$\frac{dS}{dt} = -\frac{S}{\tau(T)}, \tag{21}$$

where S is the specific internal surface area, and $\tau(T)$ is the time of the process. The activation energy found for the rate of the process through an approximation of the curve in Fig. 11 is unacceptably high, however, so doubt is cast on the approximation of these data at high temperatures. At any rate, it can be seen that this process occurs effectively at high temperatures, so it may be regarded as one possible heat-evolution process in real ball lightning.

The fact that the thermal process is occurring within the framework of ball lightning has implications for the nature of this process. The framework of ball lightning suppresses convective motions within itself, so the transport of energy away from the hot zones occurs by virtue of conduction and radiation. As the density of the framework increases, the radiation plays a progressively larger role in the heat transfer. (We are discussing the region of low framework densities, for which the heat flux is transferred not along the framework itself but by air molecules within it.) Table XVIII shows the results of a calculation[86] on the combustion of coal in an aerogel. This process models the transport and radiation inside ball lightning.

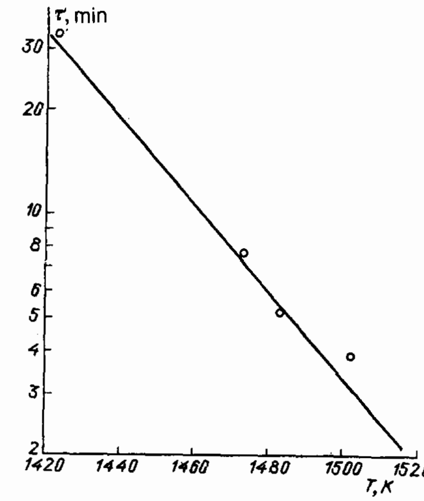

FIG. 11. Time required for the condensation of a silicon dioxide aerogel as a function of the temperature. Points—Analysis of Mulder's data;[85] solid line—an approximation of those results.

The data in Table XVIII refer to a silicon dioxide aerogel with a density of 0.05 g/cm^3 in air at atmospheric pressure, with a sample of activated charcoal of spherical shape and radius R within the aerogel. The external source (a laser beam) causes the temperature of the charcoal to rise to T_1, at which the charcoal undergoes a thermal explosion and combustion in the air in the aerogel. An energy ϵ is expended on heating the sample to the temperature T_1. The sample then rises to a higher temperature T_2, at which it burns in a diffusion regime; i.e., the burning rate is limited by the rate at which oxygen is supplied to the sample. As the sample is burned up, and its radius decreases, the burning temperature rises. The reason is that the oxygen density gradient near the surface of the sample increases, so the rate at which oxygen is delivered also increases. Note that the time[4)] τ is comparable to or longer than the lifetime of ball lightning, and most of the energy which is released is expended on radiation (η is the fraction of the energy which is carried off by heat conduction, and $1-\eta$ is the fraction carried off by radiation). The model-based calculation presented in Table XVIII gives an idea of how the transport processes in ball lightning are related, and it may provide a basis for a modeling of these processes.

Using an aerogel as a model of the framework of ball lightning, let us determine the surface-tension coefficient for

TABLE XVIII. Parameters of a process modeling energy transfer and radiation in ball lightning.

R, mm	0,2	0,4	0,8
T_2, K	1410	1220	1060
T_1, K	990	940	890
τ, C	8	28	105
η	0,14	0.10	0.07
ε, J	0,01	0,09	0.6

an average ball-lightning formation. We assume that the aerogel is constructed of spheres of radius r_0, of which there are n per unit volume. Introducing the density of the material of the sample, $\rho_0 = 2$ g/cm^3, and the average density of the aerosol, $\bar{\rho}$, we have the following relation:

$$\bar{\rho} = n \cdot \frac{4}{3} \pi r_0^3 \rho_0. \tag{22}$$

If the aerogel is split by some plane, there will be an area of $n^{2/3} \pi r_0^2$ covered by the aerogel material per unit area of this plane. Introducing ε_0, the energy per unit surface area of the internal surface ($\varepsilon_0 = 3$ J/g according to the comment regarding Table XVII), we find the following result for the surface-tension coefficient:

$$\alpha = \varepsilon_0 n^{2/3} \pi r_0^2 = \varepsilon_0 \left(\frac{4\pi \bar{\rho}}{3\rho_0}\right)^{2/3} \tag{23}$$

From (23) we find the surface-tension coefficient for an average ball-lightning formation: $\alpha = 0.06 \cdot 10^{\pm 0.5}$ J/m^2.

The use of an aerogel as an analog of ball lightning thus makes it possible to analyze certain properties of ball lightning and to point out ways to model experimentally the processes which occur within the framework of ball lightning.

4.3. Radiation models constructed from analogs of ball lightning

Adhering to the general logic of this review, we lean toward analogs in nature and technology to model the processes which occur in ball lightning. One of the basic properties of ball lightning is its emission. Ball lightning is a chemical source of light. In this regard, there are two analogs of ball lightning. The first comes from the realm of technology: the combustion of pyrotechnic compositions.[87-89] The second is the flame accompanying the combustion of organic components, in particular, the flame of a candle or match.[90,91] A pyrotechnic composition includes both fuel and oxidant as well as light-emitting components and binders. The process by which this composition burns produces a high temperature, 3000–3500 K, in the combustion zone and causes an effective emission of the flame in the selected visible part of the spectrum. Another analog of the chemical process and of the emission process in ball lightning is the combustion of an organic substance in atmospheric air. Oxygen of the air serves as the oxidant, and the flame temperature is slightly under 2000 K. Substances of both types can be used to model the processes which occur in ball lightning, as the chemically active substance in it.

We turn now to an analysis of these two models, making use of the properties of these flames. In both cases, we are dealing simultaneously with many seats of flame. By virtue of the nature of the heat removal and the radiation, the efficiency at which a flame emits depends on its dimensions. If the size of the hot zone is small, chemical energy is converted into heat, and the efficiency at which the chemical energy is converted into radiant energy is low. Since we are given the luminous efficiency of ball lightning, we can work from it to estimate the size of the hot zone. Estimates based on the first model, in which the emission results from resonantly excited atoms, were made in Refs. 33 and 60. The size of the hot zone turned out to be of the order of a few millimeters. This estimate is also good for the second model.

If all the "fuel" from the emitting zone is collected in a single droplet, the size of this droplet will be a matter of microns. Consequently, under the assumption that the fuel in the emitting zone comes from a condensed phase, we reach the conclusion that the fuel is not an element of the framework of the ball lightning, for which the size of the elements is a matter of nanometers. The fuel is in the pores of the framework of ball lightning and is characterized by the size of these pores, which is a matter of microns.

We have thus opened up a path for modeling ball lightning. In the process by which an aerogel is produced, the solution contains, along with the aerogel, a certain amount of fuel, which remains in the pores after the aerogel is produced. For the second model, the fuel can be added to the aerogel after its preparation, in the gas or liquid phase. If a pyrotechnic composition is used (with a specific energy of 6 kJ/g), its density in the aerogel will be $5 \cdot 10^{-4 \pm 0.5}$ g/cm^3 according to the average characteristics of ball lightning (Table XVI). In other words, its density will be smaller than the specific gravity of air. In the second model, the density of the fuel is smaller by a factor of several units.

The analogs of ball lightning can thus be used to produce a laboratory model of ball lightning which can be used to study the nature of the processes by which a flame arises and propagates within a porous substance. Research on models of this type will provide answers to fundamental questions regarding ball lightning. For example, it will become possible to select an appropriate component as the chemically active substance.

Let us analyze these two models of ball lightning, which make it possible to describe the nature of the emission of ball lightning. In the first model,[19,20,23,32,33,35,39,60,92] the hot zone forms as a result of a microscopic explosion of certain elements of a chemically active substance containing both oxidant and fuel. This process propagates in the form of chemical-reaction waves in certain directions, with a typical velocity of the order of a meter per second. We have a suitable candidate for the role of the chemical component: ozone, which doubles as fuel and oxidant and which is rapidly formed in electrical processes in the atmosphere. Another suitable process of this type is a contraction of the framework of ball lightning due to a combining of the particles making up the framework into larger particles. This process is accompanied by a release of energy by virtue of the contraction of the internal surface area of the framework. The fundamental problem of this model concerns the time over which the chemical-reaction waves branch out. These waves propagate simultaneously along many "filaments" of active substance. If we work from the lifetime of ball lightning, we conclude that the time over which an individual wave is damped, or the time over which it branches out, would have to be of the order of 1 s. Such an estimate is difficult to derive for this model description.

The second model[93] differs from the first in the nature of the existence of hot zones: Many steady-state seats of flame exist simultaneously. The fuel in the hot zone could hardly be a solid: The framework would not withstand the high temperature. More likely, the hot zones are similar to a candle flame: The fuel enters in the form of vapor and microscopic particles. The parameters of the candle flame—its temperature and luminous efficiency—are the same as the corresponding parameters of ball lightning (Fig. 10). It is thus interesting to consider the parameters of a ball-lightning model in which the hot zones are candle flames. An average ball-lightning formation corresponds to $10^{1.6 \pm 0.5}$ such seats of flame; the ratio of the total surface area of the flame to the surface area of the ball lightning is[5)] $10^{-1.2 \pm 0.8}$; the initial content of the stearin fuel is $0.5 \cdot 10^{\pm 0.2}$ g; and the combustion of this fuel would require $1.5 \cdot 10^{\pm 0.2}$ g of oxygen, which is present in $6 \cdot 10^{\pm 0.2}$ g of air. Initially, there is $7 \cdot 10^{\pm 0.2}$ g of air inside the ball lightning. These estimates are based on identical energy characteristics of the average ball-lightning formation and its model.

It can be seen from these estimates that the amount of oxidant originally present in the ball lightning is of the order of magnitude of the amount required for use as fuel. It is possible that some deficiency of oxygen would promote stability of the observed picture: the appearance of many seats of flame. This model requires an understanding of yet another problem: the inflammation mechanism. The model is based on steady-state seats of flame, in which the evaporated fuel mixes with the oxidant and undergoes combustion. We need an initial stage for this process: the ignition of the flame.

These models of ball lightning, at which we arrive in a logical way by making use of the scientific basis available, thus make it possible to choose some directions in which to move. In addition, they raise some definite questions which require answers. These models, which are based on existing analogs of ball lightning, contradict each other. Further research will make it possible to discard one of them.

4.4. Gas dynamics of ball lightning

To reach an understanding of the nature of ball lightning, we need to supplement the observational data with a detailed analysis of the individual properties of ball lightning on the basis of its analogs and quantitative analyses of models of ball lightning pertinent to its corresponding properties. Substantial progress toward an understanding of the gas dynamics of ball lightning has been achieved due to a series of studies by Gaĭdukov.[94–97] This research has made it possible to reach an understanding of the nature of the motion of ball lightning in air and to explain the behavior of ball lightning as it flows around obstacles and passes through slits and apertures. It also explains the capture of ball lightning by flowing air.

In the analysis of the gas dynamics of ball lightning it is assumed that this is an autonomous entity and that as air flows interact with it the air molecules do not adhere to it. To analyze the motion of ball lightning in air flows, and also for cases in which ball lightning passes through wide apertures, one can model it by an undeformable sphere (or an object of some other shape).[94,95] This model makes it possible to explain many observed effects, e.g., the capture of ball lightning by vortex flows (e.g., associated with the motion of an aircraft) and the capture of ball lightning by a heated smoke plume or airflow emerging from a source of heat.[94–96]

A more complex problem is the motion of ball lightning as it passes through slits and apertures with dimensions smaller than that of the ball lightning itself. A suitable model for ball lightning in this case is an incompressible ideal fluid.[97]

As it, along with an airflow, approaches a small aperture, the ball lightning sends out a cylindrical jet into it and thereby flows from one side of the obstacle to the other. Internal forces which create a surface tension then restore the spherical shape of the substance of the ball lightning.

The results of a series of studies by Gaĭdukov[94–97] on the gas dynamics of ball lightning in airflows are of interest not only from the standpoint of reaching an explanation of the observed facts; they also formulate a model of the internal structure of ball lightning. Ball lightning is made up of elements: fractal clusters which interact with each other. It is this interaction which is responsible for the surface tension, which is in turn responsible for the spherical structure of ball lightning. On the other hand, this is a relatively weak interaction, so flows can change the shape of ball lightning.

The results found by Gaĭdukov and observational facts make it possible to find some estimates of the surface tension in ball lightning. Specifically, let us assume that the substance of ball lightning passes through an aperture whose radius b is smaller than that of the ball lightning, R_0. The ball lightning is then being acted upon by a force[96]

$$F \sim \frac{12\pi\rho\gamma^2}{R_0^2}, \tag{24}$$

where ρ is the mass density of the substance of the ball lightning, and γ is the volume of the lightning which flows through the aperture per unit time. With τ as the total time of the passage, we have $\gamma = (4\pi/3)R_0^3/\tau$. Near the aperture a stress $\sigma_F = F/(\pi b^2)$ is set up. This stress, which must exceed the surface tension of the lightning, is

$$\sigma_F \sim 200\frac{\rho R_0^4}{b^2\tau^2}. \tag{25}$$

The physics of the passage of ball lightning through an aperture can be outlined as follows.[96] We assume that the ball lightning approaches the aperture and that the air pressure is different on the two sides of the aperture. This pressure difference causes air to move toward the aperture and forces the substance of the ball lightning to flow from one side of the aperture to the other. The stress given by (25), which is set up at the surface of the lightning by this effect, must exceed the stress due to surface tension. In other words, the relation $\alpha < \sigma_F R_0$ must hold. Only in this case will the gas-dynamics forces pull a jet of substance out of the ball lightning and thereby transport the substance of the lightning from one side of the aperture to the other. We thus have an upper estimate on the surface tension in the substance of ball lightning:

$$\alpha \lesssim \frac{200\,\rho R_0^5}{b^2\tau^2}. \tag{26}$$

Adopting the plausible parameter values $b \sim 5$ cm and $\tau \sim 1$ s, we find $\alpha \lesssim 0.1 \cdot 10^{\pm 1.6}$ J/m^2. This value is of the order of the surface tension of water (0.07 J/m^2), although this estimate is not very accurate. (In estimating the error here we have allowed for the uncertainty regarding the density of the substance of the lightning, ρ, and the passage time τ.)

4.5. Electrical properties of ball lightning

The models presented above make it possible to analyze only one aspect of this phenomena: the nature of the production of glowing hot spots inside the ball lightning. Although this problem is presently the leading problem of ball lightning, it does not exhaust this complex phenomenon. In this subsection we will take a quick look at another list of problems, which concern the electrical properties of ball light-

TABLE XIX. Electrical properties of an average ball-lightning formation.

Property	Value	Accuracy
1. Charge, C	$8\cdot10^{-7}$	$10^{\pm0.5}$
2. Charge density, e/cm^3	$4\cdot10^{8}$	$10^{\pm0.3}$
3. Surface tension, J/m^2	0,2	$10^{\pm0.8}$
4. Charge-to-mass ratio, C/g	$5\cdot10^{-8}$	$10^{\pm0.5}$
5. Electric field near surface, kV/m	400	$10^{\pm0.6}$
6. Electric potential, kV	50	$10^{\pm0.6}$
7. Electrical energy, J	0.04	$10^{\pm0.9}$
8. Electric pressure at surface, Pa	1	$10^{\pm0.6}$

ning. These properties are of fundamental importance for the formation and existence of ball lightning.

The electrical properties of ball lightning are of interest in the following regards. First, ball lightning is formed by electrical processes in the atmosphere, which create nonequilibrium conditions allowing the framework of ball lightning to form. Second, electric charge imparts stability to the framework and is present according to the observational data. Table XIX shows the electrical properties of an average ball-lightning formation.[3] These properties were found from the condition that the force attracting ball lightning to metal objects is of the same scale as the weight of the framework. Third, ball lightning interacts actively with external electric fields in the atmosphere and may be responsible for breakdown which causes damage.

The data in Table XIX show that ball lightning forms under nonequilibrium conditions in the atmosphere. The average charge density in the quiet atmosphere, 10^2–10^3 cm^{-3}, is significantly lower than the charge fixed in the frame of ball lightning. It follows that this framework forms in a region of an electric discharge with a high electric potential.[32,92] Active research on the formation of fractal clusters from solid particles in solutions and gases has been carried out over the past decade. From the standpoint of the formation of ball lightning, it would be interesting to study this process in strong electric fields.

Table XIX and this interpretation are based on the presence of electric charge in ball lightning. This presence is supported by observational data, in particular, by the motion of ball lightning along conductors. The presence of a charge is also important to the stability of ball lightning: It creates a surface tension and thereby stabilizes the framework of ball lightning,[58] preventing this framework from"collapsing."

Another interpretation pertinent to the electrical properties of the framework of ball lightning was advanced by Aleksandrov *et al.*[98] They suggested that a corona discharge is caused near the framework of ball lightning by a strong external electric field. The currents which arise in the process create a force which acts on the ball lightning. As a result, the lightning can float, hover in the air, and so forth. Aleksandrov *et al.*[98] supported their interpretation with an elegant experiment. A ball 1 cm in radius, made from wire 0.15 mm in diameter, was placed in a strong electric field (the distance between electrodes was 30 cm, and the potential difference was 50–160 kV). The ball weighed 0.1 g. The electric field caused a weak corona discharge near the filaments of this ball. This discharge stabilized the position of the ball in air. This position could be changed as the result of a change in the position of a nearby object, a person, etc. The basic assertion of the authors as a result of their experiments was that the stable motion of the ball in the air beside surfaces was due to a corona discharge.

Note that the ball used in those experiments is not a model of the framework of ball lightning. It contained several turns of wire, while the framework of ball lightning contains a large number of structural elements. For this reason, the conditions for the initiation and existence of a corona discharge may be very different in these systems. It is much easier to maintain a corona discharge near an individual wire than near a branching system. Consequently, although this experiment is attractive, its results must be interpreted extremely cautiously.

On the other hand, the interpretation itself—involving the existence of a corona discharge near the framework of ball lightning—deserves serious consideration. It should be kept in mind here that a corona discharge produced near the charged framework of ball lightning will cause a discharge of this framework, and this discharge may result in a collapse of the framework and its destruction. There is another mechanism which would operate to discharge a framework in the absence of an external field. If an easily ionized impurity (e.g., potassium) enters the hot zones of ball lightning, a plasma of relatively high density will be produced in these zones.[92] This plasma will then serve as a source of ions which will cause a discharge of the framework of the ball lightning.

The concepts of an electrically charged framework and of a corona discharge near it are mutually exclusive. It would seem that preference should be given to the first of these concepts in view of the observational data and the requirement that the ball lightning be stable. Nevertheless, this question requires serious analysis. It is interesting to note that these opposite interpretations were advanced by the same scientists;[58,98] this circumstance reflects the complexity of this phenomenon.

An important problem in the analysis of the electrical properties of ball lightning is the occurrence of electric breakdown in the atmosphere as a result of the ball lightning. According to observational data, ball lightning causes damage and other effects which can be explained as the result of the imposition of an external electrical source. Under these conditions, ball lightning—as an ionizing agent—alters the electrical properties of the air in the electric field of the atmosphere, causing its breakdown. A description of the physical picture of the processes operating here will require an additional analysis of the qualitative elements of this picture. A similar situation apparently developed previously in the problem of Saint Elmo's fire, in which case recent studies[99,100] have changed the interpretation of this phenomenon. One can expect the same sort of progress in the development of the problem of the effect of ball lightning on electric breakdown in the atmosphere.

4.6. Time variation of the processes in ball lightning

It can be concluded from the history of research on ball lightning that this is a complicated phenomenon and that it should be broken down into parts, to be studied independently and in detail. One should use the observational data as a starting point and model the basic properties of ball lightning by means of its analogs: physical systems and phenomena which share certain processes or properties with ball lightning. An observational model of ball lightning has been introduced as a step in this direction. This model makes it possible to avoid many hypothesis and also to select correctly the major problems concerning the nature of ball lightning. Again, our experience has shown that the ball-lightning phenomenon is an extremely complex one, so the observational model which has been introduced reflects this phenomenon only crudely. Specifically, in introducing an average ball-lightning formation, with average observational properties (Table XVI), we are making the assumption that these properties persist for a time comparable to the lifetime of the ball lightning. One cannot conclude from observations that this is a steady-state phenomenon. The analysis below convinces us that it is not.

We consider a model based on some facts which have already been established. (1) Inside ball lightning there are a number of seats of heat evolution, which we will assume for simplicity are spheres of radius r_0 with a temperature T_0. These hot zones create the emission. (2) Because of the rigid framework, heat can be transferred within ball lightning by conduction. For simplicity we assume that the corresponding thermal conductivity is the same as that of air (we are assuming that the framework is very sparse). We approximate the thermal conductivity of air[47] over the temperature range 300–2000 K by $\varkappa(T) = \varkappa(T_0)(T/T_0)^{0.8}$, where $T_0 = 300$ K, $\varkappa(T_0) = 0.27$ mW/(cm·K), and the error of this approximation is less than 10%.

Working from our steady-state model, we construct isotherms inside the ball lightning, running through points of the same temperature T. We denote by $S(T)$ the total area of the corresponding surface. The total heat flux across it is

$$\mathscr{P} = -\varkappa(T)\, S(r,\, T)\frac{\mathrm{d}T}{\mathrm{d}r}\,, \tag{27}$$

where r is the average radius of curvature of the surface. Here $S(R_0 T_0) = 4\pi R_0^2$, where R_0 is the radius of the ball lightning, T_0 is its surface temperature, and $S(r_0, T_1) = n\cdot 4\pi r_0^2$, where r_0 is the radius of the seat of heat evolution, T_1 is the temperature of this hot zone, and n is the number of such zones. Since heat is evolved only in the hot zones, we have $\mathscr{P} = \text{const}$ outside them; i.e., expression (27) is an equation. We solve it, setting

$$S(T) \propto T^{-\gamma}, \quad S(r) \propto r^{\alpha}. \tag{28}$$

We find the relationship between these parameters:

$$\gamma = \frac{1{,}8\,\alpha}{\alpha - 1}, \quad \alpha = \frac{\gamma}{\gamma - 1{,}8}\,. \tag{29}$$

Since $S(T)$ and $r(T)$ are monotonic functions, we can find the ranges of these parameters:

$$1 < \alpha < 2, \quad 3{,}6 < \gamma. \tag{30}$$

From these relations we can find the electrical properties of ball lightning. The power of the heat which is transferred within ball lightning is

$$\mathscr{P} = \frac{S(T)\,\varkappa(T)\,T}{r(T)}\,\frac{\alpha - 1}{1{.}8} = \mathscr{P}_0(\alpha - 1),$$

For the average ball-lightning formation we would have $\mathscr{P}_0 = 10^{1.0\pm0.3}$ W. Assuming that the hot zones emit as blackbodies, we find the power of the radiation emitted to be

$$\mathscr{P} = \sigma T_1^4 S(T_1) = 4\pi R_0^2 \sigma T_0^4 \left(\frac{T_1}{T_0}\right)^{\delta} = \mathscr{P}_0\left(\frac{T_1}{T_0}\right)^{\delta},$$

where

$$\delta = 4 - \gamma = \frac{2{,}2\,\alpha - 4}{\alpha - 1}\,.$$

For the average ball-lightning formation we find

$$\mathscr{P} = 250\cdot 10^{\pm 0{,}6}\ \mathrm{W}$$

The energy which must be supplied to the ball lightning in order to reach this steady state is

$$E = \int_{r_0}^{R_0} S\,\mathrm{d}r \int_{T_0}^{T(r)} c_p \rho(T')\,\mathrm{d}T',$$

where c_p is the specific heat (per unit mass) of air, and $\rho(T') = \rho_0(T_0)T_0/T'$, is the density of air. The integral is dominated by the regions with temperatures close to the surface temperature of the ball lightning. We have

$$E = \frac{4\pi R_0^3 c_p \rho(T_0)\,T_0(\alpha - 1)}{1.8(\alpha + 1)^2} = \frac{9E_0(\alpha - 1)}{(\alpha + 1)^2} < E_0,$$

and for the average ball-lighting formation we have $E_0 = 400\times 10^{\pm 0.4}$ J.

Let us analyze these results. It follows from them that the energy required to reach a steady state is small in comparison with the characteristic energy of ball lightning and that the loss of energy from the ball lightning is a consequence of the emissibn from the hot zones. However, the actual power which is converted in the process is smaller by at least an order of magnitude than the power of an average ball-lightning formation. This discrepancy can be attributed to an error in the determination of the energy of ball lightning, since in most of the observational cases the energy evolution has apparently occurred under the influence of an external source of electric energy. If we calculate the light flux from ball lightning, however, it turns out to be an order of magnitude lower under the conditions of this model than according to the observational data. There is thus a clear discrepancy between this model and the observational data.

The contradictions between a steady-state model of energy transfer and the observational data leads to the conclusion that the processes which occur inside ball lightning are not in a steady state. This conclusion finds support in certain observational facts. Figure 12 (Ref. 101) shows the amount

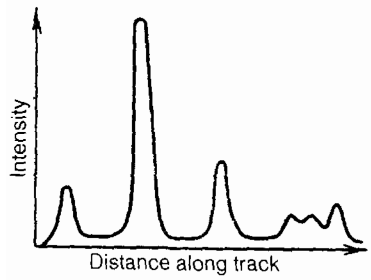

FIG. 12. Photometry of ball lightning along its track.[101]

of light striking various parts of photographic film in an open-shutter camera which is photographing ball lightning. If we assume that the ball lightning is moving at a constant velocity, we can interpret this figure as the time dependence of the intensity of the ball lightning. The time variation of the processes in ball lightning of course seriously complicates the analysis of this phenomenon.

4.7. Analysis of the nature of ball lightning

Let us summarize the results of this analysis, which makes it possible to select directions for further research on ball lightning. This analysis has been based on an observational model of ball lightning which has properties which are averages over many observations (Table XVI). As a result of this analysis, we can add to the average ball-lightning formation the new properties shown in Table XX. As a result of this analysis, we are thus in a position to add to our understanding of ball lightning.

Let us look at one of the properties in Table XX: the surface tension of ball lightning. This tension has been found by three methods. First, it has been found by modeling the framework of ball lightning with a silicon dioxide aerogel ($\alpha = 0.06$ J/m^2). Second, the possibility that ball lightning can change shape as it passes through slits and apertures has been taken into account ($\alpha \lesssim 0.1$ J/m^2). Third, the possibility that the shape may be changed by electric forces has been taken into account (0.2 J/m^2). These forces are the same forces which cause ball lightning to be attracted to metal objects. An important point is that the values of these three estimates agree within their errors; this agreement is evidence that the result is reliable. Interestingly, the surface tension of ball lightning turned out to be close to that of water (0.07 J/m^2).

The next property, the size of the particles making up the framework, can be found from the condition that the time scale for the formation of the framework as a result of the aggregation of microscopic particles does not exceed the lifetime of ball lightning.[32,33] The size of the particles in a silicon dioxide aerogel is about 3 nm.

The elastic properties of ball lightning are characterized by the Young's modulus, whose value has been found by approximating the data on a silicon dioxide aerogel[102] in the low-density region. The large error in the value in Table XX is a consequence of both the uncertainty regarding the density of the framework of ball lightning and the error in the approximation of the data at low densities. The value of the Young's modulus can also characterize the strength of the framework of ball lightning. The strength of this framework decreases with its density. Estimates show that the framework of ball lightning can be destroyed by energy-evolution processes occurring in it if its density is about an order of magnitude below that of air at atmospheric pressure.

Energy-evolution processes within ball lightning raise the pressure within the framework. According to estimates, the difference between the air pressures inside and outside the framework of ball lightning is relatively small. Since the energy evolution occurs independently at many points (in many zones) of the framework and is an irregular process, however, it is accompanied by the excitation of sound waves. The spectrum of these waves is concentrated in the region which can be perceived by the human ear. Estimates show that ball lightning is a weak sound source; the loudness of the sound from an average ball-lightning formation, at a distance of 3 m from it, is estimated to be 58 ± 3 dB.

The logic of the above analysis lies in the circumstance that, on the one hand, ball lightning has analogs, with corresponding properties, and, on the other hand, the properties of ball lightning have been reconstructed from observational data. In moving from the real objects toward the properties of ball lightning, we draw certain conclusions about the internal structure and other properties of ball lightning. This approach is useful in two regards. First, it offers reliability, since in both limiting cases we are dealing with real systems, and we need to relate these cases in order to reach an understanding of the phenomenon. Second, this approach provides a key to the modeling of the individual properties of ball lightning. The modeling is based on real, available objects. This approach is thus promising, since it will ultimately lead to answers to the various questions.

Nevertheless, until a successful modeling has been carried out, the reality of the conclusions found by this ap-

TABLE XX. Additional properties of an average ball-lightning formation.

Property	Value
1. Ratio of weight of framework to weight of air in it	$1\cdot 10^{\pm 0,8}$
2. Weight of chemically active substance, g	$10^{0,1\pm 0,6}$
3. Air temperature at boundary of lightning, K	$60\cdot 10^{\pm 0,6}$
4. Temperature of hot (emitting) regions, K	1800 ± 200
5. Size of individual hot zone, cm	$10^{0,2\pm 0,4}$
6. Number of hot zones	$10^{2,5\pm 0,7}$
7. Optical width of ball lightning	$10^{-1,7\pm 0,8}$
8. Surface tension, J/m^2	$0.1\cdot 10^{\pm 0,5}$
9. Size of particles of framework, nm	$3\cdot 10^{\pm 0,4}$
10. Young's modulus of framework, Pa	$5\cdot 10^{\pm 3}$

proach will remain under doubt. This comment applies primarily to the framework of ball lightning. It follows from experiments on fractal aggregations that a system of this sort should exist, but the strength of the framework and the time it takes to consolidate remain unclear. For certain values of these parameters, the existence of this structure as the framework of ball lightning becomes unrealistic.

Fortunately, we have several examples which support the possibility of a fairly long existence of a skeletal metal structure of laboratory size with a specific gravity of the order of that of air. Let us consider one such example, which concerns the deposition of metal coatings on bolometers and detectors of thermal radiation. The surface of a device of this sort, consisting of fractal clusters of metals, effectively absorbs thermal radiation. In one study in this direction,[103] a surface consisting of clusters of cobalt was produced. Small microscopic particles of cobalt formed in an argon atmosphere during the evaporation of the metal in the standard way,[104] with a hot tungsten coil and a convective transport of vapor. The argon pressure lay in the range 0.25–10 torr. The metal particles, which resembled soot, were collected on a copper grid coated with carbon and studied in an electron microscope. The average thickness of the metal deposit was 10–200 μm. The fractional volume of the cobalt particles in this layer was estimated to be 10^{-4}–10^{-2}; i.e., the deposit had a porous structure, and the pores accounted for most of the volume. The average radius of the particles was a few nanometers. We see that at the lower limit the specific gravity of the film is of the order of that of air. Since the thickness of the film is significantly greater than the size of the pores, this procedure makes it possible to produce a thicker film, i.e., ultimately, a three-dimensional object of laboratory size.

As another example of this type we consider the study reported in Ref. 105, in which SiH_4 was burned in air to produce objects of millimeter size consisting of fractal clusters of silicon dioxide. The minimum density of these objects was 7 g/liter. They suffered essentially no damage, so a variety of experiments could be carried out with them.

As the density of this structure decreases, however, it consolidates sooner; i.e., the lifetime of the framework decreases. From this circumstance and the set of observational data one gets the impression that ball lightning could form just after the surface of a condensed object experiences some abrupt effect: a lightning strike, short-circuiting, etc. After a time, the system formed as a result "gets old" and is no longer capable of leading to the formation of a skeletal structure: the framework of ball lightning.

We thus see that following the fundamental questions concerning the nature of ball lightning there are some special additional questions. Some of them are also of fundamental importance, since their answers will determine the reality of the particular (general or specific) scheme of processes governing this phenomenon. These questions require careful analysis.

5. CONCLUSION

Our purpose in this review has been to formulate the current problems in the physics of ball lightning and thus the directions for future research. This analysis has been based on the assumption that ball lightning is controlled by known physical laws. Working from the logical closure of the world around us, we can then find other physical entities or phenomena in which these laws are manifested, and we can use them to model ball lightning. In this manner we can find an optimum path for solving this problem.

The difficulties in reaching an understanding of this phenomenon stem from the lack of information about the physical processes which occur under the conditions pertinent to ball lightning. Only recently have we obtained the information about fractal clusters which supports the concept of a rigid framework for ball lightning. It is necessary to study flames in porous systems, electrical phenomena in an atmosphere containing a disperse phase or burning objects, etc. The information found from this research will promote an understanding and a modeling of the processes in ball lightning. The purpose of this research is not to produce long-lived glowing formations in the atmosphere to model ball lightning but to carry out a multifaceted study of processes in the atmosphere for reaching an understanding of the physics of ball lightning. The history of the development of this problem shows that it cannot be solved in any one step or by any one brilliant idea.[6)] An understanding of this phenomenon will have to await a detailed study of its various aspects. Since definite progress has been made in this direction over the past decade, we can expect further progress, especially since many scientists have recently been attracted to this problem.

Even at the present stage of research on ball lightning, we can make several confident assertions about its nature. Among these assertions are that ball lightning has a rigid framework, that the internal energy of the ball lightning is of a chemical nature, that the emission has a spotty structure, which means that the emission from ball lightning is produced by small hot zones inside it, etc. Future research will lead to a better understanding and thus a clearer physical picture of ball lightning.

[1)]It is interesting in this connection to compare the situation in research on ball lightning with that on UFOs (unidentified flying objects). At present, 48 officially registered societies outside the USSR are voluntarily studying UFOs. This situation is evidence that the phenomenon is real. However, the absence of a description of this phenomenon based on a large number of cases leaves fertile ground for the growth of distorted information. The research on ball lightning grew out of this stage a long time ago, after the development of methods for defending against sensational but false information.

[2)]Specifically, if we use expression (13) for the velocity of air, and if we use as R the radius of the average ball-lightning formation, we find the following estimate of the Reynolds number: $\mathrm{Re} \sim 10^5(\Delta T/T)^{1/2}$. According to (15), this number increases ($\mathrm{Re} \sim R^{2/3}$) with distance from the ball lightning.

[3)]This result agrees with Stakhanov's estimate[12] of the specific gravity of the substance of ball lightning, which has been able to bounce off a table many times during its existence.

[4)]The aerogel is not destroyed over this time at the temperatures under consideration.

[5)]For the average ball-lightning formation this parameter is $10^{-1.7\pm0.8}$ (Subsection 3.2).

[6)]As an example of this approach we might cite the paper by Likhosherstnykh:[106] "138 approaches to the puzzle of the nature of ball lightning." That paper summarizes the results of a debate among a number of readers of a journal about just what ball lightning is. The approach taken there did not involve an analysis of each interpretation of the nature of ball lightning by the other participants of the debate; instead, one interpretation after another was offered in turn. That approach clearly leads down a blind alley: The effort results in certain ideas (sometimes extremely attractive) which are difficult to make use of, since the work on each idea terminated with its suggestion.

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