Observational properties of ball lightning

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Information from data banks involved in collecting results of observations of ball lightning is presented. The methods of treatment of these data are analyzed, comparisons of data from different data banks are made, and accuracy of determination of various parameters is evaluated. The resultant data and their distributions over the main parameters of ball lightning are described. A brief analysis of laboratory analogs of ball lightning is given, and also of the processes of formation and evolution of ball lightning in nature and in the laboratory.

1. INTRODUCTION

Ball lightning is one of the more interesting phenomena in nature. It is generally considered a major piece of good fortune when a person happens to observe ball lightning. On the other hand, the history of such observations extends over millenia.[1,2] The conclusion must be that the phenomenon involves unique events in the atmosphere.

Studies of ball lightning include two elements: on the one hand, there is the collection and analysis of observations and, on the other, the exploration of the underlying processes. Substantial advances have been made during the last decade in both these directions. Moreover, there have been organizational changes that have accelerated further progress in this field. International symposia on ball lightning have been held[3,4] since 1988, and an international ball lightning committee has been set up.[4] This has resulted in close interactions between scientists with different views about the phenomenon, which in turn has led to the development of a unified attitude to the study of ball lightning, and also to a measure of agreement about its nature, at least to the extent that this is possible in science. This tendency is continuing, and I believe that, in the next few years, scientists generally will come to accept ball lightning as a phenomenon of the same kind as linear lightning, St. Elmo's fire, polar auroras, and other atmospheric phenomena.

We recall in connection with all this that the problem of ball lightning has traditionally attracted more popular attention in Russia than in other countries. The result has been that Soviet scientists have always been in the vanguard of such studies. For example, our All-Union Seminars on Ball Lightning have been comparable in their status and number of participants to international symposia. However, this situation is now undergoing a change. The general deterioration in science and culture in our country has had an immediate impact on the fundamental research interests of individual scientists as opposed to research groups. This is reflected in the fact that the last, i.e., the fifth, All-Union Seminar on Ball Lightning was held in 1991 and the last (second) publication of the work of Soviet Scientists on ball lightning has now appeared.[5] The Soviet center for ball lightning will close in 1992, and it is at present difficult to estimate the scale of this loss. However, it is clear that, even in the most favorable course of events, only a small proportion of what we had in the 1980s will survive.

Two years ago, I published a review of publications on ball lightning,[6] the purpose of which was to analyze the then existing information and to identify those elements of the problem whose reliability caused no misgivings. Since there has been renewed interest in ball lightning studies, it will be useful to re-examine the situation. Although the structure of this review is similar to that of Ref. 6, its aim is different: our intention is to summarize these studies at the stage at which Soviet research on ball lightning is coming to an end.

We begin with a brief look at the present state of the ball lightning problem and the contributions made to it by Soviet researchers whose work is distinguished by a different dynamics of the ensuing development. Having divided the ball lightning problem into two parts, namely, observation and interpretation, we note that there are at present many data banks across the world in which observations of ball lightning are collected and analyzed. The total number of recorded events is now about 10 000. They include just over 4 000 cases that lie outside the scope of these data banks. In 1990, a new observational data bank was established at the Soviet center for ball lightning, which includes about 2 000 observations.[7] It is called the Stakhanov–Bychkov–Keul bank because it is based on the data collected by Bychkov and Keul.[10,11] The advantage of this bank is that it employs the methodology developed by I. P. Stakhanov and presents the information as formats and programs for a computer, i.e., it relies on modern data processing techniques. This takes the analysis of observational data to a new stage, which is why observations of ball lightning will take up most of our space here. Analysis of these data enables us to interpret the nature of ball lightning with some confidence.

There has been a change in the last two years in the general attitude to the analysis of ball lightning. In my view, the situation has become much calmer. This is largely due to experimental studies, performed with the view to developing models of ball lightning or new interpretations of the phenomenon. There are a large number of cases in which luminous atmospheric formations have appeared in the laboratory, including instances in which this was done deliberately, although the number of such experiments is usually small. For example, the proceedings of the third and fourth All-Union seminars on ball lightning[5,12] contain twenty papers in which luminous formations—the analogs of ball lightning—were investigated experimentally or arose fortuitous-

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ly in physical experiments. All the evidence obtained with artificial ball lightning or its analogs shows that it occurs when an electric field or laser radiation is applied to a surface. Ball lightning as a physical object has a structure created from evaporated material. This means that if ball lightning is a luminous atmospheric formation, which exists without the need for an external supply of energy, then all ball lightning experiments are found to fit into this scheme. Although the subsequent detailing of the nature of ball lightning can take different forms, especially since ball lightning is a multifaceted phenomenon that combines a number of surprising properties, this type of approach to ball lightning leads to well-defined programs of experimental studies.

In this review, we examine the ball lightning problem from the modern point of view. We analyze observational data that enable us to draw some conclusions about the nature of the phenomenon, and conclude with a brief analysis of ball lightning.

2. COLLECTION AND ANALYSIS OF OBSERVATIONS OF BALL LIGHTNING

2.1. Ball lightning as an observed phenomenon, and ball lightning data banks

Before we can describe and analyze ball lightning, we must define the phenomenon in a way that will separate it from other phenomena. We define ball lightning as a luminous formation in air, which can freely move both in the atmosphere and in the interior of rooms, and is observed for periods of several seconds or tens of seconds. The formation is usually spherical.

This definition distinguishes, at least to some extent, ball lightning from St. Elmo's fire which is the emission of radiation in the neighborhood of individual objects and is observed in stormy weather when the electric field strength is high. St. Elmo's fire is normally attached to objects because it is essentially a corona discharge in the vicinity of such objects (Fig. 1). Ball lightning differs from UFOs[1)] because it is an atmospheric phenomenon with smaller dimensions, shorter lifetime, and greater proximity to the observer. These properties ensure that roughly half of observed instances of ball lightning occur in the interior of rooms, whereas UFOs are always said to occur outside.

Despite the fact that ball lightning can be separated from atmospheric phenomenona, some published observations of ball lightning actually refer to other events. For example, the bright flare that appears when linear lightning strikes a terrestrial object is sometimes perceived to be a case of ball lightning. The number of such cases is relatively small and careful analysis does identify them.

Studies of ball lightning have a rich history. The phenomenon has been discussed and analyzed in the scientific world for nearly two millenia.[1,2] Modern ideas on ball lightning are based on surveys and analyses of observational data. We now have at our disposal a large volume of information about ball lightning because, first, the collection of such events has continued for more than a hundred years (Table I) and, second, it is possible to provide a clear definition of ball lightning that distinguishes it from other atmospheric phenomenona.

The extensive empirical material that is now available can serve as a basis for the reliable determination of the quantitative parameters of ball lightning. Table I lists the respective collections of ball lightning observations. Significantly, the data banks included in Table I are all independent, and each of them employs its own method of analyzing empirical data, as well as being based on eye witness accounts from different regions across the world. Hence the data deduced from different sets of observations are mutually complementary and, as a whole, provide reliable information about the properties of ball lightning. This material is augmented by a variety of reviews, monographs, and popular publications on ball lightning.[36–45]

2.2. Authenticity and accuracy of reported data

Existing studies provide an unambiguous answer to the question whether ball lightning actually exists as a physical phenomenon. It was believed at one time that ball lightning was a mere optical illusion, and this continued for a considerable time (see, for example, Refs. 2 and 46). The essence of this hypothesis is that a powerful linear lightning event can produce a trail on the retina as a result of photochemical processes, which persists as a spot for 2–10 s. This spot is perceived as an example of ball lightning. This interpretation has been rejected by all authors of reviews and monographs devoted to ball lightning, which provided preliminary analyses of a large number observations. There are two reasons for this. First, each of the numerous observations used as evidence for the existence of ball lightning includes many details that could not have originated in the observers brain as a consequence of ball lightning. Second, there are many au-

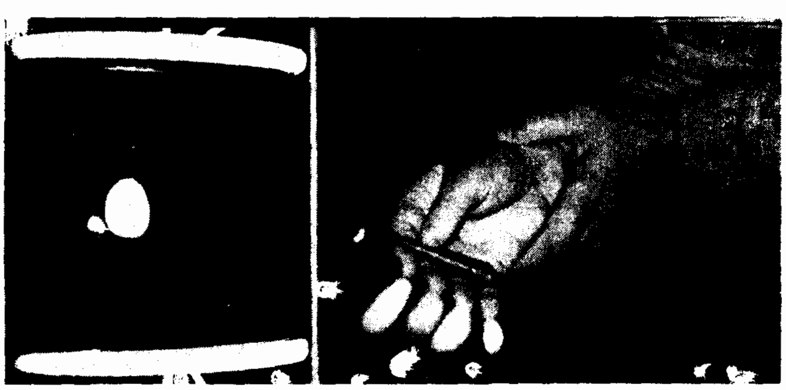

FIG. 1. St. Elmo's fire reproduced in the laboratory.[13] It was interpreted in Ref. 13 as being due to a corona discharge in an external electric field and a humid atmosphere.[14,15] The photograph shows a dry leaf (a) and a hand (b) placed in a strong field in humid air.

TABLE I. Collections of observations of ball lightning.

Authors	Year	Country	Number of processed cases	Ref.
Arago	1859	France	30	[17]
Brand	1923	Germany	215	[18]
Humphreys	1936	USA	280	[19]
McNally	1966	USA	513	[20]
Rayle	1966	USA	112	[21]
Dmitriev	1969	USSR	45	[22]
Arabadji	1976	Holland	250	[23]
Grigor'ev/ Dmitriev	1978,1979	USSR	327	[24]
Charman	1979	England	76	[25]
Stakhanov	1979,1985	USSR	1022	[8,9]
Keul	1981	Austria	150	[10,11]
Grigor'ev, Grigor'eva*)	1986	USSR	2082	[26–28]
Ohtsuki, Ofuruton	1987	Japan	2060	[29–31]
Egely	1987	Hungary	300	[32–35]
Zoï	1990	China	200	—
Bychkov	1991	USSR	1840	[7]

*)In the rest of the paper we shall for brevity often refer to this set of data as being due to Grigor'ev.

thentic photographs of ball lightning that demonstrate its objective reality. Existing empirical data on ball lightning and the analysis of such data enable us to conclude with full confidence that ball lightning is a real phenomenon.

When reported data are examined, it is important to remember that they are often distorted in newspaper reports. There are many examples in which a newspaper report is significantly different from the observer's report (see, for example, Refs. 38 and 43), mostly because of the incompetence or unconscientiousness on the part of journalists.

It is much more difficult to evaluate the authenticity of descriptions supplied by individual observers of ball lightning because, very often, there is nothing to compare them with. The reliability of eye-witness reports is analyzed in practically all books on ball lightning, and this has led to the conclusion that there are two factors that reduce the reliability of the reported data. First, ball lightning occurs unexpectedly, so that the human observer is not ready for it. Having become excited, the observer is liable to make mistakes while describing the observed phenomenon, and actually may come to believe his own account. Second, as he evaluates his experience and tries to fit it into a particular scheme, the observer distorts to some extent a coloring of the picture he is attempting to reproduce, and this can affect the reliability of the individual details. However, each of the data banks containing descriptions of ball lightning have procedures for rejecting accounts that appear to be unreliable. This means, of course, that there is a degree of arbitrariness in all this, so that the output parameters of a data bank may depend on the attitude of its administrator, but, on the other hand, this procedure does remove unreliable information.

Apart from the foregoing, there are also objective errors in the reproduction of observed events, which are due to human factors in the estimation of the parameters of the perceived picture. These human factors can be established by statistical processing of the extensive observations of other phenomenona. A successful example of this kind is reported by Charman[25] who describes an analysis of reported sighting of meteorites in the USA. These objects were simultaneously observed by many people. In each case the common physical characteristics of the events were well known, and by questioning eyewitnesses it was possible to establish the accuracy with which they were able to determine the meteorite parameters. This experiment is useful in the analysis of ball lightning observations. It has shown that the reliability of an individual report decreases with increasing interval of time between the observation and description. Moreover, the reliability of geometric and temporal parameters is much greater than that of optic or acoustic parameters.

The accuracy of observed data is limited by the performance of the eye as a measuring device. The Grigorevs[28] have estimated this accuracy for a large number of students, and have concluded that they were able to estimate the size of a sphere to within $10^{\pm 0.06}$, an interval of time to within $10^{\pm 0.2}$, and the brightness of a source of light to within $10^{\pm 0.2}$. It is clear that these are upper limits of the accuracy with which the parameters of ball lightning reported by observers are estimated.

It is important to remember that the reliability of some reports is low and that they can distort the overall information on observed ball lightning. The only way of escaping from this dilemma is to reduce the influence of unreliable information, by collecting a large number of events, but even this would leave an error, which can be estimated by indirect methods, e.g., by calculating correlations between different data banks. (See Sec. 2.3).

2.3. Output values of data banks and their estimated accuracy

The reliability and accuracy of data reported for individual ball lightning events determines the character of presentation of observational data. The general approach to the numerical presentation of ball lightning parameters was developed by McNally[20] and Stakhanov.[8,9] By generalizing their experience, it is possible to construct an optimum presentation of numerical data. First, each parameter evaluated for a set of ball lightning observations can be conveniently presented in the form of a histogram, having divided the parameter scale into suitable intervals. Second, it is convenient for this purpose to use a logarithmic scale with roughly equal intervals on the axis. Experience shows that the most convenient scale consists of the following intervals (in dimensionless units): <1, 1–2, 2–5, 5–10, 10–20, 20–50, 50–100, and >100. The upper and lower limits can be shifted.

This method of presentation takes account of the fact that the accuracy of the reported data is limited by a factor of the order of 2. Moreover, since the numerical intervals of these quantities are not very different, this enables us to identify the most significant intervals in the distribution of the required quantity. Finally, the same type of presentation can be used to compare the data in different data banks.

There is now a very large volume of statistical data on ball lightning, with a total number of values amounting to several thousand for most parameters. It is interesting to consider the precision of these data. Experience shows that the distribution of instances of ball lightning over the values of a given parameter depends not only on the region in which the respondents reside, but also on the nature of the data bank, including the method used to select reliable data. Since this involves a degree of arbitrariness, it is important to have a criterion for comparing the distributions for different banks. A criterion of this type should also enable us to determine the extent to which, with existing information, a given distribution is valid for a particular ball lightning parameter.

In my view, a suitable criterion is the correlation coefficient between distributions for different data banks, which can be constructed in the usual way (see for example, Ref. 47):

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

where X_i is the number of observations in the first bank for which the particular parameter lies in the ith interval, Y_i is the same quantity for the second bank, and $\bar{X}$, $\bar{Y}$ are the mean values of these variables, i.e., the total numbers of observations divided by the number of intervals.

If the phenomena under consideration are the consequences of a common origin, their probabilities are related, i.e., $X_i = AY_i + B$ where A and B are numerical coefficients. The correlation coefficient is then equal to unity. In the other limit, X_i, Y_i are random quantities and

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

i.e., the correlation coefficient is zero. Thus, the correlation coefficient is equal to 1 for identical distributions and 0 for random distributions.

Table II lists values of the correlation coefficient between the parameter distributions for the Grigorev[27] and Stakhanov–Bychkov–Keul[7] data banks. This comparison is interesting in two respects. First, these data banks were constructed on the basis of very similar schemes, using the Stakhanov methodology.[8,9] Second, they include most of the collected and processed observations (the two banks contain about 80% of all the published data).

The values of the correlation coefficient enable us to judge the accuracy of the distributions for each particular parameter. We shall perform the following operation to estimate this relation. We shall take the resultant brightness distribution of instances of ball lightning (see Fig. 13) and transform the numbers X_i in the respective intervals in accordance with the following scheme: $X_i \to X_{i-1}$, $X_1 = 0$, $X_7 \to X_6 + X_7$ where i is the interval running number. Next, we take the correlation coefficient between the initial and final distributions. This gives $k = 0.39$. If we transform the numbers X_i in accordance with the scheme $X_i \to X_{i+1}$, $X_7 = 0$ $X_1 \to X_1 + X_2$, we obtain the correlation coefficient $k = 0.43$ between the initial and final distributions. The correlation coefficient 0.4 is thus seen to correspond to the case where the uncertainty of each brightness estimation is equal to 2. If we change the brightness by the factor $\sqrt{2}$, the correlation coefficient between the initial and final distributions becomes approximately 0.8.

When the distributions are given in analytic form, it is possible to obtain the corresponding expression for the correlation function. Let $P(X)dX$ be the probability that the parameter X lies in the range X, $X + dX$, and suppose that $P_1(X)$ and $P_2(X)$ correspond to the first and second distributions, respectively. The correlation coefficient between these distributions is then given by

TABLE II. Correlation between between the data in the Grigor'ev[27] and Stakhanov–Bychkov–Keul[7] collections.

Parameter	Number of events: Stakhanov –Bychkov–Keul[7]	Number of events: Grigor'ev[27]	Correlation parameter
Month of observation	1796	1614	0.98
Time of day	1436	668	0.45
Connection with thunderstorm	868	1186	0.98
Nearest distance to observer	1454	1617	0.89
Diameter	1796	1614	0.99
Lifetime	437	1604	0.31
Color	1803	1573	0.42
Brightness	1321	802	0.70

$$k = \int_0^\infty \frac{dP_1(X)}{dX}\frac{dP_2(X)}{dX}dX \times \left[\int_0^\infty \left(\frac{dP_1(X)}{dX}\right)^2 dX \int_0^\infty \left(\frac{dP_2(X)}{dX}\right)^2 dX\right]^{-1/2}. \tag{2}$$

For example, if the ball lightning diameter distribution is given by[9] $P(X) = X\exp(-X/d)/d^2$, we find that the correlation coefficient becomes $k=(Z+Z^{-1})^3$ where $Z=(d_1/d_2)^{1/2}$. In particular, if d_2 differs from d_1 by a factor of 1.5, we have $k=0.82$, and if $d_2/d_1=2$, the result is $k=0.51$.

2.4. Distribution of ball lightning over parameter values

The form of the distribution of ball lightning over a given parameter is a separate problem. The form of this function cannot be chosen on the basis of empirical data. The fact is that observational data are presented as histograms with a limited number of intervals of the values of the variable. At any rate, this number is less than 10, and any attempt to increase it results in lower accuracy and a distortion of information. This means that different continuous functions of the parameter under investigation can be chosen to represent approximately the same empirical data.

Dijkuis[48] has analyzed this problem and has concluded that the log-normal function is particularly suitable for this purpose. He supported this conclusion by arguing that it provided the best fit to the current and the associated parameters of ball lightning for cloud to ground discharges.[49] The log-normal distribution takes the form

$$f(X) = (2\pi\sigma)^{-1/2}\exp[-(\lg X - \lg \bar{X})^2/2\sigma^2], \tag{3}$$

where $\bar{X}$ is the mean of X and σ is the standard deviation.

We shall use the log-normal distribution with the following proviso. The definition of the distribution function shows that it has a maximum within its domain of existence, and is small or vanishes at the limits of this domain ($X=0, X=\infty$). It can therefore be used whenever these conditions are satisfied, e.g., for the diameter, emission intensity, and energy distributions of ball lightning. In other cases, when the distribution function has a maximum for small X, the log-normal distribution ceases to be valid. This occurs for the distribution of ball lightning over its lifetime and over the shortest distance from the observer.

We note that the log-normal involves the evaluation of the following average:

$$\lg \bar{X} = \frac{1}{N}\sum_i N_i \lg X_i; \tag{4}$$

where N_i is the number of observations for which X_i lies in the ith interval and N is the total number of observed events ($N=\Sigma_i N_i$). This can be rewritten in the form

$$\bar{X} = \left(\prod_i X_i^{N_i}\right)^{1/N}, \tag{5}$$

i.e., $\bar{X}$ can be the geometric mean. The standard deviation is given by

$$\sigma^2 = \frac{1}{N}\sum_i N_i(\lg X_i - \lg \bar{X})^2. \tag{6}$$

In this distribution, the average X_{av} is greater than the most probable value $\bar{X}$:

$$X_{av} = \int Xf(X)dX = \bar{X}\exp(\sigma^2 \ln^2 10/2) = \bar{X}\exp(2{,}65\sigma^2). \tag{7}$$

The log-normal distribution is the most convenient distribution function for the analysis of most observational data on ball lightning. Figure 2 illustrates Dijkhuis' fit of the log-normal distribution to the data from the Stakhanov–Bychkov–Keul bank.

The correlation coefficient

$$k = \frac{\sum_i X_i Y_i}{(\sum_i X_i^2 \sum_i Y_i^2)^{1/2}}$$

where $X_i = \int f(X)\,dX - n^{-1}$ and $Y_i = N_i N^{-1} - n^{-1}$, is a measure of the adequacy of the log-normal distribution (the integral is evaluated over a given interval, n is the number of intervals, N_i is the number of observations for which X lies in the ith interval, and N is the total number of observations).

3. PROPERTIES OF BALL LIGHTNING OBSERVATIONS

3.1. Conditions of observation

The conditions under which ball lightning is observed, and its behavior during observations, are important in helping us to understand the nature and behavior of ball lightning. It is commonly believed that the formation and continuing existence of ball lightning is controlled by electrical

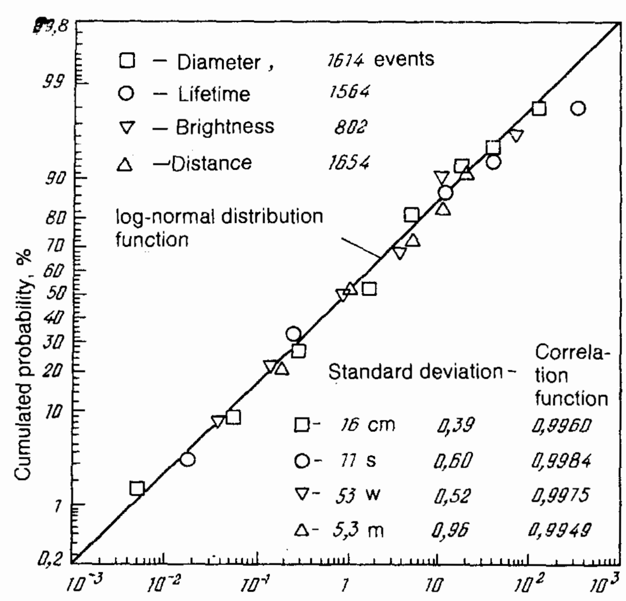

FIG. 2. The Stakhanov–Bychkov–Keul data fitted to the log-normal distribution function. The Dijkhuis data for the cumulated (i.e., resultant over all preceeding intervals) data are reproduced.

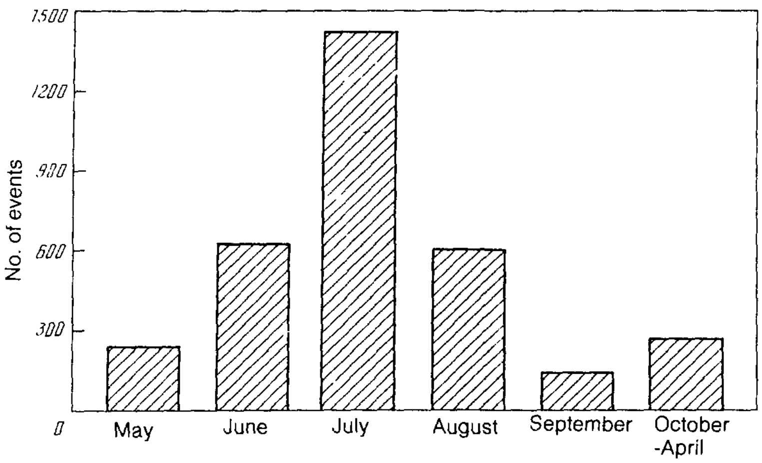

FIG. 3. Seasonal ball lightning distribution in Austria, Hungary, and the USSR (3 286 observed events): 1 713 cases from Ref. 27, 133 from Refs. 32 and 34, and 1 440 from Ref. 7.

processes in the atmosphere. There is usually a correlation between stormy weather and observations of ball lightning. Inspection of the data of McNally (513 cases), Rayle (112 cases), Stakhanov–Bychkov–Keul (1 328 cases), and the Grigor'ev (1 924 cases) shows that out of the total number of 3 877 events, 79% occurred in stormy weather (during storms, and for an hour before and after a storm). These results are in conflict with the Japanese ball-lightning data[29–31] (2 060 events): 89% of the events occurred in clear weather, 7.6% were recorded during rainfall, and 2.5% during storms. Moreover, there is a strong correlation between seasonal distributions of ball and linear lightning, and also between their distributions over Japan. Ohtsuki and Ofuruton maintain that the discrepancy between the data for Japan and the 'continental' observations may be due to the particular weather conditions over Japan. Atmospheric humidity over Japan in the summer and on clear days is in excess of 80%.

The monthly distribution of ball lightning (Fig. 3) provides indirect evidence for the correlation between ball lightning and stormy weather. We write the correlation coefficient in the usual way:

$$k = \sum_i (X_i - \bar{X})(Y_i - \bar{Y}) / [\sum_i (X_i - \bar{X})^2 \sum_i (Y_i - \bar{Y})^2]^{1/2},$$

where X_i refers to the distribution of ordinary lightning, Y_i to ball lightning, the subscript i identifies the month (or a group of winter and adjacent months), $\bar{X}$, $\bar{Y} = 1/n$ are the average values of these variables, and n is the number of selected intervals ($n = 6$ in this case). Table III lists the values of the correlation coefficient between the probabilities of ball lightning and ordinary lightning. It is clear that the results obtained for different data banks are similar and that the average correlation coefficient is $k = 0.84 \pm 0.04$.

Hence it may be concluded that linear and ball lightning have a common origin. Figure 4 shows the resultant distribution of ball lightning over the time of day. It also correlates with the corresponding distribution of linear lightning.

3.2. Point of observation and distance to observer

The place of observation and the conditions under which ball lightning is observed are of considerable interest. In about half of all instances, ball lightning is observed in the interior of rooms. According to Rayle,[21] the proportion is 48%. Charman[25] has analyzed 71 events and reports that in 45 cases ball lightning was observed in open air, in 15 cases it occurred in a room, and in 11 cases it entered the room from outside. Table IV lists the corresponding data reported by the Grigor'evs.[26,27] We add that, according to the data in Ref. 27, 35% of ball lightning events were recorded in towns and 64% in the countryside.

We note that ball lightning has also been seen from aircraft. This means that ball lightning can appear at high altitudes. In a few cases, ball lightning was observed in the interior of an aircraft;[42–45] collisions between ball lightning and aircraft are not so rare.

It is interesting to consider the distribution of ball lightning over the shortest distance to the observer. This also yields information on the brightness of ball lightning, which depends on the separation between the event and the observer. This distribution is shown in Table V and Fig. 5.

We shall write the probability of detecting ball lightning in the distance range between R_1 and R_2 in the form $W(R_1) - W(R_2)$. If we use the expression $W(R) = (R + R_0)^{-n}$, the optimum parameter values are $n = 0.59$ and $R_0 = 1.5$. Hence it follows that half of the ball lightning events are observed from distances of less than 3 m and 80% from distances of less than 20 m.

TABLE III. Correlation coefficient between probability of observation of ordinary and ball lightning.

Type of distribution	Ordinary lightning	Ball lightning
Correlation coefficient	0,83 [9]	—
	0,79 [27]	0,88 [27]
	0,86 [29, 30]	—

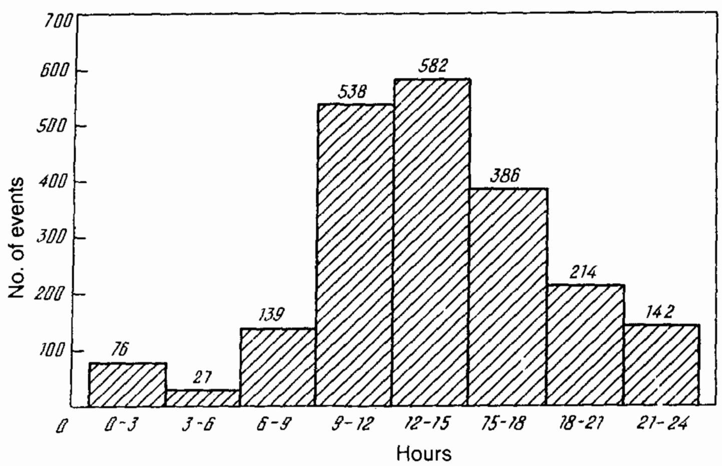

FIG. 4. Distribution of ball lightning over time of observation during a day (1 436 cases from Ref. 27 and 668 from Ref. 7).

TABLE IV. Place of observation of ball lightning[26,27] (1 984 cases).

Place	Fraction, %	Place	Fraction, %
Room interior	50.2	River or lake bank	4.0
Street	24.5	Mountains	2.3
Open field	9.5	Sky seen from Earth	4.1
Wood	4.4	Clouds seen from aircraft	1.0

TABLE V. Distribution of ball lightning over the shortest distance to the observer.

Distance range, m	No. of events				Fraction, %
	Stakhanov *et al.*[2]	Grigor'ev[16]	Egely[21]	Total	
0 — 1	335	505	25	865	26
1 — 5	556	476	119	1151	34
5 — 10	146	87	22	255	8
10 — 20	151	95	21	267	8
20 — 50	180	92	21	293	9
50 — 100	135	62	5	202	6
> 100	151	137	31	319	9
Grand total	1654	1454	244	3352	100

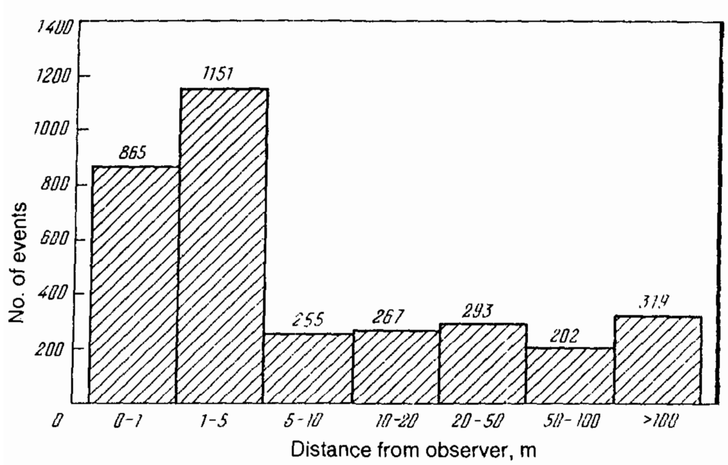

FIG. 5. Resultant distribution over the nearest distance to ball lightning (3 352 cases: 1 454 from Ref. 27, 244 from Refs. 32 and 34, and 1 654 from Ref. 7.

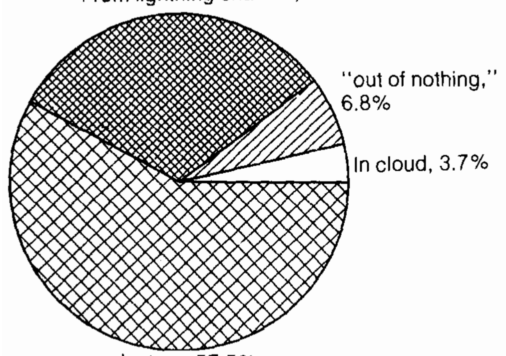

FIG. 6. Origin of ball lightning (353 observed events: 67 from Ref. 9 and 286 from Ref. 27).

3.3. The onset and decay of ball lightning

Electrical phenomena in the atmosphere facilitate the formation of ball lightning. Figure 6 shows the distribution of ball lightning onsets. Ball lightning is found to arise directly in the discharge channel of ordinary lightning or in its vicinity; it can appear on different metal objects and devices such as electrical sockets, radio receivers, heat distribution units, and so on, but it can also arise in air "out of nothing."

Ball lightning ends its life either quietly or with a bang. Figure 7 shows the resultant distribution over the ball lightning decay channels, using the information drawn from different data banks. It is clear that, in most cases, ball lightning ends with a bang, but there is a substantial number of slow decays. Disintegration into pieces is observed in some cases.

The explosion of ball lightning usually occurs without much damage. The 335 explosions in the Stakhanov data[9] include only 34 cases of reported damage. This usually takes the form of the splintering of trees and poles (19 cases). Light walls and partitions are sometimes penetrated by ball lightning. The strength of a ball lightning explosion is relatively low, so that anyone entering the explosion zone is unlikely to suffer tragic consequences.

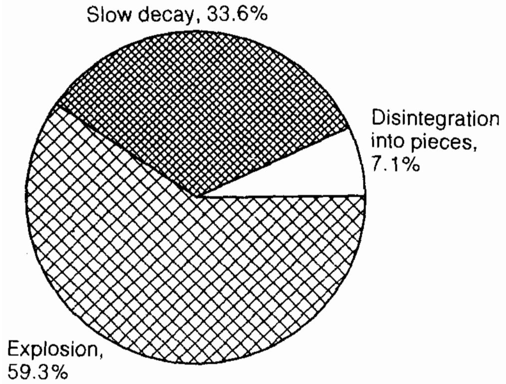

FIG. 7. Distribution of ball lightning over decay channels (2 864 observed events: 421 from Ref. 20, 78 from Ref. 21, 51 from Ref. 25, 1 131 from Ref. 27, 127 from Refs. 32 and 34, and 1 056 from Ref. 7.

3.4. Effect of ball lightning on people

Encounters with ball lightning do not usually have any special consequences for observers, especially if this happens in the interior of a room. However, such encounters are not always harmless. For example, I. P. Stakhanov has collected over 1 000 cases of observed ball lightning of which five ended in a fatality, but not always as a direct effect of it. The Grigor'evs have shown[27] that such reports must be treated with caution if only because this type of information is not always supplied by the actual observers of the events. At any rate, the probability of a fatal encounter with ball lightning is very small, except for cases in which the electrical explosion results in considerable damage.

Explosions initiated by ball lightning can lead to considerable damage. All the data banks contain quite a few cases of demolition of buildings or damage to their interior by ball lightning. There are also photographs of such events (see Ref. 50). They usually occur in the countryside where protection from linear lightning is less effective than in towns. All this suggests that, in these cases, ball lightning produces a current in the atmosphere, so that the danger to the public arises from the fact that, in stormy weather, ball lightning can initiate electric breakdown in the atmosphere. The resulting electrical current draws energy from the atmospheric electric field, and this energy is much greater than the internal energy of ball lightning. Hence the effect of the electric current generated in this way on people and on conductors far exceeds the effect of ball lightning itself.

It is important to note that in all encounters with ball lightning in which the latter produces marks on the body, or causes a fatality, the effect on the human body is similar to injury caused by an electric current. In most cases, it is noted that quiescent ball lightning can produce burns or wounds. One such case was reported[51] in England in 1975. A woman came into contact with ball lightning and, after she waved her left hand in an attempt to deflect it, she developed symptoms of reddening and swelling of her hand. Her legs also showed some reddening, and numbness was found to develop. These are symptoms that typically accompany the passage of an electric current through the body. In addition, the Grigor'evs[27] have three cases of ball lightning burns in their collection, which are similar to those suffered as a result of exposure to ultraviolet radiation.

3.5. Probability of observation and appearance of ball lightning

One of the interesting ball lightning problems is the determination of the probability that it will be observed. Ball lightning is a rare event, but the mean probability that it will be observed can be estimated. According to Rayle,[21] 180 NASA staff members out of a total of 4 400 interviewed stated that they had observed ball lightning. Stakhanov[9] has estimated that the probability of seeing ball lightning in a lifetime is $P = 10^{-3}$. The most reliable information relating to this question follows from Egely's data.[32,34] He appealed for information through Hungarian newspapers with a total circulation of 1.5 million copies and received reports of 520 cases of ball lightning observed by about 1500 people. If we assume that, on average, the people who saw the events were half way through their life, and that all observations were reported, we find that the upper limit for the probability of seeing ball lightning in one lifetime is $P = 2 \times 10^{-3}$.

After Egely's relationship with these newspaper subscribers became firmly established, he received 39 reports[34] of ball lightning in 1987. This gives a further upper limit for the probability of seeing ball lightning in one lifetime: $P = 2\times 10^{-3}$. Combining all these data, we find that

$$P = 10^{-2.2\pm0.5}. \tag{8}$$

This enables us to estimate the ball lightning incidence density. If we take the whole of the Earth's surface, we find that the incidence density is given by

$$W = P/\tau p(0), \tag{9}$$

where τ is the human lifetime and $p(R)$ is the distribution of ball lightning over the distance to the observer. According to Table V, $p(0) = 10^{-0.6\pm0.5}\ \mathrm{m}^{-2}$, so that the ball lightning incidence density is

$$W = 10^{1.3\pm1.0}\ \mathrm{km}^{-2}\,\mathrm{y}^{-1}. \tag{10}$$

This result may be compared with the incidence density for ordinary lightning, which is[52] $5.4\pm 2.1\ \mathrm{km}^{-2}\mathrm{y}^{-1}$. By taking the ratio of these quantities, we find that the number of ball lightning events per ordinary lightning is

$$n = 4\cdot 10^{\pm1.2}. \tag{11a}$$

We note that Barry's estimate[37,53,54] for the probability per unit time per unit area of observing ball lightning is

$$w = 10^{-4.1\pm1.3}. \tag{11b}$$

Hence it is clear that ball lightning is not a rare phenomenon. However, it is observed mostly at short distances from the observer. Hence, although the probability that ball lightning will occur is not small, only a small fraction of ball lightnings is seen by people, i.e., the probability that it will be observed is small.

4. PROPERTIES AND PARAMETERS OF OBSERVED BALL LIGHTNING

4.1. Type of motion

The motion of ball lightning is usually smooth and horizontal. Horizontal motion has been observed in 53% of the 110 observed events in Rayle's list,[21] 68% of the 1 006 cases in Stakhanov's list,[8,9] and 75% of the 1 743 cases in the Grigor'ev collection.[27] Moreover, Rayle[6] has reported that in 18% of all cases the motion was vertical (up or down) and in 18% of cases it was tortuous. According to Stakhanov,[8,9] downward motion was observed in 18% of all cases (183) and upward motion in 5% of all cases (47). Analysis of the Grigor'ev data showed that in 0.4% of all cases (7 events) ball lightning rose upward toward clouds, while in 5% of all cases (84 events) ball lightning fell downward from clouds. Despite the different methods employed to process the data, it is clear from these results that ball lightning usually propagates in the horizontal direction.

The surprising feature of ball lightning is that it can enter a room through narrow slots and apertures. Many examples of this are cited in Stakhanov's book.[9] Ball lightning seems to be able to "see" open doors or windows, can pass through them, and can "locate" such openings unaided. Examples of such events can be found in the data banks.

Ball lightning usually travels in air, but it is often found to roll on the ground or on the ceiling. I have observed luminous spheres with diameters of a few centimeters, rolling along the ground. They were formed when the electrical wires of a streetcar line were short-circuited.

A ball lightning falling on the ground is sometimes found to rebound like a tennis ball. For example, Timoshuk[55] has described a ball lightning, 10 cm in diameter, travelling down a thick branch, accelerating and bouncing up and down as it met surface irregularities. It eventually fell on the pavement and bounced up and down like a tennis ball, the successive heights reached by the hopping ball being 20, 12, and 5 cm. It then split into pieces. Another example[9] of this kind is illustrated in Fig. 8 in which ball lightning was produced by shorting the rod of a soldering iron. It rebounded several times along the table, as shown.

4.2. Geometric parameters and lifetime

Its very name (both in Russian and in other languages) implies that ball lightning should be spherical in shape, and this is indeed confirmed by observations. Thus, the review data published by Stakhanov–Bychkov–Keul[7] and the Grigor'evs[27] show that $91\pm 1\%$ of the observed 3 123 cases of ball lightning are spherical in shape.

Significantly, ball lightning usually retains its spherical shape during its lifetime. A change of shape was noted by the Grigor'evs[27] in only 134 out of a total of 2 082 processed events. In 25 cases the ball became a ribbon, in 15 cases the ribbon became a sphere, in 4 cases the ball was deformed on each rebound, and in 12 cases the ball lightning became elongated in the direction of a conductor. Moreover, in 226 cases (11%), the ball lightning was found to have a semitransparent envelope, in 119 cases (6%) it had a tail, and in 143 cases (7%) there were indications of an internal structure associated with the random motion of luminous points and filaments in the interior of the ball lightning. Hence it is clear the simple spherical shape of ball lightning conceals a complicated picture of internal processes.

When the ball lightning parameters are analyzed, it must be remembered that all the empirical data are the result of visual observation by people in a heightened emotional state. The uncertainties in the resulting information cannot be removed by improving the statistics. This must be borne

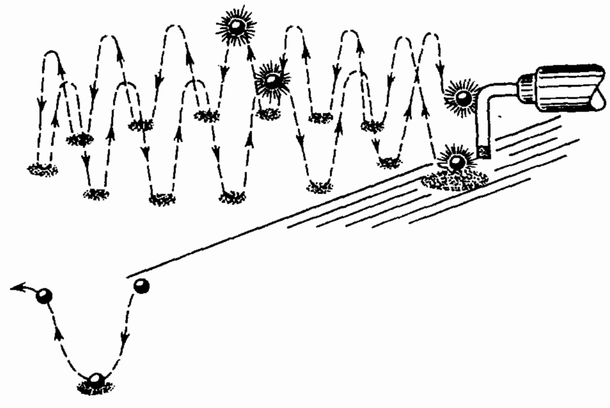

FIG. 8. Series of rebounds by a luminous object produced by short-circuiting a soldering iron.

TABLE VI. Average diameter of observed ball lightning.

Collection	McNally[20]	Rayle[21]	Charman[10]	Stakhanov–Bychkov –Keul[7]	Grigor'ev[27]	Egely[32,34]
No. of data	446	98	64	1614	1796	204
d, cm	30	32	26	24	19	35

in mind during the subsequent analysis of observational data. Table VI lists the ball lightning diameters reported by different sets of observers. The mean diameter is $\bar{d} = 23 \pm 5$ cm. We note that the previously reported value, obtained without taking account of the new sets of data, was $\bar{d} = 28 \pm 4$ cm. Clearly, the greater volume of data has not resulted in a smaller uncertainty. Moreover, the diameter distribution functions deduced from different collections of observational data are found to be different. Figure 9 shows the ball lightning diameter distribution for the combined data. When this distribution is fitted with the log-normal function (3) proposed by Dijkhuis, the parameters of the distribution turn out to be $\bar{X} = 18$ cm, $\sigma = 0.4$ and the mean diameter is 27 cm, which agrees with previous values to within the limits of accuracy.

The ball lightning lifetime distribution function has a complicated form. Let $P(t)$ be the probability that the ball lightning will not split into pieces at time t. One would expect this function to be an exponential. However, analysis of observational data[27] shows that the result is actually the sum of several exponetials:

$$P(t) = \sum_i A_i \exp(-t/\tau_i). \tag{12}$$

We now introduce a number of time constants that characterize the lifetime of ball lightning. Thus, the mean lifetime is

$$\tau_1 = \int_0^\infty t|dP/dt|dt, \tag{13a}$$

the time

$$\tau_2 = -\frac{dP}{dt}\Big|_{t=0}, \tag{13b}$$

is a measure of the rate of decay at the initial time, and

$$P(\tau_3) = 1/e, \tag{13c}$$

$$P(\tau_4) = 1/2 \tag{13d}$$

define the times of survival of the indicated fractions of ball lightning. Table VII lists the time constants deduced from different sets of observational data. We note that Grigor'ev[27] used only the data from his own collection for which the lifetime was clearly defined, i.e., the onset and decay of ball lightning was observed, or the decay of ball lightning formed after a linear lightning was observed. In other collections of data, the lifetime of ball lightning was taken to be the time of its observation.

If we suppose that ball lightning decays exponentially, then $\tau_1 = \tau_2 = \tau_3$ and $\tau_4 = 0.69$, as in the case of the Rayle collection.[21] In other collections, which include long-lived and short-lived ball lightning, these average time constants are significantly different. The ball lightning lifetime is usually described by τ_4 which, when Table VII is taken into account, is $\tau_4 = 8 \times 10^{\pm 0.3}$ s. Another constant that is often used is τ_2. This is a measure of the rate of decay at the initial time. The average of the data of Table VII is $\tau_2 = 9 \times 10^{\pm 0.3}$ s. It is clear that these values agree to within the indicated errors. We shall therefore use these constants as measures of the ball lightning lifetime. Figure 10 presents a histogram of

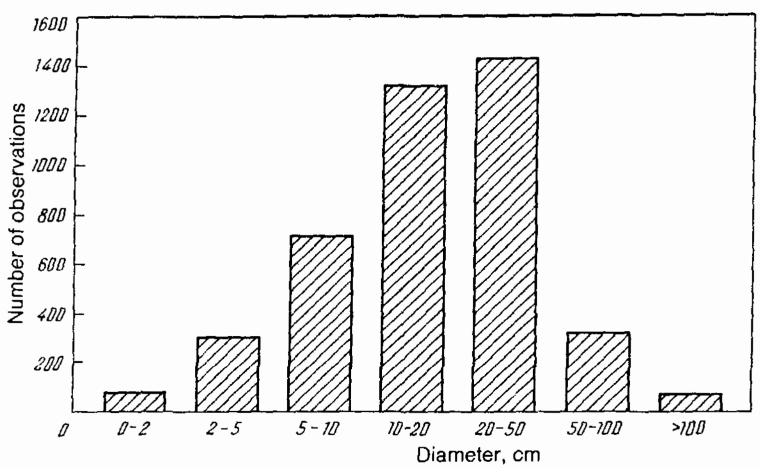

FIG. 9. Global diameter distribution of ball lightning (total of 4 219 events) 446, 98, 64, 1 796, 204, and 1 611 events from Refs. 20, 21, 25, 27, 32 and 34, and 7, respectively.

TABLE VII. Mean lifetime of ball lightning, s.

	No. of events	τ_1	τ_2	τ_3	τ_4
Mc Nally[20]	445	12	4	4,5	3
Rayle[21]	95	14	14	14	10
Stakhanov–Bychkov–Keul[7]	1564	26	31	16	10
Grigor'ev[27]	437	40	5	9	4,5
Egely[32]	152	38	9	18	7,5

the ball lightning distribution for the combined data from the different collections.

It is interesting to note that the lifetime correlates with the ball lightning diameter: the lifetime becomes longer as the diameter increases. This was first established by Stakhanov[8,9] (Table VII). We shall analyze the Stakhanov data, using his expression for the probability $P(t)$ that the ball lightning survives at time t. We shall take this expression in the form [see (12)]:

$$P(t) = A\exp(-t/t_1) + (1-A)\exp(-t/t_2), \tag{14}$$

where, in accordance with Stakhanov's data, $t_1 = 11$ s, $t_2 = 54$ s. We shall assume that A is a function of the ball lightning diameter d:

$$A = \exp(-d/d_1),$$

where d_1 is a parameter. Analysis of the data in Table VIII gives $d_1 = 34$ cm. Figure 11 shows the mean lifetime τ_1 as a function of the diameter according to the Stakhanov data and also the data of Grigor'ev[56] and Amirov and Bychkov.[7]

4.3. Ball lightning as a light source

The emission of light is a principal feature of ball lightning. Its color is another. Table IX collects together existing observational information on the color of ball lightning. It is based on the simplified color distribution scheme proposed by Stakhanov.[8,9] The numbers in parentheses indicate the percentage probability of particular color, and the last column gives the probability a particular color based on all the results. Comparison of the data in the different collections shows that the color probabilities are subject to large uncertainties, and that the probabilities of white, red and pink, yellow, and orange colors are the same and amount to about 20%. Figure 12 summarizes existing data on the ball lightning color distribution.

It is important to note that, in addition to the colored ball lightning, there have been reports of gray or black ball lightning, i.e., structures observed in reflected light. An example is given in Ref. 68.

Approximate analysis[21] shows that ball lightning is a source of moderate intensity. Significant advances were made in this area by Stakhanov[9] who collected data on the brightness of ball lightning as a source of light. Since the eye is an imperfect brightness-measuring instrument, and because of the unusual conditions under which the intensity of ball lightning is observed, it seems likely that the brightness of each ball lightning is estimated to within a factor of 2 or 3. This uncertainty is reduced to some extent by the extensive statistics now available. The Stakhanov scheme relies on a comparison of the brightness of ball lightning with that of an electric lamp. The scheme was therefore used in subsequent data banks. The present day situation is summarized in Fig. 13.

Let us examine these results on the assumption that the brightness distribution is $f(J) = \exp(-J/J_0)$ in which $f(J)dJ$ is the probability that the brightness lies in the range between J and $J + dJ$. Hence the probability $W(J_i,J_k)$ that the brightness of ball lightning lies between J_i and J_k is $W(J_i,J_k) = \exp(-J_i/J_0) - \exp(-J_k/J_0)$. Consider the functional

$$\varkappa(n, J_0) = \sum_i (W(J_i, J_k) - W_{\rm obs}(J_i, J_k))^2, \tag{15}$$

where $W(J_i,J_k)$ is given by the above expression and

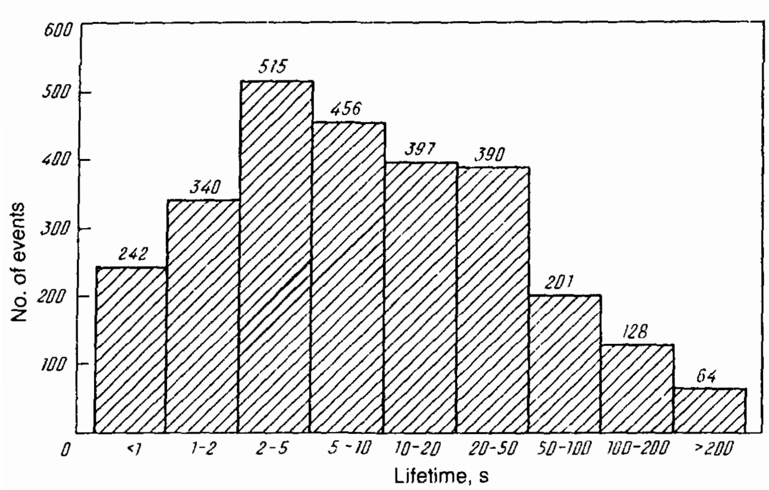

FIG. 10. Global lifetime distribution of ball lightning (2 733 events: 445, 95, 437, 152, and 1 604 events from Refs. 20, 21, 27, 32 and 34, and 7, respectively).

TABLE VIII. Probability of survival of ball lightning as a functiton of its diameter d.

Range of d, cm	No. of events	Survival probability $P(t)$		
		$t=0$	$t=20$ c	$t=50$ c
0 — 10	246	1	0,22	0,08
10 — 30	548	1	0,36	0,16
> 30	211	1	0,58	0,32

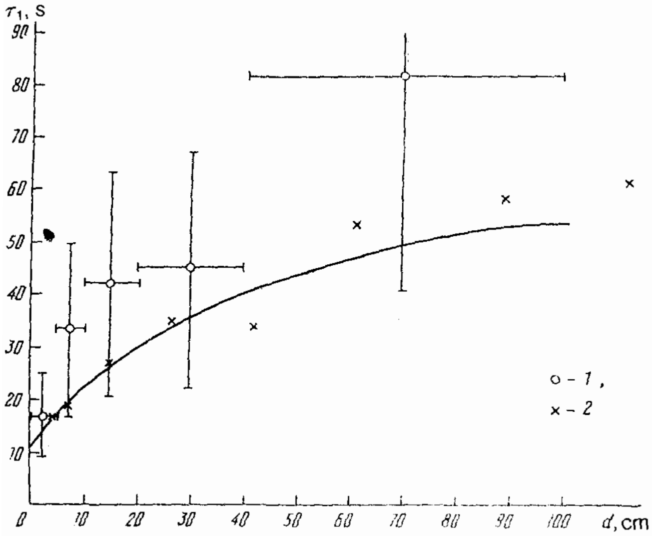

FIG. 11. Mean ball lightning lifetime τ_1 as a function of diameter. Solid curve—(14) and (15), using the data from Ref. 9; *1*—Ref. 55, *2*—Ref. 7.

TABLE IX. Color distribution of ball lightning.

Observed color	No. of observations			Probability of color %
	Total from Refs. 20, 21, 25, and 32	Ref. 7	Ref. 27	
White	141(19)	473(30)	247(14)	21 ± 7
Red or pink	116(16)	316(20)	297(16)	18 ± 2
Orange	115(16)	200(13)	633(35)	23 ± 10
Yellow	140(19)	384(24)	307(17)	20 ± 3
Green	15(2,0)	22(1,4)	22(1,2)	1,5 ± 0,3
Blue, dark blue or violet	90(12)	148(9)	230(13)	11 ± 2
Mixture of colors	119(16)	30(2)	67(4)	8 ± 6
Grand total	736	1573	1803	100

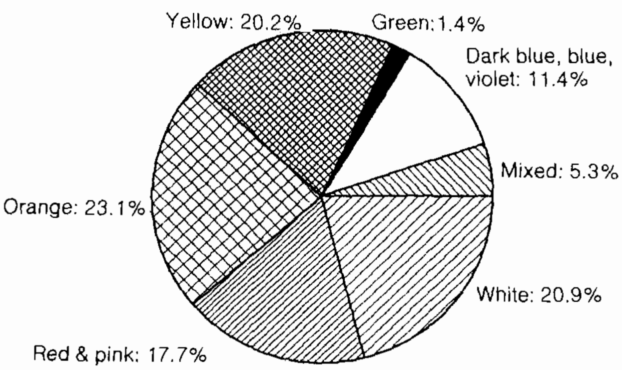

FIG. 12. Color distribution of ball lightning (4 112 cases: 311, 152, 68, 1 803, 205, and 1 573 cases from Refs. 20, 21, 25, 27, 32 and 34, and 7, respectively).

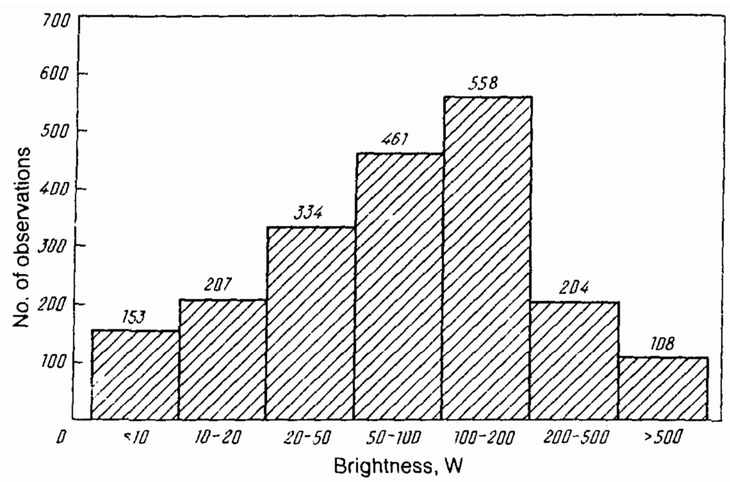

FIG. 13. Brightness of ball lightning compared with the brightness of an electric lamp of appropriate rating (2 123 observed cases: 1 321 and 802 from Refs. 9 and 27, respectively).

$W_{\rm obs}(J_i,J_k)$ represents the observations. The optimum brightness J_0 will be determined by demanding that the functional be a minimum, and the uncertainty corresponds to a reduction in the functional by a factor of 2. This yields the following figure for the mean power dissipation in the equivalent electric lamp: $\bar{J} = J_0 = 110 \pm 20$ W or, in photometric units, $\bar{J} = 1500 \pm 300$ lm. The indicated uncertainty is a measure of the statistical spread alone. The true uncertainty is much greater because the method used to determine each observed brightness value is very approximate.

If we process these data by fitting them to the log-normal distribution (3), we obtain the most probable brightness expressed in units of the power dissipation in the equivalent electric lamp: $\bar{J} = 70$ W for mean brightness $J_0 = 130$ W and standard deviation $\sigma = 0.5$. It is clear that the uncertainty due to the data processing is much smaller than that associated with visual observation.

4.4. Energy balance of ball lightning

In most cases, ball lightning decays without leaving any traces. However, in some cases, the process leads to effects and damage that can be used to estimate the energy expended in this. Such cases have been analyzed by Barry,[25] Stakhanov,[12] and Egely.[34] The observations for which the energy of ball lightning was estimated can be divided into two groups. The first contains cases in which the aftereffects of ball lightning could have occurred at the expense of its internal energy. The other group contains cases relying on the energy of an external electric source. These estimates have been used to construct the internal energy distribution function for the recorded cases of ball lightning and the result is shown in Fig. 14. A more detailed analysis is given in Refs. 38, 40, and 58. The most probable ball lightning energy corresponding to this distribution is 7 kJ$\cdot 10^{\pm 0.2}$ The mean internal energy of ball lightning is 200 kJ$\cdot 10^{\pm 0.2}$. When the data of Fig. 14 are fitted with the log-normal distribution (3), this gives the following distribution parameters: most probable internal energy 6 kJ, mean internal energy 60 kJ, and standard deviation $\sigma = 0.93$.

The results obtained in this way yield the following value for the mean ball lightning power:

$$P = \bar{E}WS = 10^{4.1\pm 1.2}\ \text{kW}, \qquad (16)$$

where W is the probability of occurence of ball lightning per unit area per unit time and $S = 5.1 \times 10^8$ km^2 is the Earth's surface area. We note that the mean power of linear light-

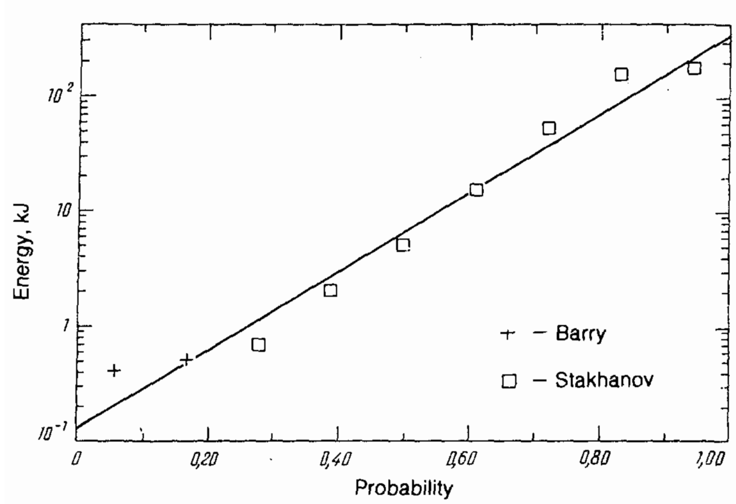

FIG. 14. Probability that the ball lightning energy exceeds a given figure. The graph is based on estimates by Barry[37] and Stakhanov[9] for those cases where the energy release was definitely due to internal energy.

ning[59-61] is of the order of 5×10^7 kW. It is clear that if we consider that ball lightning is a secondary effect of ordinary lightning, then the fraction of linear lightning energy expended in the formation of ball lightning is $10^{-3.6\pm1.2}$.

We note that the internal energy of ball lightning is relatively low and cannot lead to serious damage. Its most probable value corresponds to the chemical energy of a few matches or a few grams of explosive material.

4.5. Other properties of ball lightning

Another feature of ball lightning is that it is a source of heat. According to Rayle's data,[21] the release of heat was reported in 4 cases in his collection, but did not occur in 100 cases. In Stakhanov's collection,[8,9] 25 out of 294 people reported that they detected the release of heat when they observed ball lightning at distances of less than 1 m, 8 out of 131 people reported similarly for distances of 1–2 m, 20 out of 379 people reported on 2–5 m, and 9 out of 676 people noted heat release for ball lightning at distances in excess of 5 m. According to the data of Grigor'ev,[27] of the 383 reported cases of ball lightning there were 64 firm reports of heat release. All in all, these data show that only a few percent of respondents report the release of heat, but there is no well-defined relation between the probability of heat detection by these observers and the distance to the ball lightning event.

Ball lightning may be accompanied by the emission of low-intensity sound in the form of crackling, hissing, or whistling. It can also interfere with radio reception. Dmitriev[22] has noted that the 45 cases of ball lightning collected by him included 6 cases of interference with radio reception.

Ball lightning has electrical properties, but there are no clear statistics on this question. However, ball lightning has often been found to be attracted by metal objects, and frequently travels toward conducting objects or electrical leads. According to McNally,[20] this phenomenon is observed in 20% of cases, whereas Rayle's collection[21] contains 16% of such instances. The charging and attraction of dielectric objects such as dry leaves, sheets of paper, and so on is occasionally reported. All these phenomena can be explained by the fact that ball lightning carries a small electrical charge.

A different situation arises when ball lightning gives rise to electric current that causes damage, including the fusing of electric leads. Egely[32,34] has analyzed a number of such cases and has estimated that the charge circulated in leads as a result of such events was of the order of 10–100 C. Since this charge cannot be carried by the ball lightning itself, we again come to the conclusion that ball lightning causes electric breakdown in the atmosphere which in turn leads to the damage.

Let us now analyze the hypothetical electric properties of ball lightning. The maximum charge that, in principle, ball lightning can carry corresponds to the breakdown field on its surface, which amounts to[62] 25.5 kV/cm. If this field is produced by an electric charge on the surface of a sphere with a diameter of 23 cm, the corresponding total charge is 4×10^{-6} C. This is a relatively small charge that presents no danger to people. For example, suppose that a person shorts a 220-V socket through his body. If we assume that the resistance of the body is 30 kΩ, we find that the above charge flows through it in a time of 5×10^{-4} s (the current is 7 mA). In our experience, this presents no danger to anyone.

The above electric charge corresponds to an energy of 1 J which is much less than the internal energy of ball lightning. All this leads to the conclusion that the electrical properties of ball lightning are insignificant in the energy balance between ball lightning and its ambient objects, especially since we have used parameter values that must be regarded as high.

Ball lightning can leave behind a smell typical of the chemical composition of its material. This can be the smell of sulfur, the oxides of nitrogen, and ozone.

There is just one case in which it was possible to determine the chemical composition of the trail of ball lightning.[62,63] The author of these reports, D. M. Dmitriev—a specialist in atmospheric chemistry—was a member of an expedition that visited the river Onega in 1965. He was prepared for taking samples of air for other purposes when, quite fortuitously, ball lightning appeared and travelled past him, leaving behind a trail in the form of bluish haze. Dmitriev was able to use his equipment to analyze the ball lightning trail and showed that it contained enhanced amounts of only two components, namely, ozone and NO_2. The maximum ozone and NO_2 concentrations were 1.3 and 1.6 g/m^3, respectively. These are higher by factors of 50–100 than in normal air.

4.6. The average observed ball lightning

It is convenient to use the above ball lightning data banks and the analyses of observations of ball lightning in these banks to construct an empirical model and hence deduce the average parameters of ball lightning based on observations. This model has a collective significance and can be used as a basis for the analysis of the nature of ball lightning. It is significant that the parameters are obtained by averaging over a large volume of data, i.e., they are very reliable, within their limits of uncertainty. We have analyzed the size of uncertainties due to the primitive method (essentially "by eye") used to determine the observational parameters. It is clear that, to a large extent, the imprecision of this method remains even when averages are taken over the extensive data banks. Nevertheless, even within these limits of uncertainty, the above collections of observational data and the corresponding analyses (Table X) are of major scientific value.

The empirical model of ball lightning is convenient because it incorporates only facts that have emerged as a result of numerous observations of ball lightning. It is important to note, however, that the development of this model unavoidably involves a significant loss of the information contained in the large data files. This is so because we use the distribution function for a given parameter to extract only its average value, and this may involve the loss of qualitative indicators contained in the distribution function. For example, analysis has revealed that there are two types of ball lightning according to Stakhanov[9] (and three types according to Grigor'ev[27]) that differ significantly by their lifetimes. The other important element that is ignored by the mean ball lightning model is the correlation between the individual parameters.

Despite the above shortcomings, the empirical model of ball lightning is of considerable value. It has the virtue of simplicity and can serve as a testbed for different hypotheses about what happens in the interior of ball lightning.

TABLE X. Mean parameters of ball lightning.

Parameter, unit	Parameter value
1. Probability of spherical shape, %	91 ± 1
2. Diameter, cm	23 ± 5
3. Lifetime, s	$8 \cdot 10^{\pm 0.3}$
4. Internal energy, kJ	$10^{0.8 \pm 0.2}$
5. Color	White, red, orange, yellow (about 20% each) Blue, dark blue, violet, green, ($11 \pm 2\%$)
6. Luminous flux, lm	1500 ± 300
7. Luminous yield, lm/W	$0.6 \cdot 10^{\pm 0.5}$
8. Correlation with atmospheric electricity	$80 \pm 10\%$ of ball lightning events in continental regions observed during stormy weather
9. Seasonal features	Over 80% of ball lightning events observed in the summer
10. decay	$50 \pm 10\%$ of all ball lightning events end in explosion
11. Probability of observing ball lightning in one human lifetime	$10^{-2.2 \pm 0.3}$

5. MODELING OF BALL LIGHTNING

5.1. Ball lightning in industry and in the laboratory

Ball lightning is formed not only under natural conditions, but also in factories and dwellings in which it is associated with power and electrical equipment. We note, for example, the reported[64] observation of ball lightning in the Kuĭbyshev car plant in the course of nozzle tests using hydraulic simulation with a liquid dielectric. Ball lightning was found to arise from the corona discharge at the sharp circular edge of a muffle as a result of accumulation of electrostatic charge. When the speed of the pump motor in the nozzle test rig was abruptly reduced or turned off, the ball lightning was found to break off and hovered in air for 3–5 s; it was observed to have a spherical shape. After this period of time, it either just disappeared, as if dissolving in air or, more frequently, it vanished with a bang. Neither the appearance nor disappearance caused any damage to staff or equipment.

Once the nature of ball lightning is understood, this should, in principle, enable us to reproduce the phenomenon at will. The creation of a laboratory model of ball lightning should assist us in achieving a greater understanding of it. Numerous attempts were therefore made throughout the history of ball lightning studies to reproduce ball lightning in the laboratory, some of which were successful in producing a luminous formation in air. However, even these successful attempts have not in the end resulted in a deeper understanding of the phenomenon. They did not constitute a stage in these studies that led to more detailed experiments or to answers to new questions. The reason for this lack of success lies in the complexity of the phenomenon which prevents us from establishing the connection between observational facts and experimental modeling of ball lightning as a whole.

Nevertheless, laboratory modeling of ball lightning, designed to reproduce the phenomenon, did result in useful studies. It showed that it was indeed possible to produce such luminous formations, i.e., analogs of ball lightning, in air, with the help of electrical equipment. Early work of this kind is summarized in published monographs and reviews.[6,36–38]

In all early experiments, the source of energy for ball lightning was an electrical discharge in a gas because this is a convenient way of introducing energy in the medium, and the corresponding discharge devices are simple to operate. Most attempts at modeling ball lightning in this way were based on the assumption that it was a plasma phenomenon. In most cases, therefore, the basic problem was to produce a spherical discharge at atmospheric pressure which, under certain conditions, could continue to exist even after the external source was turned off.

We shall now briefly consider the principal methods of producing ball lightning in the laboratory. Experimental modeling of ball lightning can be divided into three groups. The first[65–69] employs an electrical source of energy containing about 1 *MJ*. An electrical arc discharge is produced by short circuiting a set of batteries. A magnetic field, an electrical current, or some other way is then used to eject the discharge from the space between the electrodes. These studies originated in the random short circuits experienced in the electrical system of American submarines. The experiments were costly and not very reproducible; they were not completed and the corresponding results must be regarded as preliminary.

Another line of research involves the initiation of a spark in a chemically active mixture. These experiments are due to Barry.[37,70–72] They were performed in air containing propane, and were continued by Japanese scientists[30,73] who extended the range of chemical additives and used modern diagonistic equipment, including video recording. The electrical energy involved in these experiments was typically of the order of 300 *J* and the volume of the working chamber was 100–250 l. The spark occasionally initiated the formation of a luminious sphere with a diameter of a few centimeters and a lifetime of 1 s. The poor reproducibility of this process was also noted.

The third line of research began before the others. At the end of the last century, Tesla developed high-power discharge techniques which *inter alia* enabled him in 1900 to produce ball lightning under laboratory conditions. After his tragic demise, his work on the production of ball lightning was not published in full. His results therefore suffer from considerable uncertainties and, without knowing all the details, it is difficult to estimate the degree of his achievement. His experiments were recently repeated by the Corum brothers[74,75] who employed a modern version of the Tesla technique. The basic element of the Tesla radio-frequency generator is a helical waveguide, coupled inductively to a spark converter operating at 67 kHz. The signal power delivered to the electrodes (approximately 3 kW) produces a discharge in air over a length of 7.5 m.

The radio-frequency discharge can be used to initiate breakdown in air with relatively low energy input. Under certain conditions (relating to geometry and electrode material), this leads to the appearance of luminous objects in the atmosphere. The Corums observed spherical luminous objects with millimeter dimensions, which appeared in the streamer channel and grew to a few centimeters in diameter, with a total lifetime of the order of a few seconds. The growth of these structures appeared to be maintained by the addition of material transported along the streamer channel.

When experiments with ball lightning modeling are analyzed, it is important to remember that they also reflect the general attitude to the ball lightning problem. On the one hand, it is sometimes possible to produce luminous formations similar to ball lightning, which shows that the phenomenon is related to natural processes in excited air. On the other hand, the poor reproducibility of experiments with these luminous formations, and the difficulties encountered in controlling such experiments, have meant that they have not yielded additional information about the properties of ball lightning.

Numerous experimental studies have been carried out, and published, in recent years in which luminous formations were produced in air and could be looked upon as laboratory analogs of ball lightning. It was noted earlier that the only other source of such data were the two dozen or so publications by Soviet scientists.[5,12] Moreover, since previous experience showed that these luminous formations in air were not mere sensations, and did not provide a solution to the ball lightning problem, the attitude to such research has undergone a change. Nevertheless, the original goal was not to reproduce ball lightning, but to investigate particular processes in the gas-discharge and laser plasmas. This approach has enhanced the professionalism of this research and has yielded information about the details of the process that are essential for the analysis of the phenomenon. The results of some of these experiments will be used later.

5.2. Fractal model of ball lightning

Ball lightning is a complex, multifaceted phenomenon that requires individualized description and special models for its comprehensive investigation. There is a large number of different models of ball lightning that treat the phenomenon at different levels. Some of them are discussed in exisiting reviews and monographs.[6,8,36–40] At the same time, different models based on rigorous scientific analysis and existing scientific information are useful in helping us to understand different aspects of ball lightning despite the apparent contradictory nature of such models. All the same, the central problem in the study of the nature of ball lightning is its structure. We therefore turn to a brief discussion of the fractal model of ball lightning[76] which provides an answer to this question and is in agreement with current information on the relaxation of highly excited matter.

Consider the relaxation of weakly-ionized plasma produced as a result of a strong action of a surface. This can involve a pulsed electric discharge, including linear lightning, laser radiation, electron or ion beams, and so on. This type of action results in the partial evaporation of the surface material, and the resulting weakly-ionized plasma expands into the ambient atmosphere at the end of the pulse. The plasma cools down as it expands, which leads to condensation of the material on plasma ions that act as condensation nuclei. The process of condensation and coagulation (coalescence of droplets) occurs until the particle temperature falls to the point at which solid particles are produced and continue to exist, participating in subsequent processes as stable elements.

These particles eventually combine into micron-sized structures called fractal aggregates or fractal clusters. These are highly rarified systems that exibit the fractal property whereby the mean density of matter within them decreases with increasing size. This is accompanied by a reduction in the strength of the system, which limits the cluster size to a few microns.[77] The formation of such systems has been investigated in some detail during the 1980s and there are published experimental studies and computer models (see, for example, the various reviews and monographs).[76,78–81]

The central element of the fractal idea is a rigid ball lightning body. Sometime ago, I. P. Stakhanov asked whether ball lightning was a physical body or a phenomenon, i.e., a set of processes in air. The fractal idea rests on the assumption that ball lightning is a structure, i.e., a physical body, and the presence of rigid matter in ball lightning is not a trivial idea. It is difficult to point to the first person who suggested this. It is possible that the idea has a long history. For example, Zaïtsev[82] asserted in 1972 that "ball lightning starts with the formation of three-dimensional grid structures." However, it was not until 1982 that Aleksandrov *et al.*[83] formulated this idea with sufficient rigor. They based this on their studies of exploding metal wires under the influence of electric current.[84] They found that, under certain particular conditions of relaxation of the metal, certain web-like structures are formed in the vacuum chamber and attach themselves to the walls, remaining there for one or two days. Measurements by these workers indicated that the transverse dimensions of these structures were of the order of 0.01 μm. The authors of Ref. 83 extended these properties to ball lightning and referred to it as a filamentary aerosol. They used this as a basis of their analysis of some of the properties of ball lightning. In particular they verified the stability of the ball lightning structure under the influence of its own electric charge.

The fractal ball lightning hypothesis is evolving together with the development of science itself. The idea could not have arisen in the 1970s because fractal aggregates were not known at the time. The fractal hypothesis originally relied on the assumption that the body of ball lightning was structurally similar to that of an aerogel,[85–87] since at the time this was the only microscopic object with fractal aggregates as its elements. Aerogels are produced in solutions and consist of nanometer particles. They are a low-density porous material with minimum specific weight only just above the specific weight of air.

However, it has been found that the coalescence of fractal aggregates develops differently in gases and in solutions, and leads to the formation of different macroscopic structures although both structures have fractal aggregates as elements. This became clear after the elegant experiments of Lushnikov, Pakhomov and Negin[88] who showed that, when the relaxing plasma containing such fractal aggregates is in an external electric field of moderate intensity, the fractal aggregates combine into fractal filaments. The diameter of an individual fractal filament is of the order of 10–100 μm and its length is of the order of 1–10 cm. In the experiment described in Ref. 88, in which a laser beam was used to vaporize a metal target, dozens of filaments were produced simultaneously.

The fractal filament is a new concept in physics (see Ref. 89) that is of both scientific and technological interest. From the stand-point of ball lightning, the filament is interesting as an element of its structure. Fractal filaments that are present in these objects tend to become entangled, forming the fractal coil[90,91] that constitutes the body of the ball lightning. It is readily seen that the evaporation of the target material in the form of weakly-ionized vapor, and the presence of an external electric field, which are the basic conditions for the formation of a fractal filament and a fractal coil, are indeed satisfied in all the experiments with laboratory analogs of ball lightning. This is indeed the basis of the fractal interpretation of ball lightning in the version presented here. The question is: can fractal coils explain the cobweb structures that were sometimes observed on the periphery of a glowing discharge in the experiments of Lushnikov, Negin, and Pakhomov in which the discharge was produced between electrodes? We see in this a further possible confirmation of the fractal hypothesis.

The fractal hypothesis has a number of advantages that make it the preferred and more advanced solution as compared with other suggestions. First, the formation of fractal coils is not in doubt, since it is confirmed by experimental studies and theoretical analyses. Second, the actual formation of fractal structures in the presence of powerful pulses applied to a surface, including linear lightning, can be verified directly. Third, many of the unusual properties of ball lightning can be explained by the presence of this structure.

Let us briefly consider these properties. The fractal coil is a doubly rarefied material. On the one hand, the particles occupy a small fraction of the volume in the interior of fractal filaments, and, on the other, the filaments themselves occupy a small fraction of the coil. The mean specific weight of the fractal coil is therefore lower by 3–5 orders of magnitude than the specific weight in the condensed state. This means that the fractal coil, i.e., a set of fractal filaments, is a peculiar physical object. Its density is that of a gas, but as a bound state of matter, it has the properties of a liquid or a solid. Ball lightning displays a combination of such properties and this explains the ability of ball lightning to fly in the air and to penetrate narrow slots and apertures under the influence of air flows, which is due to the low surface tension of the material of fractal coils.

As a system consisting of intersecting filaments, the fractal coil can undergo the coil-globule phase transition that has been investigated for self-crossing polymer filaments.[92–94] At low temperatures, the fractal coil is then spherical, but becomes shapeless at high temperatures. For the average dimensions of ball lightning, this phase transition point is expected[91] to be 700 ± 200 K where the uncertainty refers only to the uncertainty in the parameters of the average ball lightning, i.e., in reality the uncertainty is much higher. Hence, we may expect that ball lightning can assume spherical and other shapes, and also transitions between them. This has indeed been observed in practice.

Energy and radiative processes in ball lightning are the most important. Since the fractal coil consists of nanometer-sized particles, a significant fraction of the molecules in the fractal-coil material lies on its inner surface. This means that the fractal coil has a high surface energy density which is not much lower than the specific chemical energy of explosive materials. The surface energy of a fractal system is liberated when the size of its constituent particles is increased.

The condensation of the fractal structure can be accompanied by a temperature wave[95] that propagates along the fractal filament. The internal energy of the system is expended in this case in melting the structure, and the energy release occurs as a result of the coalescence of liquid particles that are the elements of the structure. The temperature at the front of the temperature wave reaches about 2 000 K which gives rise to strong emission that continues until this region cools down. The temperature wave passes over many fractal filaments at the same time, i.e., there are many simultaneous luminous elements. We note that numerical estimates of the parameters of the mean ball lightning are not inconsistent with observational data. They include the size of a luminous element, which is of the order of 1 nm, and the number of simultaneously glowing elements, i.e., 100–1 000.

With this mechanism of energy release and emission, ball lightning can produce any color, depending on the impurities in its structure. It can be black or gray if energy release does not occur in its interior. Ball lightning is then similar to a cobweb.

We note one further property of the system. Since the individual regions in its interior have temperatures of the order of 2 000 K, ionization processes occur in these regions. Ball lightning then becomes a source of plasma, and a conducting channel is formed along its path. However, the degree of ionization in the interior of ball lightning and along its trail is very low, but it does exceed by several orders of magnitude the ionization in the atmosphere. Ball lightning can therefore initiate electrical breakdown in the atmosphere in stormy weather when high electric fields are present in the atmosphere.

The fractal structure of ball lightning can take a variety of forms. My present view is that the most likely conjecture is that the body of ball lightning consists of oxides (in this respect it is similar to a ceramic), i.e., compounds with the strongest chemical bonds. This is confirmed by experiments with fractal filaments and coils consisting of them, and also the fact that existing aerogels consist of oxides only. They include carbon and organic structures, and also polymeric structures. The last of these processes has been analyzed by Bychkov.[96]

Summarizing our analysis of the fractal model of ball lightning, we note that it explains the basic properties of ball lightning, namely, its shape, weight, emission, and relation to electrical phenomena in the atmosphere. A significant advantage of the model is that it can serve as a basis for the explanation of the existence of long-lived plasma and non-plasma luminous objects produced under laboratory conditions. The fractal model enables us to analyze the evolution of the system in these experiments. Such analyses will continue to be a feature of future research into ball lightning.

5.3. Models of ball lightning and analysis of its nature

It would be wrong to conclude that a single, however attractive, model can succeed in describing the entire range of properties of ball lightning. Ball lightning is a multifaceted phenomenon and its different aspects require specific models for their description. This is why many of the ball lightning models that aspire to the description of its individual properties retain their value independently of the general view of the physics of ball lightning. We shall illustrate this by considering the motion of ball lightning in the atmosphere.

As we examine these properties, we shall leave on one side the question of the structure of ball lightning; it will be sufficient to assume that ball lightning is a bound, low-density object. This general model will enable us to analyze the interaction between ball lightning and ambient air in terms of observational data, and this will yield estimates of some of its parameters.

We begin by examining heat transfer between ball lightning and ambient air. The energy released in the interior of ball lightning is partially transferred to the ambient air and is removed by convection. Well away from ball lightning, the character of air flow and the temperature distribution are the same as at large distances from the exit from a pipe. Classical results[97] relating to the air flow at the exit of a pipe can therefore be used to analyze heat transfer between ball lightning and ambient air. The jets of air flowing around ball lightning produce an uplift that is equal to the atmospheric drag[98] acting upon it. The greater the energy release in the interior of ball lightning the greater the heating of air on its boundary, and the higher its velocity and the lift force.

This problem was modeled in Ref. 99, where a piece of wire suspended from a quartz thread was heated by a laser beam. Its temperature was determined by measuring the infrared power emitted by it, and the lift force was found from the tension in the quartz thread. The results of this experiment enable us to establish the relation between the parameters of air flowing around ball lightning.[99] In particular, if we assume that the power released in the interior of the mean ball lightning is 3 kW, we find that the rise in temperature in its vicinity (as compared with more distant air) is

$$\Delta T = 60\,\mathrm{K}\cdot 10^{\pm 0,6}, \tag{17}$$

and the lift force is equal to its weight (i.e., the mean ball lightning floats) when the ratio of the mean specific weight of air in ball lightning to the specific weight of air is $10^{\pm 0.8}$. It is clear that these results were obtained without introducing any particular assumptions about the structure of ball lightning and show that its average temperature is relatively low.

The same model of ball lightning as a bound state of its material can be used to analyze different gas-dynamic problems, including the motion of ball lightning in jets of air, the passage of ball lightning through slots and apertures, its interactions with flying objects, and so on. We note that problems of this type are not often solved in physics because the parameters of the interaction in the interior of ball lightning are very different from those encountered in known liquids and solids. Moreover, they are mathematically complicated because they require a self-consistent solution, since the motion of air modifies the shape of ball lightning which in turn affects the motion of air.

This range of problems was solved by Gaĭdukov.[100–107] We note that the value of his research is not limited to the derivation of mathematical solutions for these conditions. Moreover, comparison with observational data yields estimates of the parameters of ball lightning, namely, its surface tension and the character of its interaction with the moving air on its surface. An important conclusion of this comparison is the absence of a viscous boundary layer on the surface of ball lightning.[107] This is a further confirmation of the fractal structure of ball lightning.

We shall illustrate the efficacy of this theory by one of the results in which ball lightning is 'attracted' from infinity to the propeller of a helicopter or aicraft, and takes up a stable position at some distance from the propeller. This can explain some of the reports by pilots who said that a UFO or ball lightning has followed their aircraft.

It is significant that analyses of the gas dynamics of ball lightning lead to a better understanding of the mechanisms responsible for the individual processes. For example, the passage of ball lightning through a narrow aperture occurs in the following way. Flowing air brings the ball lightning to the aperture. It slows down when it reaches a distance equal to its diameter. This produces a boss on the surface of the ball lightning that eventually transforms into a cylindrical jet. The ball lightning flows through this jet to the other side of the aperture without touching its edges, i.e., the ball lightning passes through the center of the aperture while the air flows over its edges. All this is possible only if the surface tension of the material of ball lightning is low. The corresponding numerical estimates can be made by analyzing the observational data.[91]

We note that deeper understanding of ball lightning, including its structure and interaction with air on its surface, can be achieved through a theoretical analysis coupled with laboratory modeling. The experiments reported in Ref. 108, which presented a study of the passage of ball lightning analogs through apertures, slots, and tubes, are relevant in this connection. Ball lightning was simulated by a luminous object with complex structure, obtained from erosion plasma.[109,110] It consisted of a core with a diameter of 1–2 mm that contained most of the energy, a glowing region with a diameter of 6–8 mm, and a non-luminous envelope with a diameter of 30–40 mm. It was shown that the object could pass through apertures with diameters of 1, 2, and 3 mm without breaking up. When there were two apertures separated by a distance of less than the object diameter, the formation passed through only one of them. Its dimensions remained unaltered after passing through a dielectric tube, if the tube length did not exceed a certain specific value, and decreased with increasing tube length.

The experiments reported in Ref. 108 showed that the laboratory analog of ball lightning retains its integrity after passing through apertures and slots, and after enveloping a target. The continuation of such experiments in conjunction with theoretical analyses of the gas dynamics of ball lightning is likely to produce new results that will lead to a deeper understanding of ball lightning.

We thus see that modern analyses of the nature of ball lightning employ observational data together with scientific information on different physical processes and systems. They reduce to the development of all possible models of the individual aspects of ball lightning and to comparisons of these models with observational data, leading to conclusions about the properties of ball lightning. We shall now illustrate this for the radiative properties of ball lightning.

Let us compare ball lightning as a source of light with a hot sphere of radius equal to that of the mean ball lightning and surface that behaves like a black body. We need to determine the surface temperature of the sphere for which the luminous flux from it is identical with the corresponding flux from the ball lightning. The result is $T = 1360 \pm 30$ K. Next, we determine the temperature of the sphere that produces the same luminous flux as the mean ball lightning. The result is $T = 1800 \pm 200$ K. Finally, to achieve agreement with the parameters of the mean ball lightning, we assume that the hot sphere produces the same luminous flux and the same light output as the mean ball lightning, but that only part of its surface area radiates. We then find that the relative area of the radiating surface is $10^{-1.7 \pm 0.8}$.

Two important conclusions follow from this analysis. First, the temperature of the radiating surface elements of ball lightning is about 2 000 K At the same time, we must remember that ball lightning has additional energy-loss channels as compared with a black body. This means that the true temperature of the radiating elements cannot be lower than is indicated by the comparison with the black body. Second, ball lightning contains many radiation foci that together occupy a small fraction of the total volume, or if the emission is produced at all points within the volume, the system is transparent in the optical range of the spectrum.

The temperature of the radiating ball lightning is thus much higher than the air temperature on its boundary [see (17)]. This discrepancy can be explained by the nonequilibrium conditions in the system as far as the radiating atoms or molecules are concerned. The departure from equilibrium occurs because of the short atomic excited-state lifetime—a situation familiar in a variety of problems in atomic, plasma, and high-temperature physics. However, at atmospheric pressure, the main channel for the de-activation of excited atoms and molecules is provided by collisions with air molecules and not by radiative processes. According to the calculations reported in Refs. 38, 40, and 41, the probablity that a resonantly excited alkali-metal atom in air at 2 000 K will emit a photon is of the order of 0.01. This means that the excited atom will be quenched with probability approaching unity as it undergoes a collison with an air molecule, i.e., the excited atoms are in thermodynamic equilibrium with the air molecules. This conclusion was deduced for resonantly excited atoms, so that it is even more valid for other excited atoms and molecules with long excited-state lifetimes. The density of excited atoms or molecules is therefore determined entirely by the temperature of the hot region, and is independent of the method used to produce the excited particles. The above radiation temperature is therefore the temperature of the portions of ball lightning that are responsible for its emission.

The temperature of air in the vicinity of the mean ball lightning is typically of the order of a few tens of degrees [see (17)]. This constitutes a discrepancy as compared with the 2 000 K obtained above for the radiating regions of ball lightning. The discrepancy can be overcome by assuming that the ball lightning has a spotty structure and contains many luminous regions that jointly occupy a fraction of its volume. Radiation emitted by these regions is seen by the eye as the emission of the entire volume of the ball. We note that these conclusions are based on the observed parameters of ball lightning and do not rely on any assumptions about its structure or processes occuring in its interior (although they are supported by the fractal model of ball lightning).

This type of analysis, applied to the individual aspects of ball lightning, can be used to deduce certain numerical parameter values for the mean ball lightning. These are listed in Table XI. We note that they are based on a number of different models and approaches.

5. CONCLUSION

Comparison with our previous review[6] will show that significant advances have been made in research into ball lightning during the last two and a half years. Analyses of observational data have led to the development of clear-cut methods for the determination of the output parameters of banks of observational data and to estimates of their precision. There has been a tendency to combine such data banks. All this has resulted in better output parameters for the empirical ball lightning, although there has been no fundamental change in the existing picture of the phenomenon.

The problem of the nature of ball lightning is no longer as acute as it once was. The studies performed so far (mostly experimental studies) have led to the conclusion that ball lightning is a structure that arises as a result of the evolution of gas-discharge or weakly-ionized laser plasma produced in the course of vaporization of matter by high energy fluxes. This has led to a change in the attitude to this research, which is now focused on the individual aspects of the prob-

TABLE XI. Additional parameters of mean ball lightning model.

Parameter	Value
1. Specific weight, g/cm^3	$10^{-3.9 \pm 0.5}$
2. Weight of ball lightning body, g	$10^{-0.1 \pm 0.9}$
3. Air temperature on the surface of ball lightning, K	$60 \cdot 10^{\pm 0.6}$
4. Temperature of hot regions (emitters), K	1800 ± 200
5. Size of individual radiating zone, mm	$10^{0.2 \pm 0.4}$
6. Number of hot zones	$10^{2.5 \pm 0.7}$
7. Surface tension, J/m^2	$10^{-1.5 \pm 0.5}$
8. Size of particles of ball lightning body, nm	$3 \cdot 10^{\pm 0.4}$

lem and the associated processes rather than the problem as a whole.

At the same time, there has been a change in the order of priorities. In earlier work, the main problem was the structure of ball lightning whereas now the more topical question is: how does ball lightning initiate an electrical discharge in the stormy atmosphere and what are the associated processes? These and other topical problems relating to ball lightning will be solved in the course of the next few years. The pity is that Soviet scientists will not be able to participate in this effort to the extent that they did in the past.

[1)] Comparisons between ball lightning and UFOs now clearly demonstrate that ball lightning has now passed the stage in which it was the subject of anecdotal newspaper reports. The ball lightning problem is firmly in scientific hands, and attitudes to it have moderated. The UFO problem, on the other hand, is at a stage where it attracts indiscriminate comment. Periodic reports of UFOs on Russian television are founded on ignorance, and newspapers stories border on the absurd. For example, two years ago, The *Sun* newspaper, published in the United States, reported about a 16-year old Bulgarian girl who allegedly encountered a humanoid that arrived on an UFO, and eventually gave birth to a freak. It was suggested that this being was held in a Soviet military hospital and that quite a few such freaks could be found in Soviet military hospitals across Eastern Europe. This report was reproduced by a number of progressive Russian newspapers that are quick to react to anything that is new. There is, however, another version of this particular event, which is closer to the location of the incident: the girl actually met a group of Soviet soldiers. This version explains, *inter alia*, the interest of military hospitals in such events.
We note more in sorrow than in anger that the problem is now in the hands of ignorant people, and the public is being misled. Radio and television programs would have us believe that UFOs are controlled by humanoids, i.e., living creatures that land on the Earth and contact people. However, scientific books devoted to the UFO problem do not report a single verified case of an encounter with a humanoid (in some books, this is particularly emphasized). The present state of the UFO problem is well documented in the book by Platov and Rubtsov[16] which provides a penetrating scientific analysis of the problem.

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