THE PHYSICAL NATURE OF BALL LIGHTNING

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Abstract

This book contains an analysis of the results of observations of ball lightning, the main attention being paid to data obtained during the last two decades. The work also includes a brief review of the hypothesis involved and the nature of ball lightning. A more detailed description is given of the cluster hypothesis, according to which ball lightning consists of complex compounds of ions and neutral molecules.

The work is intended for a wide circle of readers, although a certain level of knowledge of physics and chemistry (on the scale of a university course) is required when reading the sections devoted to the nature of ball lightning. A considerable amount of the material consists of original results, and here again the book is not classed as popular science. However, the author has made every effort to present the material in the most lively and entertaining manner possible. It is to be hoped that the book will interest those who wish to know more about this hitherto mysterious phenomenon.

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In memory of Pavel Petrovich Stakhanov, district doctor

Foreword

In 1975 the journal "Nauka i Zhizn" (Science and Life) published an article by the author of this book and S.L. Lopatnikov on ball lightning. The article included a short questionnaire intended for all those who had witnessed this phenomenon, with a request that they send their answers to the editorial office of the journal. Someone gave this venture the imposing name of the "Ball Lightning Experiment", and we decided to wait patiently and see what happened, not even hoping that such a frail "being" would succeed in thriving and growing up. However, within less than six months it became clear that we were mistaken. The success of the venture exceeded our wildest hopes which we (like all sceptics everywhere) cherished deep down. In the course of six or eight months in 1976 we received about fifteen hundred letters and descriptions of cases where ball lightning had been observed.

A variety of circumstances prevented me from processing these data immediately, and the first results were not received until the end of 1976, the major part of the work being carried out in 1977. During the same period, thanks to the kind help from Dr. K. Davis, V.L. Sadovskii and Dr. MacNally of the USA, to whom I would like to express my sincere gratitude, I succeeded in obtaining reports containing material in response to two surveys carried out in America among staff at the scientific centre NASA. A comparison of the data revealed a wide difference in the results obtained and, since the results of our survey had not yet been published, the thought occurred to me to write a small book on this subject.

As early as 1972 I had managed by chance to draw attention to the small amount of electrical energy in a bond comprising dipole molecules of water with ions, which could lead to the formation of stable shells of these molecules

around the ions. The question then arose as to whether these shells could delay recombination in some cases, and could the nature of ball lightning be explained in this manner. In 1973-75 I was "careless enough" to publish a number of works on this subject, thereby adding one more hypothesis to the numerous hypotheses regarding the origin of ball lightning. Although I was working at that time at an institute which was engaged in research into the ionosphere and the propagation of radio waves, it was only after the publication of the first of these works that I learned that similar hypothetical compounds of ions with neutral molecules do in fact exist in the D layer of the ionosphere and are referred to as clusters.

Naturally, it was difficult for me to resist the temptation of including in the intended book on ball lightning a description of the cluster hypotheses, especially since this, in the same manner as the results obtained from processing data obtained by the journal "Nauka i Zhizn", could not have been included in other monographs devoted to this question, for instance in the book by Singer "The nature of ball lightning" (Ref. 2) recently translated into Russian. This, in turn, necessitated some kind of survey, however brief, of other hypotheses. This gave rise to Chapters 3 and 4, and the contents of the book departed very considerably from the original intention of publishing only facts. However, even after this it was still possible to ease one's conscience with the thought that the factual material on ball lightning is sufficiently strictly detached from attempts to explain this material and is contained in the first two chapters. That, perhaps, is all that can be said about how this book came to be written.

It only remains for me to thank those to whom this work owes its existence. I would like to express my sincere gratitude to academician V.L. Ginsburg, whose seminar frequently discussed the results of the work, to the editorial office of "Nauka i Zhizn", with whose help information on ball lightning was gathered with such success, to S.L. Lopatnikov, candidate of

physico-mathematical sciences, who initiated the survey, and also to all those participating in the survey, and all those who submitted descriptions of their observations, irrespective of whether they are mentioned by name in this book. In particular I would like to take the opportunity of thanking O.S. Nikolskaya and the chief curator of the Moscow Kremlin Museum, E.S. Sizov, for their help in the study of ball lightning occurring on the ground around the Kremlin in Moscow. I am also grateful to M.M. Fiks, candidate of physico-mathematical sciences, for his great help in processing the results obtained from the observations made.

"About the mighty thunder. On the fifth day of August of that year a great cloud gathered over Moscow with frightful thunder, the stone cathedral church of the Archangel Michael being struck by lightning. On the thirteenth day of August there was a great storm and the cross on the same church was broken."

Collected Russian Annals, Vol. 12 St. Petersburg, 1901

Introduction

The event which is recalled in the fragment of the Nikonov Annals, quoted in the epigraph, occurred in the year 6958 counting from the Creation of the World (according to the "hypothesis" of those times), i.e. in 1450 by our calendar. However, between eight and nine o'clock in the morning on 5 August 1977 a violent thunder-storm broke out over the Kremlin and one flash of lightning struck the area occupied by the Kremlin. One of the people on duty, A.E. Nikulin, who was sitting in a wooden booth near Uspensk Cathedral, heard a clap of thunder of exceptional force from the direction of the Great Kremlin Palace. He managed to stand up and lean out of the booth, but quickly withdrew when he saw a pale yellow band coming from the direction of the spire on the Great Palace. The band passed by a few metres from the entrance to the booth in a downward direction and disappeared beyond the fence surrounding the square around Uspensk Cathedral where restoration work was in progress. All this was over in two or three seconds. The phenomenon was noiseless; in any case there was nothing resembling thunder. This causes us to think that we are dealing here not with a channel of linear lightning, but with ball lightning which had occurred at the time of the preceding, close strike, the thunder from which attracted the attention of the duty-man. Apparently the lightning occurred around the spire of the Great Kremlin Palace and rushed downwards at an angle of approx. 30° to the horizon at a speed of about 10 or, perhaps, several dozen metres per second, producing the impresion of a luminous band. The fact

that this ball lightning travelled in a straight line and not along a parabola causes us to think that it acquired a high velocity at the moment it occurred, and not under the effect of the force of gravity.

The clap of thunder was also heard in the Archangel Cathedral, situated 100 m from Uspensk Cathedral, the entrance to which faces the Great Kremlin Palace. This clap of thunder was followed by ball lightning measuring approx. 5 cm in diameter entering the Archangel Cathedral. This was witnessed by three people: N.S. Antonova and S.A. Savkin, both attendants, and the duty-man A.P. Novikov, who had just left the cathedral (all this happened before the start of the working day when the usual throngs of tourists had not yet arrived). All that Novikov noticed was that some luminous object rushed past him in the direction of the entrance to the cathedral. It should be noted that the entrance to the cathedral has two pairs of double doors, and that the right-hand door of one of them was open, whilst the left-hand door of the other pair was half open. Because of this the ball lightning was unable to enter the building in a straight line, instead it had to go round the closed halves of the doors, thereby following an S-shaped trajectory.

The two attendants were inside the cathedral near the exit. The ball lightning passed between them about 80 cm from the floor and it was at that very moment that they saw what appeared to be a luminous ball of regular shape travelling in a straight line from the entrance to the iconostasis. It passed within 10-20 cm of one of the attendants, rising gradually, striking the holy gates at a height of 2 m from the floor, and then vanishing in an explosion. The noise of the explosion was audible through the walls in other rooms in the cathedral. It was however less loud than the thunder from the preceding lightning strike. A charred spot measuring 3-4 cm in diameter, where the gilding had been removed, marked the place where the explosion had occurred on the altar.

The velocity at which this ball lightning moved was high (although it was noticeably less than that of the lightning which passed Uspensk Cathedral): in 3-4 seconds (according to the reckoning of those witnessing the event) the lightning travelled approx. 20 metres. Its trajectory was observed by eyewitneses as it travelled from the entrance to the point where the explosion occurred (it went in a straight line over this section). A cleaner was also present near the altar. She was standing with her back to the ball lightning and did not see it, but heard the explosion and thought at first that one of the chandeliers had fallen down. Both attendants who witnessed the passage of the ball lightning in the cathedral described the size, shape and trajectory in the same manner, although there was a slight difference in opinon regarding the colour. One of them saw a yellow ball, whilst the other one described it as "red, like glowing coal". Although the lightning passed quite close to one of the eye-witnesses, he was not aware of any heat. It is interesting to note that the lightning travelled upwards. This means that it was not moving by inertia from the initial impulse received at the moment it occurred.

Thus, the discharge of linear lightning* which, apparently, struck the spire of the Great Kremlin Palace (it should be noted that during this thunder-storm St. Elmo's fire - a spiral of fire around the spire - was seen on the Palace), caused two fireballs, which moved at an angle of approx. 40° in a manner such that one of them rushed past Uspensk Cathedral, whilst the other travelled in the direction of the entrance to the Archangel Cathedral. I have described this incident in such detail not only in order, so to speak, to acquaint the reader with what the eye-witnesses saw, i.e. ball lightning. This story has an interesting sequel. Approximately two weeks after the event (i.e. "hot on its heels") one newspaper carried a description of it under the heading "Lighting - a guest of the museum". The article said that during the thunder-storm there appeared above the bell-tower of Ivan the Great (the tower is on the

opposite side of the Archangel Cathedral in relationship to the Great Kremlin Palace) a "bright red, glowing ball" which started to descend onto the cathedral. The ball, measuring 50 cm in diameter floated slowly in through the cathedral doors and proceeded in the direction of the iconostasis. "There was a flash accompanied by a bang and the air smelled of ozone. Fortunately the airy visitor did not do any harm".

Indeed, as we now know, the lightning entering the Archangel Cathedral had a diameter of 5 cm, and not 50 cm, and did not descend slowly or float through the air, but instead flew at great speed. It probably occurred on the opposite side and, consequently, came to the cathedral along a completely different trajectory. This event could, at least in a highly modified form, enter, so to speak, the present Annals. Our somewhat lengthy introduction can end with this instructive example of what in the eyes of any critical research worker must be included in descriptions of ball lightning when they are based on well founded, direct evidence by eye-witnesses, and not on second-hand sources.

It is not known whether this discharge was in fact exceptional in strength. The "unprecedented" noise of the thunder can be fully explained by the short distance to the channel of the linear lightning.

1

1.1 The mysteries of ball lightning

For ages past people have noticed how luminous spherical shapes appeared in the air or around objects during a thunder-storm. These shapes were referred to as ball lightning. The most important feature of ball lightning is its autonomous nature, ie it is not 'attached' to conductors or any other bodies and can move about freely in space, whilst preserving its shape, colour and size. Such shapes have, although much more rarely, been observed even without a thunder-storm. The size and life span of ball lightning vary in a wide range, sometimes as the result of unavoidable errors made in the observations. The movements are very varied and appear to be most unusual for bodies of such a size. They can float in the air, move horizontally, going around objects as they do, although they are sometimes attracted to objects, and may attach themselves to objects or move along them (electrical conductors, for example).

One of the most mysterious and capricious characteristics of ball lightning is that it frequently appears in closed rooms, having sometimes gained entry through narrow apertures smaller than the diameter of the fire ball itself. Finally, it should be noted that ball lightning possesses a certain energy. This is indicated both by its glow and the explosion which frequently marks the end of its existence. In other instances it can disintegrate or become extinguished without any explosion. At a first glance, this

appears to happen without any extraneous reason, spontaneously and quite unexpectedly for the observer.

Ball lightning is only very slightly reminiscent of phenomena which are well known to us in everyday lift, including ordinary (linear) lightning. It radiates light like a heated body, but, at the same time, it radiates practically no heat at all. Its movements are hardly associated with the force of gravity, which usually determines the movement of bodies surrounding us. At the same time, if it is a heated, radiating gas, why does it not rise in the cold air surrounding it?

Ball lightning differs very considerably from ordinary gases in yet another respect: it does not occupy the entire volume available to it and does not mix with the air. The majority of observers speak of a clear (although not always smooth) boundary separating the ball lightning from the surrounding atmosphere, which is preserved throughout the entire life span of the lightning. The life span can amount to one minute and even longer. The movement of ball lightning likewise does not lead to blurring of the boundary and to mixing of the matter constituting the lightning with the surrounding air, in spite of the fact that the lightning can cover a considerable distance during its life span. Its behaviour thus differs very appreciably from the well known behaviour of heated gases, smoke or gaseous combustion products.

Furthermore, the question arises regarding the form in which the energy is stored in ball lightning. Repeated calculations carried

out to determine the rate at which a volume of air of corresponding preportions heated to a high temperature cools indicate rapid cooling during a period which is considerably less than the life span of ball lightning (Ref 1). Moreover, ball lightning usually retains more or less a constant brightness throughout its life span, something which could not occur upon the heated matter being cooled. The explosion which frequently marks the end of such a phenomenon indicates that the major part of the internal energy in ball lightning is preserved until the final moment of its existence.

If ball lightning consists of charged particles, then, in the absence of an energy source from without, these particles must recombine and rapidly transmit the energy released to the surrounding atmosphere (recombination time $10^{-10} - 10^{-11}$ sec, but with allowance for the time taken to remove the energy from the volume, this figure is less than 10^{-3} sec). Thus, after the current has ceased, the linear lightning channel cools and vanishes within a period of time of the order of a few milliseconds.

It should be remembered that a single discharge or, as it is called, a lightning stroke, consists of a number of pulses separated by short intervals, when the current in the lightning channel vanishes or, at least, decreases sharply. The number of such pulses usually equals 3-4. Each pulse starts with a process called a leader. The first leader, which forms the channel, is called stepped. In the intervals between the pulses the conductivity and the glow of the channel drop sharply, although it

is impossible to determine this visually due to the brevity of the Because of this the beginning of the second and subsequent pulses is preceded by a so-called dart leader which restores the conductivity of the lightning channel. The minimum time elapsing between pulses is 3 msec, and the maximum 100 msec (Ref 1). It will be seen from these figures that during a period of time of the the order of a few milliseconds the degree of ionisation and the channel temperature and conductivity have time to decrease sharply (by several orders of magnitude), and within 100 msec all traces of the lightning channel have disappeared to such an extent that the next discharge occurs in a different place. It is thus impossible to expect the simple formation of ball lightning from a small section of a linear lightning channel. any case it is necessary to indicate the cause of a certain part of the channel retaining for a lengthy period of time the internal energy acquired by it.

Ball lightning is described above as a physical body, although the possibility of it being in fact a process cannot be ruled out without further ado. In other words we used to assume that we were dealing with a certain volume of matter with a certain store of energy. In fact, it cannot exchange matter with the ambient air, and not only does it not transmit energy, but it actually receives energy from without. For example, ball lightning could be the luminous termination of a dark discharge or wave channel, ie a region, in which the energy received from without is dissipated.

This point of view removes some of the problems described above, although it creates fresh ones in their place. In fact, the question as to why ball lightning does not cool down or recombine does not arise, although its place is taken by a no less complex question regarding the supply of energy necessary for maintaining the ionisation glow of the matter in the volume of the ball lightning. Estimates show that very high energy flux densities are required for this. It is also unclear why this energy is absorbed not along the entire parth, but only in a particular region with clear spherical boundaries which, in addition, move in space. Ball lightning behaves like an autonomous body and does not reveal any properties of wave-guide or current channels associated with it.

1.3 Sources of information on ball lightning

Eye-witness accounts remain the main and, indeed, the sole source of information available so far on ball lightning. There is no need to mention how unreliable this source is. We have had occasion above to convince ourselves of this. Indeed, we have been dealing with an event which, one might say, took place before our very eyes.

In the course of the past few centuries several hundred cases involving the occurrence of ball lightning have been recorded and described. However, the authenticity of the majority of these reports is on a level with the above-mentioned newspaper reporting or, as the case may be, even inferior to it. The main difficulty arising when using old descriptions resides in the fact that what

has actually been observed largely remains unclear. terminology, the nature of the comparisons and the actual concept of the world about us undergo such sweeping changes in the course of a generation that it is very difficult to understand a description of an unknown phenomenon given 100-200 years ago. In particular, for the want of a better comparison, ball lightning was frequently compared with fire, although, in fact, it has hardly any similarity to a flame. In the XVIII and even XIX centuries it was often confused with meteorites, so that there was even a term 'electric meteor' or 'slow bolide' in use. It is especially difficult to distinguish ball lightning from corona discharge on conductors, which occurs during a thunder-storm. It is not surprising that the German scientist, Brand, who in 1923 compiled the most detailed survey of information on ball lightning so far, selected no more than 200 reports from the 600 available to him, rejecting the others as doubtful or unreliable. The cases selected referred to the period after 1820. One of the people investigating ball lightning noticed, not without some doubt, that there are numerous phenomena which are beyond the understanding of man, but there are not many where observations only make an explanation more difficult.

The lack of authenticity of the material, on whose basis it is necessary to form concepts of ball lightning, and also the large number of failures in a theoretical explanation of this phenomenon, gave rise to an obstinate scepticism with regard to the problem as a whole, which, of course, is quite understandable, but which can hardly be justified. At the end of the XVIII and beginning of the

XIX century the French Academy of Science refused to believe reports on meteorites or examine any attempts to explain this phenomenon. The grounds for this were very similar: firstly the reports were received from a very unreliable source, ie from ignorant, superstitious peasants and were, of course, full of inventions and contradictions; secondly, they did not agree with the scientific concepts of the structure of the atmosphere, according to which, stone simply came from nowhere - the air, of which it consisted. 'What if we were to reject everything we are unable to explain?' asked the French physicist Arago precisely with regard to the arguments about ball lightning.

According to current data the probability of seeing ball lightning in the course of one's life is not excessively small — approximately 0.01. Even if this value is increased by an order or two of magnitude it would mean that there would be tens of thousands of people in our country who would have seen ball lightning. With such a large number of witnesses, all the random errors associated with the individual peculiarities of the observers could be precluded. Thus, extensive and statistically reliable information on ball lightning is available in each generation, but it is concentrated not in monographs and scientific journals, but instead dispersed in the memories of thousands of witnesses lost among the remaining population.

This information can be retrieved by one method only, ie by a statistical survey. The advantage of such methods over a simple comparison of written accounts is obvious. It is possible to

obtain considerably more numerous and uniform (in terms of nature) bodies of data, since people belonging to the same generation use similar comparisons and concepts. Moreover, it is a matter of obtaining information 'first hand' from direct eye-witnesses of the phenomenon, and not from re-told accounts of sightings sometimes distorted to a degree making them unrecogniseable. Also the increase in the level of education during recent decades has made itself felt. Finally, the questionnaire affords the possibility of asking the same questions of everyone involved and, to a certain extent, of standardising the answers, for instance, by giving the eye-witnesses the opportunity of selecting one of a number of answers prepared in advance. All this will enable a more definite description of an event to be obtained.

Similar methods of obtaining information started to be used in the last century. In this way, even Arago gathered information on some thirty cases of ball lightning observed by his contemporaries (Ref 2). In the 1930's the American meteoriologist Humphreys gathered data on 280 cases where ball lightning was observed, on the basis of which he arrived at the conclusion that the ball lightning is an optical illusion or one form of brush and spray discharge (Refs 3 and 4). However, the widest and most systematic surveys based on specially prepared questionnaires were carried out in the USA and USSR as recently as within the last twenty years.

At the end of the 1950's the Oak Ridge (USA) laboratories engaged in nuclear and thermonuclear research conducted a survey among laboratory staff with a view to finding out how many of them had

seen ball lightning. Of the 1,962 persons asked, a positive answer was given by 110, ie more than 5%. The staff of the Union Carbide Nuclear Co, likewise located at Oak Ridge then received a questionnaire containing fourteen questions on ball lightning, the answers to which were not governed by any regulations. For example, this meant that, in answer to the question regarding the size of ball lightning, it was possible to indicate any size or size range. Moreover, the questionnaire contained questions about the life span of lightning, its shape, colour, movement etc. It transpired that, of the 15,923 persons receiving the questionnaire, 513 had observed ball lightning, ie approximately 3% of the total number of people answering the questionnaire. A detailed report on the results of the survey was published within a few years (Ref 5).

Later on, at the beginning of the 1960's a survey was carried out among the staff of one of NASA's research centres. This survey was also conducted in two stages. At the outset (1963) an extensive survey was conducted by means of a questionnaire which contained only a few questions aimed at finding those persons who had witnessed ball lightning. Of the 1,764 members of the staff at the research centre at Lewis, who received the questionnaire, 180 had witnessed ball lightning, ie approximately 10%. The second survey involved a questionnaire containing 56 questions referring both to the characteristics of ball lightning and the conditions under which it appeared, and also to the description given by the eyewitness. In the case in question the answers to the questions were strictly regulated because, in the majority of cases, variants of possible answers were indicated. This questionnaire was sent to

eye-witnesses who had seen the phenomenon first-hand and who had been identified from the first survey. The second survey resulted in 112 completed questionnaires being received and processed. Statistical processing was also carried out on a computer for the purpose of establishing a correlation between the various properties of ball lightning (Ref 6).

In contrast to the USA, where the questionnaires were sent to the staff of a particular establishment, the questionnaire in the USSR was addressed to a wide public (see, for example, Ref 7). In December 1975 the journal 'Nauka i Zhizn' (Science and Life) approached its readers with a questionnaire containing 13 questions regarding the size, life span, colour of the ball lightning, the distance covered by it during the observation time etc (Ref 8). Possible variants of answers were indicated, although not all those writing to the journal adhered to such answers.

The survey conducted resulted in a wide response from its readers, and in the course of 1976 it received approximately 1,400 letters (the majority of them between January and May). Approximately 100 of them contained details of observations of linear lightning at close range (the journal had actually asked for such information), and roughly the same number of letters contained only theoretical discourses on the part of the authors. In addition, approximately 100 answers were rejected because of unclarity or incompleteness of the description given.

As a result of the 'Ball lightning' experiment, as the survey was called by the journal "Nauka i Zhizn', details of 1,062 fresh sightings of ball lightning came into our possession (Ref 9). Particularly significant is the fact that these observations referred to events which definitely did not coincide with those described in the USA. Similar approaches were made to readers in Britain by the journal 'New Scientist' (Ref 10), which received a description of 46 cases, and to readers in Czechoslovakia (Ref 11). In all, the surveys described above and carried out in the 1960's and 1970's supplemented our knowledge of ball lightning by something of the order of two thousand fresh cases, a figure which is several times greater than that of the known cases at the end of the 1950's, and exceeding by something like an order of magnitude the number of incidents known to us at the beginning of this century. Both the reliability and quality of the information increased sharply.

Thus, the dynamics involved in the increase in the information on ball lightning are very impressive. The number of sufficiently fully and clearly described cases in Arago's time (the 1830's and 1840's) was limited to a few dozen. They were included in the first survey compiled by this scientist who laid the foundation of scientific research into the phenomenon (Ref 12). By 1920, ie by the time Brand's survey was published (Ref 13), the number of cases came to about 200. It was obvious that this figure had doubled by the beginning of the 1960's, because Barry's survey was compiled on the basis of approximately 400 incidents (data on approximately 280 cases were gathered by Humphreys, but not all the descriptions were

published). Finally, as a result of the surveys carried out in the 1960's, including the 'Ball lightning' experiment containing 1,100 fresh cases, the total number of incidents described increased to more than 2,000. (It should be noted that we are dealing here with fairly fully described incidents, for which there is a necessary minimum of information on the size, life span, colour, movement, and conditions under which the fire ball appeared and vanished etc. The majority of reports on ball lightning, which are usually quoted in the press, do not meet these criteria).

In conclusion, let us dwell in somewhat greater detail on the 'Ball Lightning' experiment. Fig 1.1 shows data on the number of sightings of ball lightning in each five-year period, starting from 1901, and also for the first five months in 1976. The number of crosses in each column of the histogram is equal to the number of incidents recorded in the course of a given five-year period. The histogram was compiled on the basis of 1,022 cases, the year of observation of which was given in the letters. The largest number of cases - approximately 230 - naturally relate to the period 1971-75. In the course of the preceding five-year period their number remained almost constant (more precisely, it gradually decreased), remaining at a level of 80-100 incidents per five-year period. The noticeable reduction in the number of observations refers to the period 1941-45 and 1961-65. The first is explained by the war, and the second is apparently due to the reduction in thunder-storm activity during this period. Starting from 1935 the number of incidents starts to drop rapidly. In all, 72% of the total number of observations refer to the post-war period, ie the

sightings occurred in the course of the last 30 years and approximately 85% during the period from 1935 to 1976.

Not so long ago a weighty argument against the actual existence of ball lightning was the fact that it had been observed almost exclusively by people without the necessary professional training. It has been stated that not a single professional meteorologist or physicist witnessed ball lightning. Among those participating in the 'Ball Lightning' experiment were many scientists (including physicists and chemists), engineers, doctors of medicine, teachers, meteorologists, aviators and students. Upwards of 65% of our corresondents were intellectuals or undergraduates.

The 'Ball Lightning' experiment is still not complete. A second, more detailed questionnaire is now being compiled, which contains several dozen questions and which will be sent to several hundred of our correspondents. By the time this book will be published we shall be receiving answers to this questionnaire and starting to process the data, a task which, apparently, will take a further year.

1.3 Does ball lightning exist?

The definition of ball lightning given in the preceding section is, of course, a very superficial one. However, any more profound definition will, of necessity, include a certain view-point, adopted in advance, regarding its nature, and this may prove erroneous. For instance, to define ball lightning as a blob of

plasma or even in general a blob of matter forming during a discharge of ordinary lightning, or as a particular kind of quiet discharge (for instance, brush and spray discharge, as described by Tepler (Ref 2)), means from the very outset assuming something that is still requiring proof where ball lightning is concerned. However, a purely phenomenological definition of the kind given at the beginning of this chapter may prove to be too broad and may include a number of completely different phenomena. Indeed, luminous formations appearing around objects during a thunder-storm can be corona discharge. Luminous formations in the air can be meteorites and even birds flying at night whose wings have tiny fragments of luminous rotten wood adhering to them (Ref 4). Of course, the occurrence of meteorites is not associated with a thunder-storm, but even ball lightning is sometimes observed in clear weather. Finally, linear lightning striking metal structures can result in the formation of droplets of molten metal which acquire a spherical shape as they fall to earth.

We are thus faced with a choice between definitions, which, possibly, do not cover a single phenomenon actually existing, and definitions, which combine a number of completely different phenomena in terms of their nature, which have purely external similarity. We can either define precisely just what ball lightning is, but even then we shall not know whether it actually exists, or we can point to a similar group of perceptions, without knowing whether they are one particular object or whether they are combined together on the basis of a purely external similarity of our perception. The situation is a fairly normal one when studying

something new. In both cases we can pose one and the same question (whilst giving it a different sense it is true) 'Does ball lightning exist?'

This question acquires yet another dramatic nuance so to speak, if we consider that, according to one of the opinions expressed in the relevant literature, ball lightning is no more than a spot on the retina of the eye. This spot arises when the retina is affected by a discharge of ordinary lightning, and under certain conditions it can be luminous. Moreover, by focussing our attention first on one and then on another object we can gain the impression that the luminous spot moves in space. The material consequences of the occurrences of ball lightning, for example, traces left by it on objects, are attributed to ordinary lighting. Thus, from this point of view, ball lightning is simply an illusion and we are faced with the question as to whether ball lightning exists as an actual phenomenon? The hypothesis set out above was published recently in the journal 'Nature' (Ref 15). It is, however, by no means new. Moreover, similar doubts were frequently expressed throughout the nineteenth century and this was possibly the prevailing opinion at the time. Among its supporters were also some famous scientists, Thomson (Lord Kelvin) for instance (Ref 2).

This view-point is developed in its most complete and full form in the work by Humphreys (Ref 4) already mentioned. It is a well-known fact that a bright flash of light can give rise to persistent damage to the retina, which will be visible as a dark or (more frequently) light spot (persistence of vision). A dark spot is

referred to as a negative, and a light one as a positive after-image. In essence we are all acquainted with this phenomenon (unlike ball lightning). It is particularly easy to notice persistence of vision if we close our eyes after looking at a bright object. However, in some, considerably rarer cases a persistent after-image can also occur when the eyes remain open.

The time during which an after-image persists - from 2 to 10 seconds - coincides more or less with the life span of ball lightning. The spherical shape of the lightning can be explained by the fact that an after-image is induced by the spherical formation occurring in the lower part of the linear lightning channel, which vanishes when the discharge ceases. It is natural that, in the majority of cases, an unexpected bright flash (for example, from a discharge of linear lightning) is focussed not in the centre of the retina, but slightly to one side of its most sensitive part (if the observer was, by chance, not looking at the very spot where the lightning struck). Furthermore, the eye attempts to focus an image which has arisen (after-image) in the centre of the retina and it turns, as it would to look at the object actually existing. However, it does not succeed in doing this because the affected spot on the retina turns together with the eye, thus creating the illusion that the after- image moves against the background of the surrounding objects. The movement of ball lightning is thus explained.

The after-image vanishes quickly: the clap usually accompanying the vanishing of ball lightning is completed by our imagination.

According to Humphreys the movement of ball lightning appears to us what our every—day experience prompts us to expect from a resilient sphere, ie the latter descends and rebounds upwards a few times as it strikes a floor or the surface of the ground. The explosion of ball lightning is explained by a secondary experience of thunder from a discharge of linear lightning giving rise to this optical hallucination or (particularly when noticeable consequences resulting from the explosion remain) a fresh linear lightning stroke which, by chance, strikes precisely the same spot where, as it seems to us, the ball lightning is.

It will already be seen from the description given above how artificial the suggested explanation is. Nevertheless it is necessary to dwell in greater detail on this question because the erroneous opinion on ball lightning as an optical illusion has revealed an extraordinary viability and capacity for being passed on from one generation to the next.

First of all let us note that ball lightning does not appear exclusively after a particular linear lightning strike. According to the results obtained from the 'Ball Lightning' experiment, in 75% of the cases the observer was unable to indicate definitely whether the appearance of ball lightning was preceded by a linear lightning strike. Ball lightning can, apparently, occur as the result of a very distant discharge of linear lightning which is not definitely located by the observer (for example, in the case of cloud-to-cloud discharge), and can then descend to earth. In many cases (approximately 20-30%) ball lightning is not associated with

thunder-storm at all. According to our data (Ref 8) this occurs in approximately 25% of the cases, and approximately the same result - 30% - was obtained in response to a survey in Britain (Ref 10). However, even in those cases where ball lightning occurred following a specific linear lightning strike, the observer certainly did not always see the flash of lightning, sometimes hearing the thunder only. This was, for example, the case with all four eye-witnesses who saw the ball lightning in the Kremlin described in the Introduction. Thus, those supporting the persistence of vision theory must allow that the after-image can arise not only from a flash of lightning, but also from the noise of the thunder. Sometimes the flash of lightning is separated from the thunder by several seconds - the time taken for ball lightning to enter the observer's field of vision or for them to notice the fire ball.

In order to avoid making unsubstantiated statements we shall give a number of examples of fire balls described in letters received in connection with the 'Ball Lightning' experiment.

This is what S G Kaidan from Kaliningrad reported. In June or July 1958 she was flying in an IL-14 type aircraft over the Magadan region. The weather was thundery, but the mountains were visible. Suddenly there appeared outside the windows on the starboard side a luminous white ball with a pinkish hue the size of a football. It passed along the side of the aircraft, and after landing, a number of holes the size of a thimble were found in the fuselage. In addition to the eye-witness describing the incident, members of the crew and a few passengers had also seen what had happened.

In July 1956 B N Ivanov from the Leningrad district was working in a blacksmith's shop (measuring 90 m^2). A thunder-storm broke out at two o'clock in the afternoon. The workmen in the shop saw through the window a flash of lightning above the roof of their building. Within 3-4 seconds of the flash a white, luminous ball having a pale bluish tinge and measuring 3 cm across penetrated the shop through a hole in the tiled roof. The fire ball's pale bluish light illuminated the surrounding objects which started to reflect slight shadows in the gathering gloom (something unheard of with an after-image). The fire ball dropped to the ground at a speed of lm/sec and, losing momentum, stopped at a height of 80 cm from the earth floor of the blacksmith's shop. The fire ball then floated slowly above the floor. After floating over a pile of metal on the foor and passing within 30 cm of the writer of the letter (the fire ball passed to one side of him), it remained stationary for a while before moving off in the opposite direction, passing over the anvil to reach the rear wall of the shop, where there was a hole. A gust of wind, which had first opened the door and then slammed it shut, ejected the ball through the hole in the wall. All this took 1 minute and 40 seconds (checked by a watch). In addition to the writer of the letter, the fire ball was witnessed by a number of other people working in the shop.

It should be noted that the ball lightning did not appear immediately, but within 3 or 4 seconds of the flash of lightning occurring. Moreover, the writer of the letter gave too many details of the incident for what he had seen to be regarded as an hallucination. Similar observations are not isolated incidents.

This is what Ya V Berezovskii, a mechanical engineer, reports. observation described was made in Germany in the spring of 1945 when he was serving in the army. At 23.00 hours he lay down to rest in a room with an open window, on the second floor of a building. He placed his rifle, with the butt resting on the floor, at the head of his bed near the window. He awoke to the sound of a sharp report near his head ('as if the rifle had been fired'). Upon opening his eyes he saw a white, luminous mass, elongated in the direction of movement, which was sliding smoothly along the wall parallel to the floor. After moving round the stove and following the walls of the room the luminous mass flew out of the window (the letter included a diagram of the room showing the path followed by the fire ball). Upon examining the rifle in the morning, it was found that the head of the cleaning rod had melted, but there was no sign of any spatter of molten metal. The metal had simply vanished (evaporated), leaving behind a small crater measuring 5mm in diameter and 3mm deep in the cleaning rod. walls bore no traces of any effects produced by heat. The eyewitness was not aware of any heat on his face, although he was no more than half a metre from the rifle.

In this case it has to be admitted that a very bright after-image can occur during sleep when the eyes are closed. It must also be added that, as can be seen from the description, there was no close lightning strike in this case, otherwise the head of the cleaning rod would have suffered much more, and the eye-witness would have been deafened by the thunder. In addition, it should have been possible to follow the subsequent trace of the discharge (the rifle

was not earthed). The cleaning rod was struck not by linear, but by ball lightning which had flown in through the window and then left by the same route after following the contours of the room (a fairly common occurrence in the trajectory of ball lightning).

As will be seen from the examples given (and this is confirmed by the very large number of cases on record) the effects left by ball lightning are usually much less than those observed after a linear lightning strike. As a rule, even an exploding fire ball does not lead to noticeable damage to objects in the immediate vicinity. Because of this it is hardly possible to attribute the effects of ball lightning to a discharge of linear lightning, as the supporters of the after-image theory attempt to do. It is not particularly difficult to differentiate between them. A few more examples are given below.

In August 1960 during a thunder-storm accompanied by rain,

V A Lagutina, a doctor from Volgograd, was clearing away the dishes after dinner. She went out into the corridor for a few minutes, closing the door after her. When she returned to the room she saw a fire ball some 1.5 m from her and 1 m above the floor, onto which it slowly descended. A few seconds later the fire ball exploded with a report which caused people to come running out of the neighbouring room. The painted floor bore a scorched spot measuring 5-7 cm across and 0.5 cm deep, surrounded by several small dark spots. The eye-witness sensed a sharp pain in the leg, on which a burn appeared in the form of a number of spots varying in size from a pin-head to a lentil, which proved very painful. The marks disappeared within a few days.

In 1967 a doctor, V V Varsonofyev, was on duty in a room measuring $3 \times 3 \text{ m}^2$ in the settlement of Mirny (near the town of Kazan). He was sitting on a stool behind a 1 m high barrier. A thunder-storm broke out between three and four o'clock in the afternoon. After a loud clap of thunder a bluish-white vaporous mass measuring 30--40 cm across flew in through the open door and started to move about the room very quickly. After covering 10--15 m, the vaporous mass rolled under the stool on which the doctor as sitting. Although the mass was very close to his feet, he was unaware of any sensation of heat. The ball lightning was then drawn to the central heating radiator and vanished with a hissing sound, after melting a small part of the radiator measuring 3--4 mm.

In neither case was there any reason why the eye-witnesses should see any persistent after-image because they had not seen any discharge of linear lightning and, in any case, ball lightning had certainly occurred and had left behind quite perceptible after-effects which, by their nature, could in no way be attributed to linear lightning.

Yet another weighty argument against the optical illusion theory is the fact that ball lightning is frequently observed by a number of people, whose description of it is identical. The assertion by Humphreys to the effect that, in these cases the descriptions given 'usually' do not contain sufficient details proving that those involved have witnessed the same thing is completely groundless. The trajectory of movement, shape and size is 'usually' described in an identical manner even by observers at different locations and

it is quite impossible to explain this on the basis of the idea of the movement of an after-image, since the latter can appear to be identical to several different observers solely on the strength of a number of completley inexplicable random circumstances. Let us look at the facts.

In the summer of 1955 during a violent thunder-storm accompanied by high winds V N Gerasimova and her two sisters were in a large room in their apartment (see fig 1.2, sent by the eye-witness). mother was standing between the window and the stove in the kitchen. A loud clap of thunder was accompanied by two white balls measuring 10-15 cm entering the kitchen via the stove pipe. flèw in one after the other at a height of 30-40 cm above the floor at a speed of 2-3 m/sec (a distance of 10 m being covered in 3-4seconds). The mother saw them in the kitchen. The fire balls flew through the open doors between the middle room connecting the kitchen to the large room where the sisters were. After entering the large room the fire balls passed along the wall to the space between two windows where the earthing was installed. As they approached the earth-wire the fire balls became elongated, turning into ellopsoids and, after touching the earth-wire, they vanished silently into the hole in the floor, through which the earth-wire passed. A weak crackling sound was heard as the fire balls moved.

A number of difficult questions immediately arise regarding the after-image hypothesis. Firstly, no one saw the discharge of lightning (they heard only the thunder). Secondly, the fire balls appeared from the direction of the stove, and not from the window

and, finally, and what is most important, their trajectory is described in an identical manner by the eye-witnesses who were in different rooms. Why did an after-image, which appeared to three people standing in the large room follow the same route from the door into the room to the earth-wire, and why did no one among the eye-witnesses notice that it followed a more natural route from the window to the earth-wire. Why does this agree so well with the description given by the mother who saw how the fire ball, which flew out of the stove, moved in the direction of the door to the neighbouring room. Finally, why did all four eye-witnesses agree that they had seen ball lightning? As we can see, nothing appears to be missing from the details.

Let us examine another case, reported on this occasion by V I Buzik, a control and measuring instrument setter, who witnessed an incident at midday-sometime in June 1955. In this case the ball lightning was witnessed by six people working in a geological group. During a thunder-storm the ball lightning entered through an open, push-out window (fig 1.3), passed above a table, at which people were sitting, then through the room and out into the corridor via the door. The ball lightning was silver in colour and measured 10-20 cm in diameter. It seethed, crackled and twinkled. In addition to the writer of the letter, there were at least four other people in the room who witnessed the incident (a geologist, two sample collectors, and a topographer). The person writing mentioned the names of some of them. The corridor opened into a hall-way, the door to which was open. A workman was sitting there. He also saw how something flew past him and out into the

street. The fire ball exploded in the street near the wall of the house; all those witnessing the incident heard the explosion. the lightning covered a distance through the room of approximately 7 m in 5-10 seconds, ie it moved at a speed of 1 m/sec; the time from the moment it appeared until the explosion was 10-20 seconds.

Thus, in addition to a collective and uncannily identical delusion arising at the same time among all those sitting in the room, an after-image occurred in the case of one person at a different location (in the hall-way). All this took place without a discharge of linear lightning first occurring. It might be possible to dispense with such descriptions if they applied to single incidents. However, in reality a similar picture describing a luminous, spherical object moving independently figures in practically all the letters received. The descriptions differ solely in the extent of the details given.

The descriptions of ball lightning accompanying many of the questionnaires refer to a fairly vivid, 'living' picture of the phenomenon, usually containing too many details, which cannot be expected from a simple hallucination. The 'Ball Lightning' experiment recorded 150 cases where ball lightning had been observed at a distance of 1 m, some of which refer to direct contact with ball lightning, sometimes with tragic results, but mostly not so. In such situations it is hardly possible to confuse an hallucination with a body which actually exists. Cases where the same fire ball was observed by a number of eye-witnesses are by no means rare. Thus, the survey conducted by the journal 'Nauka i

Zhizn' revealed that ball lightning was observed by one person only in 36% of the cases, by two persons in 29% of the cases, and by three or four in 14% of the cases, and finally, by more than four persons in 21% of the total number of cases recorded. Such data were not obtained in response to the survey conducted at Oak-Ridge (the McNally report), but the NASA questionnaire contained the question: 'How many people known to you saw this ball lightning?' According to the results given in Rayle's report (Ref 6), 33% of the observers were the only ones to see the fire ball, 30% of the cases involved two observers, 29% of the cases involved three or four eye-witnesses, and more than four in 8% of the cases. A point worth noting is the good agreement between the probability of one or two people witnessing the same fire ball. As far as any difference in the probability of a larger number of observers witnessing ball lightning is concerned, the answer to this will, of course, depend on the difference in the way the relevant question is phrased.

Our questionnaire raised the question regarding the total number of people who had seen the fire ball, whereas the American questionnaire concerned only persons known to the eye-witness in question. Naturally, the number of such persons known to the observer exceeded four in rare cases only, whereas the total number of observers exceeded this figure fairly frequently in cases where ball lightning appeared on the streets of a town for example. Bearing this in mind it can be said that a more or less identical answer was given to the question concerned in both questionnaires, thus indicating that a number of eye-witnesses frequently see the same fire ball.

An interesting objection to the after-image hypothesis is given by V N Charmen, a member of the staff in the visual optics section of the Science and Technology Institute of Manchester University (Ref 16). He notes that, since the after-image was confined to the front edge of the background, against which the observation was made, and since its visible angle diameter is preserved, the after-image usually changes size considerably in the process of movement. When the background is a greater distance away, the after-image also appears to be further away and therefore (because of the angle diameter being maintained) the after-image appears to be considerably larger. The reverse occurs when the background is closer to the observer. Fluctuations in size can be quite considerable. This is not the case in sightings of fire balls whose diameter is normally within limits of 10-20 cm and does not change appreciably in the course of the observation. Moreover, it will be seen from a number of letters that ball lightning can be concealed by other objects, a fact hardly possible in the case of an after-image.

It should also be noted that if ball lightning was, in fact, governed by persistence of vision following a bright flash, it should not be particularly difficult to reproduce this under laboratory conditions. In so doing, it would not be absolutely necessary to resort to the 'services' of lightning or a high-voltage strong current discharge. Since the reaction of the eye to a bright flash (as in general the reaction of a primary system to an intensive external stimulus) has a saturation point, it could be possible to use a sufficiently bright light so as to create fire

balls in any quantity required without difficulty. This is not being done however.

In conclusion it is difficult to refrain from describing a case where the same fire ball was observed by twenty-five people who were fairly well acquainted and in frequent association with each other. A A Kuritsyn, an artist, described this incident as follows.

This occurred one evening in July 1959 in the Lyuberets district near Moscow. A group of tourists numbering twenty-five were walking through a forest during a thunder-storm. The path was narrow and the bushes wet, forcing the party to proceed in single file. Those involved were carrying ruck-sacks and the distance between the first and last person in the group measured some 25 m. The person at the head of the group suddenly called out: 'Look, ball lightning!' It was impossible for the party to gather in a bunch because of the wet bushes lining the path. The ball lightning was visible from a certain point along the path only, ie in a gap between the bushes and trees. Because of this the party continued moving, each person stopping for five or six seconds to observe the phenomenon.

Those at the head of the column saw how a blinding white ball at tree top level slowly descended to earth. It slowly changed colour, becoming yellow. The writer of the letter describing the incident was at the very rear of the party and was able to stop for a little while on the path. By this time the fire ball had already

become red. It gradually zig-zagged down to earth, losing some of its matter and emitting 'sparks' as it did. The 'sparks' became extinguished very quickly. The particles of matter likewise became extinguished, although somewhat more slowly. The sphere changed from bright red to dark red, after which a black spot appeared in its centre before the fire ball itself finally vanished.

It is not difficult to work out that the lightning in the case described above was observed for 100-200 seconds. It was a few metres away from the eye-witnesses. Mr Kuritsyn, who wrote the letter, sent a sketch, drawn from memory of what he had seen. The mass of details and agreement among twenty-five people about what they had witnessed speaks for itself.

In view of all that which has been said, it is now natural to ask a counter-question: Has there been even one authentically recorded case where an hallucination or, more precisely, an after-image arising from a flash of ordinary lightning has been taken for ball lightning? When answering this question it is best to refer to Humphreys' Survey (Ref 4). It has to be borne in mind that, from the descriptions of 280 cases in his possession, he had to select the most convincing ones to confirm his point of view. This is what we found.

A New Zealand farmer by the name of Bell had finished milking his cows in an open-sided shed. The date was 19 January 1925 (the middle of summer in New Zealand). He suddenly caught sight of a fire ball with a diameter of approximately 30 cm flying towards

him. After being concealed briefly by some logs, the fire ball re-appeared and passed through the barn at a distance of 1-1.5 m from the eye-witness. Because of the confusion, the farmer did not observe the path followed by the fire ball after it left the barn. At the moment of sighting, the observer was in no doubt regarding the reality of the phenomenon he was witnessing. However, afterwards, when recalling this incident, he was surprised that the cows had not reacted in any way to the fire ball they had seen. This appeared strange. A few years after this event he had occasion to see the after-image of an electric light bulb and he then came to the conclusion that what he had seen back in 1925 had been an illusion.

Let us emphasise every detail of the event described. course of its movement the fire ball had been briefly hidden from view by some logs. If it had actually been an after-image, then such behaviour could be explained only by auto-suggestion. However, it appears to us to be highly doubtful that the strength of auto- suggestion would be capable of healing an affected spot on the retina, the existence of which determines the perception of the after-image, and then within an instant restore the affected spot sufficiently for the previous after-image to be seen in broad daylight. Mr Bell does not describe in detail what he saw some years later when he observed the after-image from the bright flash of an electric light bulb, but, more likely than not, he saw nothing of the kind. Therefore, leaving aside the unforgiveable indifference on the part of the cows to interesting thunder-storm phenomena, we are, nevertheless, inclined to think that the New 'Zealand farmer saw real ball lightning.

Another example given in the survey (Ref 4) is based on a report by the person in charge of research at NASA.

In 1923 he observed from his own house a violent thunder-storm and witnessed how a luminous, spherical object the size of a toy balloon was moving 40 m from his house in a neighbouring wood at a height of 2.5 m above the ground. After travelling 30 m in a few seconds, it collided with a tree and exploded with a loud report. A cloud of dust formed at the point where the explosion occurred. The neighbours ran out of their houses in order to see what had happened. It transpired that the explosion occurred at a point where two nails had been driven into a tree. The bark had been stripped from the tree where the explosion had occurred.

At a first glance we appear to be dealing with an ordinary sighting of ball lightning — at a fairly great distance (approximately 40m) it is true. Dozens of similar incidents are described in the letters received by the journal 'Nauka i Zhizn'. This is the opinion of the actual eye—witness, Lewis. However, we give below Humphreys' interpretation. The eye of the observer formed an after—image which appeared to be at a distance of 40 m, although this image in fact arose from an incident considerably further away (in fact, from a linear lightning strike) of which the observer had been unaware. This after—image started to move. This was followed by another flash of linear lightning (likewise unnoticed) striking as it were the same spot as perceived by the observer. We thus have a moving after—image and a number of chance incidents: two lightning strikes which, by chance, went unnoticed, and random

coincidence between the location struck by linear lightning and the point at which the after-image was projected. The artificiality of this explanation does not require any comment. If these two events are, in fact, the most convincing cases which those supporting the after-image hypothesis have available, it can be stated with confidence that so far we are unable to quote a single example confirming that linear lightning can create after-images whose behaviour is reminiscent of ball lightning.

Let us now return to the initial phenomenological determination of ball lightning. Even if the observations made by eye-witnesses are not an illusion and refer to an actual phenomenon, it can well be that the underlying causes are trivial and are not of any particular interest in terms of physics. In particular, Humphreys himself (Ref 4) came to such a conclusion. He considered that the phenomena described by eye-witnesses (in those cases where they are not an hallucination) can be explained by well-known causes, although differently in the variuos cases. Of course, the boundary between the interesting and trivial is very subjective and largely depends on the personal choice of the research worker involved. For instance, to refer, as Humphreys does, to ball lightning as a 'fixed or moving brush and spray discharge' merely means replacing one term with another because, in such cases, we automatically attribute the unusual characteristics of ball lightning to brush and spray discharge and leave it to the future to agree all the contradications involved. (For instance, the question regarding the nature of the emf, about the discharge moving in air without having a visible link with conductors and

acquiring a stable, spherical shape, and also regarding the causes of failure in attempts to reproduce the discharge under laboratory conditions).

Nevertheless, objections to a single cause of the phenomenon undoubtedly deserve careful analysis. As always, complications and contradications occur not in the observations themselves, but in making a comparison between them and in attempts to explain them as having a common cause. If we assume various causes for explaining the various aspects of one and the same phenomenon, the contradictions eliminate themselves, although the heuristic value of the explanation is lost in such a case.

Let us examine just how well founded such an approach to the question is. All the basic characteristics observed: size, life span, colour, energy released by the explosion etc vary within a fairly wide range. This can, in fact, indicate that there are a number of types of ball lightning. However, errors made in observations, just like errors occurring in the communication of information also result in a widening of the range of characteristics observed.

If nature itself produced a number of types of ball lightning which differ noticeably in terms of character, we could expect considerably closer correlation within the corresponding group of incidents in comparison with the correlation among the groups themselves. An attempt is made in Rayle's report (Ref 6) to investigate this question on the basis of 112 replies received from

eye-witnesses. Thirty questions were selected (from a total of forty-six), which characterised ball lightning or the conditions under which it appears. The replies to each of these questions were divided into two groups (A and B). For instance, one group covered all fire balls with a diameter of less than 37 cm (15 inches), whilst the other group covered those with larger diameters. Coordinate -1 was assigned to cases of lightning belonging to group A, and coordinate +1 to those belonging to group B. If the questionnaire did not contain an answer to the question asked, it was given coordinate 0. This opertion was carried out with all 30 questions selected. In all, each of the 112 descriptions received was represented by a set of 30 numbers arranged in a certain order in accordance with the questions in the questionnaire, so that it was possible to regard it as a point in a thirty-dimensional discrete space involving three possible values for each of the coordinates (0, +1).

The square of the distance between the different points was determined as the sum of the squares of the differences in all the coordinates, ie as

$$S_{rp}^{\bullet} = \sum_{i=1}^{30} (x_i^{(r)} - x_i^{(p)})^{\bullet}, \qquad (1.1)$$

where i is the number of the question, and r, p the number of the questionnaires. A computer was used to calculate all the distances between the points representing the various replies, and all of them were arranged so as to minimise the distance between three

successive points (ie between an arbitrary point and the two preceding ones). In other words, the replies were arranged in a series in a manner such that the difference between a number of adjacent cases was the minimum of all those possible.

If it were possible to separate particular groups of closely associated incidents within the replies received, the distance between incidents in such a group would be considerably less than the remaining distances. Data processing did not yield any convincing proof of the possibility of breaking down the incidents into specific groups. From the 112 incidents in each, the distance between which was only slightly less (by approximately 40%) than between the remainder. One of these groups consisted of lightning occurring near the surface of the ground, whilst the other involved lightning observed in each case in the air.

In spite of what has been said above, it is apparent in large groups of observations that there is always a certain proportion of cases where ball lightning was in fact some other phenomenon completely different in its nature, for example St Elmo's fire or corona discharge on conductors. This, together with unavoidable errors in observations and errors in communicating information, leads to a considerable increase in the distribution width of the observed parameters of ball lightning and makes it difficult to explain the phenomenon.

It can be stated with confidence that any attempt to explain all the facts communicated with regard to ball lightning means facing an insoluble problem from the very outset. Moreover, not only insoluble, but, perhaps, also senseless, because in such a case we shall try to explain also the errors unavoidably included in the factual material. It is, therefore, quite natural to refrain at first from explaining a series of exotic facts (for instance, those such as the occurrence of black ball lightning, ball lightning with a huge energy release of the order of 10 MJ and more, or fire balls with a diameter of several metres) and be guided by the explanation found in the main mass of the observations made. In future these unusual facts will probably be explained by extraneous causes or will prove to be errors made in observations. Unfortunately, there is no surer way of separating the important facts from the secondary ones than the personal intuition of the research worker.

In conclusion, let us dwell on phenomena which are so similar to ball lightning that the need naturally arises to draw a clearer demarcation line between them. First of all we shall deal with the various forms of corona discharge. Electric fields with high voltage values cause a leakage charge from charged or polarised conductors into the air. Close to the conductors, where the current density is the maximum and where various pre-breakdown processes can develop, this can cause glowing of the air - corona which can be taken for ball lightning. There are, however, a number of important differences.

Firstly, corona discharge is only observed close to conductors and is associated with them, something which certainly cannot be said of ball lightning. Thus, according to the data received in

response to the Oak Ridge survey, ball lightning was associated with conductors in only 25% of the cases described. In 31% of the cases the lightning was in the air all the time, and for a considerable part of its life span in 19% of the cases. Our data also show that, in the vast majority of cases, ball lightning moves freely in space, remaining for the major part (or entire) life span some distance from surrounding bodies. Upon colliding with objects, ball lightning either vanishes or rebounds from them. More often than not it goes round objects some distance from them. Cases where fire balls remain motionless near an object or move along it (conductors, for instance) are relatively rare and they certainly cannot be referred to as characteristic.

Secondly, corona discharge does not terminate in an explosion or noticeable melting of conductors affected by such a discharge. The electric charge energy of conductors is usually small in comparison with their internal energy Let us take an interesting case illustrating this difference. At eight o'clock in the evening one day in the middle of June 1973 V V Venderevskikh, a measuring instrument mechanic, witnessed how linear lightning struck a metal tower carrying a high-voltage line. A sheaf of fire and sparks appeared, out of which flew a fire ball glowing like magnesium when alight. The ball (which had a diameter of 20-25 cm) started to travel along the conductor from the point where it first occurred to the next tower, where it jumped across onto the continuation of the same conductor on the other side of the tower and, after travelling some further distance, moved upwards onto the top conductor (apparently the earthed one). The fire ball then

vanished, leaving that part of the conductor where the ball was last seen, glowing reddish-yellow. As the fire ball vanished, a small glowing ball detached itself from the main mass and fell downwards before becoming extinguished. It is possible that this was a droplet of molten metal falling from the conductor which had become red hot. All this happened within the space of about 20 seconds. Although the fire ball was attached to the metal conductor throughout its life span, we are, apparently, not dealing here with corona discharge at all, because the vanishing of the fire ball was accompanied by the release of considerable energy - sufficient to heat a metal conductor to a temperature where it glowed red.

Thirdly, the glow produced by corona discharge usually does not have clearly defined boundaries and a definite shape; strong convection currents arising in the corona due to the repulsion of like (more often than not negative) charges leaking from a conductor make corona more like an ordinary flame (hence the name St Elmo's fire) than a spherical formation obstinately striving to retain its form and shape. Ball lightning frequently, although not always, has a fairly clear boundary separating it from the ambient air, a fact which is likewise not characteristic of corona discharge. For example, given below is a case witnessed by the physicist, Leb, a well known specialist in the field of gas discharge.

In the summer of 1898 or 1899 a violent thunder-storm observed by the above-named physicist from a window in his parents' house broke out over Springfield in Massachusetts (USA). He noticed a ball glowing in the same manner as excited nitrogen atoms glow. The ball descended slowly from the roof of a neighbouring bouse, following a smooth curved trajectory as it did. The diameter of the ball was equal to that of two toy balloons. After falling onto the lawn in front of the house, it jumped up again before vanishing. This was followed by the house opposite being struck by linear lightning.

When quoting this case in his survey, Humphreys regards it as corona discharge which had occurred on the roof immediately before a discharge of ordinary lightning. He considers the downward movement to be the result of the movement of the after-image of corona discharge, and its rebounding after coming into contact with the ground to the pure illusion suggested to the eye-witness by his imagination on account of the similarity in the shape of the fire ball he saw and a toy balloon. However, we have available accounts of dozens of cases where ball lightning behaved in exactly the same way when falling onto the surface of the ground or onto a floor, and details of as many cases where it rebounded elastically when striking hard objects.

A present day observer is hardly likely to confuse ball lightning with a meteorite, although in the eighteenth century and even in the nineteenth this happened quite frequently. It is mainly the nature of their movement which distinguishes them from each other. Meteorites travel in a straight line and at great speed, whereas ball lightning frequently floats in the air or moves slowly,

following a complex trajectory as it does. Moreover, unlike meteorites, ball lightning is frequently observed at close range - 2-3 m - and even less. It is also apparent that the appearance of meteorites is in no way associated with thunder-storms.

After entering a linear lightning channel, a droplet of molten metal can also form a luminous sphere whose movement, however, will differ appreciably from that of ball lightning. Because of their very considerable specific gravity such droplets unavoidably flow downwards or fall rapidly, whereas ball lightning can float in the air, move horizontally or rise upwards. Even if we assume that a droplet of molten metal acquires considerable impulse at the moment of its formation, its movement will, because of the high inertia, only slightly resemble the movements attributed to ball lightning. Finally, in the case in question, we can be dealing merely with small fire balls whose diameter is a few centimetres, whereas in the vast majority of cases of ball lightning considerably larger diameters are involved (10-20 cm and sometimes greater).

In conclusion let us examine yet another phenomenon which frequently accompanies ball lightning, namely ordinary linear lightning. At a first glance these phenomena differ from each other to such and extent that it is impossible to confuse them. Nevertheless, some surveys contain confirmation regarding a discharge of linear lightning seen 'end on', ie directed straight at the observer, being mistaken for ball lightning. This opinion is expressed by Humphreys in his survey, when he illustrates the point with two examples.

First of all it should be noted that the propagation state of linear lightning is such that there is no possibility of 'noticing' a discharge occurring in the direction of the observer. average propagation rate of a stepped leader, from which a discharge of linear lightning starts, is, as is known, approximately 100 km/sec, and the time for its development is approximately 0.01 sec. Our nervous system cannot react to such fleeting processes. It can be stated with confidence that no one can be struck by a flash of lightning they see, in the same way as one is never struck by the bullet one hears (for somewhat different reasons, it may be added). It is quite a different matter with ball lightning. As will be illustrated below, its velocity does not exceed a few dozen metres per second, ie it is several orders of magnitude below that of linear lightning. Therefore, the observer is in a position to notice at a distance of a few dozen metres a fire ball moving rapidly towards him, but is also able to react to it somehow. It was precisely so in the two above-mentioned cases quoted by Humphreys, and this makes it highly unlikely that we are dealing here with linear lightning.

Furthermore, ball lightning is noiseless. Its movement is either completely silent or is accompanied solely by a slight hissing or crackling sound. Although ball lightning does, on rare occasions, travel at a velocity of several dozen metres per second and form a short luminous band having a length of several metres (this is due to our visual analysis being incapable of distinguishing events separated by a time interval of less than 0.1 sec), this band cannot be confused with a linear lightning channel whose formation

is accompanied by deafening thunder. As a rule, the effects of ball lightning exploding are considerably less than from a discharge of linear lightning. In particular, the explosion is more often than not a clap, and sometimes, when louder, like a rifle or pistol shot, whereas thunder from linear lightning close at hand is more reminiscent in strength of a bomb or shell exploding.

On the basis of the reasons given above, Humphreys' opinion is likewise unfounded with regard to a discharge of linear lightning, whose channel passes along a conductor broken at a certain point, sometimes being mistaken for ball lightning. Numerous descriptions of a discharge of linear lightning at close range, which were given in more than 100 letters received by us in the course of the 'Ball lightning' experiment, differ to such an extent from descriptions of ball lightning (in some cases received from the same people writing in response to the questionnaire) that it is difficult to confuse these two phenomena — even when witnessed by an observer not too well trained in such matters.

1.4 How often does it occur?

It is usual to regard ball lightning as being a rare occurrence. At a first glance this opinion has been fairly reliably substantiated, since the vast majority of people may, in the course of their lives, observe several thousand discharges of ordinary lightning, witout seeing ball lightning once. However, the question does not appear quite so simple when examined more closely. First and foremost it is necessary to differentiate between the frequency of observation and the objective frequency of lightning occurring. Many species of animals which are by no means rare at the locations they inhabit appeared to be rare only because they lived in rather inaccessible regions or were shy of man. What is the situation like as regards ball lightning?

Let us first of all attempt to assess the probability of seeing ball lightning with one's own eyes in the course of one's life. As was mentioned above, the NASA survey showed that approximately 10% of all the staff receiving the questionnaire (180 from a total of 1,764) had seen ball lightning (Ref 6). How characteristic is this figure? At Oak Ridge the preliminary survey yielded 5-6% (110 from a total of 1,962), whilst the more extensive survey yielded 3.2% (513 from a total of15,923). As can be seen, the figures decrease as the range of persons covered by the survey widens. However, it also follows from these data, that the probability of seeing ball lightning in the course of a year in the USA is approximately 0.1%. However, the question arises as to whether it is possible to extrapolate these date obtained from a relatively narrow sample to

wider sections of the population. The 'Ball lightning' experiment was aimed at a wider audience, whose numbers can, unfortunately, be determined only very approximately. Since the circulation of the journal 'Nauka i zhizn' is approximately three million copies, it can be expected that between three and six million people had the opportunity of reading the article. We obtained upwards of one thousand descriptions, amounting to $1.5-3\times10^{-4}$ of the potential number of participants in the experiment, ie approximately 0.02%, a figure which is considerably lower than the figures obtained for the USA. However, it remains unclear, whether all those who had seen ball lightning and read the article in the journal had decided to write to the latter.

It is interesting to examine the distribution of the number of incidents per year during recent years:

Year	1	1971	1972	1973	1974	1975
Number of incident	s	24	32	40	61	71

Assuming that all the readers who had seen ball lightning in the course of the last year covered by the survey (1975), ie immediately prior to the publication of the article, responded to the suggestion made by the journal, we find that the probability of observing ball lightning in the course of a year in the Soviet Union is 2×10^{-5} ; the probability of encountering it in the course of one's life is then equal to approximately 10^{-3} ,

ie approximately 0.1%. This is still more than an order of magnitude less than the figure obtained from surveys held in the USA. In part, this difference can be explained by the fact that the average frequency and intensity of thunder-storms over the territory of the Soviet Union is somewhat lower than in the USA. In addition, it is necessary to take into account that, in the case in question, the survey was addressed to a considerably (more than 200 times) greater circle of people, and it appears to us that the figure of 2×10^{-5} must, in reality be close to the true probability of seeing ball lightning in the course of one year in the Soviet Union. Of course, we have in mind an observation under 'ordinary' conditions, ie without making any special preparations, for instance expeditions to regions with a higher incidence of thunder-storms, systematic observations of TV transmission masts and other structures frequently struck by lightning, the use of special equipment etc.

Nevertheless sitings of ball lightning are, in fact, fairly rare and the majority of us live out our lives without ever seeing such a phenomenon. However, it follows from the lowest estimate of the frequency of observation that in the case of the 'Ball lightning' experiment we received information on a small proportion (of the order of a few percent) of the total number of cases of ball lightning occurring, which are known to the population of our country. It can be seen from this estimate that upwards of two or three thousand cases of ball lightning are observed each year over the territory of the Soviet Union.

It appears at a first glance that encounters with ball lightning must be isolated incidents. If such is the case, as the results obtained by the NASA survey indicate, the probability of ball lightning being observed by the sample of people covered by the survey, was 0.1, the probability of its being encountered twice by the same person is equal to 0.01, and 0.001 by the same person three times. This means that, of the 1,800 involved in the survey 18 + 4 ought to have seen it twice, and 1-2 people seen it three times. Moreover, it will be seen from Rayle's report (Ref 6) that, of the 180 eye-witnesses who saw ball lightning, 111 witnessed it once, 34 saw it twice, 6 saw it three times, and 29 witnessed it on more than three occasions. This greatly exceeds the figures given above. The more extensive Oak Ridge survey does not give information on cases where ball lightning was sighted two or even three times by the same person.

In the 'Ball lightning' experiment 1,100 cases include no more than 30 where ball lightning was observed twice by the same person, ie approximately 3% of the total. There are actually no cases where ball lightning was sighted three times by the same person, and only one person claims to have witnessed it on four occasions. (It should be noted that we are dealing here not with sightings of a number of fire balls simultaneously, but sightings on two or a greater number of occasions). However, even these figures greatly exceed those which can be expected from the law of multiplication of probabilities. In fact, if, as will be seen from the estimates given above, the probability of sighting ball lightning is equal on average to 10^{-3} , the anticipated number of cases of lightning

being sighted twice by the same person must be approximately 1 per thousand single sightings. Apparently, a second sighting of ball lightning cannot be regarded as an event which is statistically independent of the first sighting. It is also possible that, in reality, letters were received from only a comparatively small proportion of those who had seen ball lightning only once, but from all those, or almost all those who had witnessed it twice.

Let us now turn to the question of the objective probability of the occurrence of ball lightning during a thunder-storm for instance. The conditions under which linear and ball lightning is observed differ very considerably, especially where the latter is concerned. The bright linear lightning channel is visible at a distance of several kilometres, whereas a relatively weakly glowing (approximately with the strength of a 20-50 watt electric light bulb) fire ball is visible at a distance of no more than a few dozen metres. Moreover, such a fire ball exists for only a few seconds, a few dozen seconds at the most, and does not attract attention by the noise of thunder. In addition, ball lightning is usually observed close to the surface of the ground where it can be concealed by other objects. It is only under very favourable, to some extent mutually exclusive conditions (good visibility, absence of interference in terms of daylight etc) that ball lightning can be seen at a distance of more than 100 m, the possibility of errors occurring in such cases increasing quite considerably.

Fig 1.4 shows a histogram of the number of fire balls, the shortest distance to which is indicated under each column in the histogram. Fig 1.5 shows a smooth curve plotted on the basis of this histogram (see curve drawn between hollow dots). The y axes of the dots in this curve represent the proportion of those incidents, where the minimum distance from the eye-witness to the ball lightning was les than or equal to the value on the x axes. Both the histogram and the graph were plotted on the basis of material obtained by the journal 'Nauka i zhizn', using 965 cases, which gave answers to the questions involved.

It will be seen from the histogram and graph that considerably more than half the cases of ball lightning (approximately 61.5%, or 593 incidents) were witnessed at a distance of less than 10 m. In 158 cases (16%) the ball lightning was at a distance of less than 1 m from the eye-witness. Only 6% of the incidents refer to sightings where the minimum distance exceeded 100 m. It should be noted that sightings involving distances in excess of 100 m appear rather doubtful to us. In fact, since the characteristic size of ball lightning, as will be illustrated below, is 10-20 cm, the angular diameter at which it is observed at a distance of 100 m is equal to approximately 7 min. In other words, four times less than the angular diameter of the moon. It should also be mentioned that, under such conditions, ball lightning can, possibly, be noticed, but is very difficult to describe accurately. Moreover, the probability of its being confused with some other phenomenon increases very considerably. However, an error is hardly possible at a distance of 10 m.

The data given in fig 1.5 do not confirm Rayle's hypothesis (Ref 6) to the effect that the number of fire balls increases proportionally to the square or cube of the distance to it (depending on whether it occurs only on the surface of the ground or in the entire volume). It is possible that, provided excessive distances were not involved, this would be the case if ball lightning were observed in an open, empty space. In reality ball lightning is more often than not encountered inside buildings where it is difficult to expect such simple conformity to the laws involved.

According to Rayle, approximately one half of all cases of ball lightning were witnessed at a distance of less than 15 m; in 32% of the cases the minimum distance was less than 3 m, and in 66% of the cases it was less than 30 m. (These data are not included in McNally's report because the question about the minimum distance did not figure in the Oak Ridge questionnaire). As will be seen from the graph (see fig 1.5), our survey shows that approximately 35% of the cases of ball lightning were observed at a distance of less than 3 m, and approximately 77% of them at a distance of up to 30 m. The distance range of less than 15 m accounts for 67% of the cases. Thus it can be considered that in this respect the observation conditions were more or less identical in both cases. In 54 cases (48% of the total number of sightings) in the NASA survey (Ref 6) the eye-witnesses were inside a building. Although even this does not mean that the ball lightning itself was inside the buildings, it was apparently the case in the majority of the sightings. As will be seen from fig 1.5, in our case, 50% of the

eye-witnesses saw ball lightning at a distance of less than 5 m, a circumstance usually applicable in the case of sightings inside a building. As will be illustrated below (see fig 2.8), in approximately 50% of the cases the distance travelled by ball lightning during the observation time was less than 8 m. Thus, in our survey too, in approximately 50% of the cases, if not more, the ball lightning was observed inside buildings.

Let us return once more to the question of the objective frequency of occurrence of ball lightning. The frequency of linear lightning is the natural scale for comparison purposes. The preliminary survey carried out by NASA also included questions about sightings of beaded lightning and about the point of impact in the case of linear lightning. (Beaded lightning is a particular form of linear lightning whose channel disintegrates into a series of luminous regions separated by dark, sausage type instabilities). The last question in the NASA survey referred to observations of a range with a diameter of approximately 3 m situated where the linear lightning channel enters the ground or objects situated on it. An answer in the affirmative to this question meant that the eye—witness had seen this point of impact sufficiently clearly for them to be able to notice a small, slightly luminous ball near the ground.

It transpired that, of the 1,764 persons asked, 180 had seen ball lightning - 112 of them witnessing beaded lightning, whilst 409 had observed the point of impact of linear lighting, ie 10%, 6% and 23% respectively of the total number of people participating in the survey. Thus, the probability of observing ball lightning is no

more than 2.5 less than the probability of observing the point of impact of linear lightning, so that in a certain sense it can be said that even linear lightning is a fairly rare phenomenon, because it rarely occurs close to the observer. According to these data the frequency of occurrence of ball lightning is of the same order as the frequency of cloud-to-ground discharge, and the impression of its being a rare phenomenon arises because the conditions involved in observing it are made very difficult (approximately as difficult as observing the point of impact of linear lightning). If ball lightning arises during a discharge of linear lightning, it can be expected that it occurs in the case of nearly each such discharge or, more precisely, this hypothesis does not conflict with the results obtained in response to Rayle's survey. On the other hand, the assumption to the effect that ball lightning forms in rare, exceptional cases, for instance when the current reaches a very high value or when a linear lightning channel passes through some particular part of the surface, does not agree with these results.

A completely different situation arises in the case of beaded lightning, the conditions of the observation of which are the same as for linear lightning. Since, in spite of this, beaded lightning is observed more rarely than ball lightning, it becomes clear that we are dealing here with a really rare phenomenon. If, as is frequently thought, ball lightning forms as a result of a discharge of linear lightning, the probability of its being observed increases considerably. All we need to do is make proper provision for regular observations of those objects frequently struck by

linear lightning (eg high spires, TV transmission masts, power transmission lines etc). Thus, the frequency with which the Ostankin tower is struck by linear lightning amounts to several dozen times per year. If the probability of ball lightning occurring during a discharge of linear lightning is not less than 0.1-0.01, there is every chance of encountering ball lightning in the course of one season. In this case it is, of course, necessary to admit that even if the tower is struck by lightning, it does not necessarily mean that ball lightning will appear. Moreover, it is necessary to use the appropriate equipment because, if account is taken of the great height of the tower, the angular dimension of the ball lightning (when observed from the ground) will be very small, and its brightness insignificant in comparison with that of a linear lightning channel.

1.5 Ball lightning and thunder-storms

At the beginning of this chapter we mentioned that ball lightning occurs during thunder-storms, and once again this unusual phenomenon confronts us with yet another unsolved problem. The point is that it can occur without a thunder-storm. Let us consult the facts. Fig 1.6 shows the distribution of the number of incidents per month. This distribution, which was complied from data obtained in response to our survey, covers 884 cases. This histogram repeats fairly well the distribution of thunder-storm activity in the course of a year. We can see a clear maximum in July, which accounts for 40% of all the sightings of ball lightning. The three summer months account for 81% of the sightings, and if we include May and September, during which

thunder-storms not infrequently occur, especially in the southern regions of the Soviet Union, this period accounts for 91% of the total number of incidents involving ball lightning. A similar picture is found in the USA. According to Ref 6, we find that, of 98 sightings, for which the month is indicated, 35 occurred in July (ie 35%), and 28 and 18 in June and August respectively. This means that the three summer months account for 81% of the total. Seven cases were observed in May, and four in September, meaning that the period from May to September accounts for 92% of all the incidents. In addition, two cases were observed in October, one in November, and three in April.

These data show convincingly that the occurrence of ball lightning correlates well with thunder-storm activity. A small number of cases (approximatley 10%) observed during the autumn and winter months, and also at the beginning of spring can easily be explained by the fact that thunder-storm activity does not cease completely in winter, those storms occurring during winter months, for example, testifying to this.

This means that a fairly high incidence of thunder-storms is apparently necessary for ball lightning to occur. Unfortunately, examination of individual observations does not yield such a clear picture of the link between these incidents. Of 1,006 cases of ball lightning being observed (in our survey), where the weather conditions were described sufficiently clearly, 699, ie 70%, indicated direct connection with a thunder-storm. In these cases

ball lightning occurred during a thunder-storm, immediately before one, or soon after one had ceased. In 17% of the cases (173 incidents) nothing pointed to a thunder-storm, although the weather was overcast or rain was falling. Finally, there were 134 cases (approximately 13%) where ball lightning was observed in clear weather. More or less the same picture - approximately 70% of cases involved the occurrence of ball lightning during a thunderstorm - was found in the British survey (Ref 10) which, unfortunately, was based on fairly limited experimental material (48 cases). As far as the American surveys are concerned, the link with thunder-storms proved to be closer. According to Rayle (Ref 6), approximately 95% of the observations were made during a thunder-storm. The McNally report (Ref 5) mentions only three cases of ball lightning occurring in clear weather. In 376 cases it occurred after a linear lightning strike, ie during a thunderstorm. The weather conditions were not precisely defined in the remaining 134 cases. In summing up it can be said that, as a rule, ball lightning occurs not only during periods of increased thunderstorms. However, cases where it appears in clear weather, although relatively rarer, still cannot be dismissed as errors made in observations. Naturally, doubts arise as to whether fire balls observed during clear weather are of a completely different nature than those occurring during a thunder-storm. Humphreys refers to them as 'will-o'-the-wisps' (ignus fatuus) and makes a humorous suggestion to the effect that a flying owl in pursuit of its prey at dusk with luminous particles of rotten wood on its wings can be mistaken for ball lightning.

Nevertheless the descriptions of these anomalous
'non-thunder-storm' fire balls are so similar to ordinary,
'typical' cases that it is difficult to refrain from thinking that
we are dealing here with the same phenomenon. In order to avoid
making any unfounded statements we shall quote a few examples of
sightings. This is what P V Shulepov, an engineer from
Chelyabinsk, reports.

It was a hot day. Towards evening clouds started to gather on the horizon and although there were flashes of lightning, no thunder was audible. Darkness then fell. A group of boys (including the writer of the letter describing the incident) were returning home from the river Miass when they saw a fire ball pass over some houses and cross the road at a height of 8-10 m. The fire ball, which had a diameter of approximately 30 cm, was 20-30 m from them at the time. It was clearly visible against the sky and appeared to consist of small, separate stars of different colours. The fire ball travelled smoothly, trailing behind it a tail of sparks which became extinguished at the far end of the tail. After flying across the road, the fire ball hung above a house. It then disintegrated in a shower of bright sparks, lighting up the entire house before it became extinguished. This took place in July 1940 in the settlement of Melentyevo in the Miass district of the Chelyabinsk region and was all over in a minute.

In this case there were, however, signs of thunder-storm activity, even if some distance away, where flashes of lightning were to be seen. But who can guarantee that this was not the case in the other instances as well. Finally, discharges of lightning have

been recorded in clear weather when no clouds were present.

Sometimes the effect of a discharge of lightning can be transmitted along telephone wires or power lines over a distance of several kilometres. Moreover, under favourable conditions (a life span of the order of one minute) the fire balls themselves can travel a distance of about 1 km or even more.

On a cloudless, sunny day sometime in 1910 a telegraphist,

I F Ryzhkov, was sitting at his telegraph set in the post and
telegraph office. As he was receiving a telegram, a fire ball
slightly smaller than a football flew out of the set. It passed
through the room at a height of 2 m, emitting a buzzing sound
before disappearing out of the window. Although the weather was
clear at the location where the ball lightning was observed, a
thunder-storm was in progress above the telegraph line some
distance away. It is possible that lightning struck the line and
caused the fire ball to appear.

Sometime between six and seven o'clock in the evening on either the 25 or 26 of August 1974 a chauffeur, Zh M Shambelev, saw two blinding white fire balls near a hv transmission line. They were moving slowly and then vanished with a hissing sound, leaving behind a slight trace of smoke. The weather was clear and there was no sign of a thunder-storm in the immediate vicinity. However, as in the case described above, it is possible that a thunder-storm was in progress somewhere above the line.

Finally, let us quote yet another case described by T S Yurkova.

This incident occurred at eleven o'clock in the evening in August

1947 on the bank of the river Kama during clear, calm warm

weather.

An orange fire ball with a diameter of approximately 50 cm was floating in the air, from time to time giving off sparks, and moving in a jerky manner. It passed over and, after rising above a wood, floated to a tree and was then concealed behind some houses, covering a distance of approximately 1 km in about 60 seconds.

It is true that all this was observed at some considerable distance - approximately 300 m, although all the information given is quite typical of 'ordinary' ball lightning.

We are thus faced with the question: To which extent are fire balls, which are observed in clear weather, similar in character to 'typical' ball lightning? This question will be dealt with in greater detail in Chapter 2.

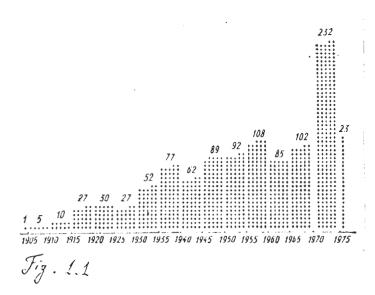
Figure Captions

- Fig 1.1 Distribution of 1022 reports of ball lightning received by the journal 'Nauka i zhizn' for five-year periods. The last column on the right-hand side refers to incidents which occurred in the first half of 1976.
- Fig 1.2 Trajectory of two fire balls which moved one after the other (diagram sent by V N Gerasimova):
 - 1 3 positions where the writer of the letter and her two
 sisters were standing.
 - 4 position where their mother was standing
 - 5 stove, out of which the fire ball flew
 - 6 earthing
 - 7 windows
- Fig 1.3 Trajectory of ball lightning (diagram accompanying letter from V I Buzik):
 - 1 6 positions where the geological team witnessing the ball
 lightning were located
 - 7 windows
 - 8 point where the ball lightning exploded
 - 9 office desks

(Those parts of the trajectory where the ball lightning was not visible are shown by a dashed line)

- Fig 1.4 Histogram of the minimum distances from the eye-witness to the ball lightning (according to data received by the journal 'Nauka i zhizn' on 965 cases). Given at the top is the number of sightings in each distance range.
- Fig 1.5 The distribution of cases of ball lighting according to the minimum distance from the fire ball to the observer. The distribution was plotted on the basis of data received by the journal 'Nauka i zhizn'. The y axis of the dots on the curve indicates the probability that the minimum distance during the observation did not exceed the value of the x axis.
 - 0 according to all the reports (965 cases)
 - + applies only to lightning in overcast weather without a thunder-storm (155 cases)
 - applies only to lightning occurring in clear weather (134 cases)
- Fig 1.6 Distribution of the results of observations of ball lightning according to month (based on 884 reports received by the journal 'Nauka i zhizn').

FIGURES



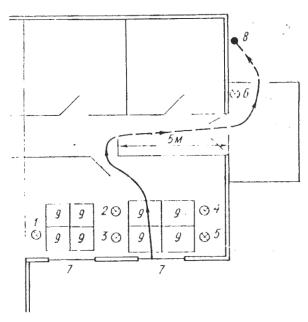


Fig. 1.3

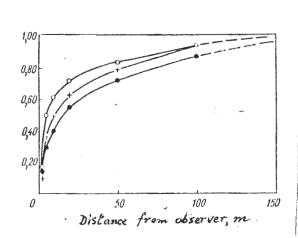


Fig. 1.5

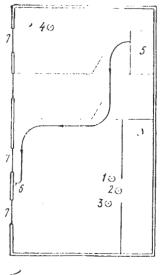


Fig. 1.2

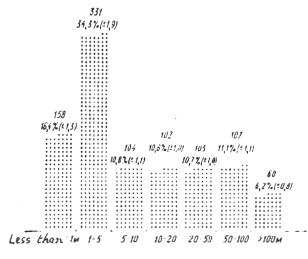


Fig. 1.4

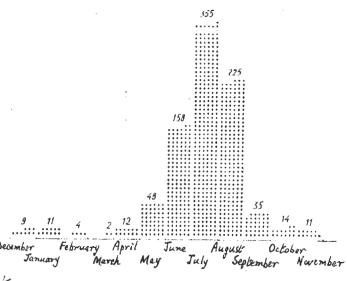


Fig. 1.6

2. THE CHARACTERISTICS OF BALL LIGHTNING

2.1 Life span

Unfortunately, the majority of people observing ball lightning either do not see the moment when it occurs or when it vanishes, or they see neither the one nor the other. Therefore, the time during which ball lightning is observed gives only an extremely rough idea of its life span. The situation is further complicated by the fact that when assessing the duration of the phenomenon it is usually a matter of using not the readings taken from a watch or clock, but instead relying on a subjective sense of time on the part of the observer. Under such conditions it is particularly important to compare the results from a large series of observations carried out at various locations, for instance in various countries, and we shall attempt to make such a comparison in this chapter.

Judging by the facts available, in many cases the time during which ball lightning is observed does not differ from its life span, and therefore henceforward, in the interests of simplicity, we shall frequently talk of the life span, and not of the duration of the observation. Fig. 2.1 shows a histogram of the distribution of the time during which lightning was observed, involving 980 incidents, information on which was obtained by the journal "Nauka i Zhizn". Shown under each column is the duration, and above it is the number of cases, in which the observation was within the limits of this The intervals were selected in a manner such that someone not observing the time by a clock might, nevertheless, distinguish these intervals with sufficient reliability. Therefore, the extent of the intervals gradually increases because it is possible to distinguish a space of time of 2 seconds, shall we say, from 7 seconds, whereas this would hardly be possible in the case of 50 and 55 seconds. Shown above each column in the histogram is what percentage of the total number of events are events referring to the column in question. The first and last columns, which contain a comparatively small number of reports, naturally may not reflect the actual

situation with sufficient accuracy because of random errors. Assuming that the random deviations from the mean values are proportional to \sqrt{n}/n , where n is the number of events in the group being examined, it is possible to calculate the probable limits of these deviations. They are shown in brackets for each column in the histogram (in percentages). In addition to random errors, systematic errors are also possible. In the case of lightning with a life span of less than one second this is quite natural: by no means all such instances of lightning (in any case a considerably lower proportion of them) can be noted by the observers. However, even a very long observation time - of more than 100-200 seconds - can also include considerable systematic errors, since normally these observations refer to objects observed at some considerable distance, thus increasing the probability of errors.

Using the data in the histogram it is easy to find the number of cases where lightning was observed for less than 5, 10, 20 etc seconds by adding together the number of events referring to the corresponding columns. After recalculating these data for one thousand cases (for which it is necessary to multiply them by the coefficient 1000/980), we arrive at the results shown by hollow dots in fig. 2.2. Similar data obtained in the Oak-Ridge (Ref. 5) and the Rayle (Ref. 6) surveys are also shown in fig. 2.2 (see symbols in the form of squares and triangles respectively). In the first case they are based on the distribution, in time, of 445 events, and 95 events in the second case; however, in order to simplify the comparison this illustration includes standardization for 1000 events in all three cases. If the observation times are actually close to the life span of the lightning, we can consider that fig. 2.2 shows the dynamics of the disintegration of 1,000 fire balls, these dynamics being obtained from the data resulting from three different surveys.

First of all it will be noticed that there is fairly good agreement between the results given. It will be seen from the graph that, according to our data, half of the fire balls caused by ball lightning vanish within 13 seconds; MacNally puts this figure at 3-4 seconds, whilst Rayle's data indicate 9 seconds. In view of the unreliable nature of a subjective estimate of time, this agreement must be regarded as fairly good.

After plotting the results obtained on a semi-logarithmic scale it was easy to see that the "law of the disintegration of ball lightning" does not have a simple exponential form, although it can be represented by two exponents with widely differing periods of disintegration (Ref. 17):

$$N = N_0 [1 - \alpha_1 \exp(-t/\tau_1) - \alpha_2 \exp(-t/\tau_2)], \quad (2.1)$$

where N is the number of fire balls which "disintegrated" in time t from a total number N_O of cases of ball lightning which had existed at the outset $(N_O = 10^3 \text{ in fig. 2.2}); \alpha_1 \text{ and } \alpha_2 \text{ are coefficients determining the proportion}$ of the cases of lightning disintegrating with a period of τ_1 and τ_2 respectively. It is obvious that

$$a_1 + a_2 = 1.$$
 (2.2)

When t \gg τ_1 all short-lived fireballs vanish and

$$\ln \frac{N_{\circ} - N(t)}{N_{\circ}} = \ln \alpha_{\circ} - \frac{t}{\tau_{\circ}}, \qquad (2.3)$$

i.e. on a semi-logarithmic scale the relationship of a relative number of cases of lightning remaining $N' = [N_O - N(t)]/N_O$ to the time must be represented by a straight line. It will be seen from fig. 2.3 that this assumption is realized satisfactory for the results obtained in response to our survey (see the hollow dots on straight line a, corresponding to 50, 100 and 200 seconds); as a result we find that $\tau_2 = 53.6$ secs, $\alpha_2 = 0.43$ and, consequently, $\alpha_1 = 0.57$. It follows from (2.1) that

$$\ln N'' = \ln \alpha_1 - t/\tau_1, \qquad (2.4)$$

where N" = $(N_0 - N)/N_0 - \alpha_2$ exp $(-t/\tau_2)$, i.e. we once more obtain a straight line on a semi-logarithmic scale. As will be seen from fig. 2.3 this is also fulfilled satisfactorily in our data (straight line b). We find that τ_1 = 11 seconds. Thus, according to the data obtained by the journal "Nauka i Zhizn", ball lightning disintegrates according to the following law

$$N=N_0[1-0.57 \exp(-t/11) -0.43 \exp(--t/53.6)]$$
 (2.5)

(time in seconds). The line in fig. 2.2 has been calculated from formula (2.5). It will be seen that it approximates the experimental points very well. Thus, there are two groups of lightning: one we shall call conventionally "short-lived" with a period of semi-disintegration of 7.5 seconds ($0.69\tau_1$), and the other one "long-lived" with a period of semi-disintegration of approx. 40 seconds ($0.69\tau_2$). Both groups were represented more or less in identical manner in the observations belonging to this series: short-lived 57%, long-lived 43%. Similar processing carried out for the results obtained by MacNally reveals

$$N=N_0[1-0.86 \exp(-t/3.5) -0.14 \exp(-t/64)],$$
 (2.6)

whereas for Rayle's data we obtained

$$N = N_0[1 - \exp(-t/13.6)].$$
 (2.7)

Fig. 2.4 shows the corresponding graphs on a semi-logarithmic scale. The solid lines shown in fig. 2.2 around MacNally's and Rayle's points represent a calculation in accordance with formulae (2.6) and (2.7). Although somewhat less satisfactorily than in the first case, these lines nevertheless approximate fairly well the results obtained from the observations. We see that in the Oak-Ridge observations and in those carried out by us there are groups of cases of short-lived and long-lived lightning, although the first constitutes the vast majority of cases (approx. 86%). In addition, their period of semi-disintegration proved to be smaller approximately by a factor of three than in our observations.

There are no cases of long-lived lightning in Rayle's sample, whilst the period of semi-disintegration of short-lived lightning is more less in accordance with that obtained by us. The small proportion of the cases of long-lived lightning, recorded by MacNally, fully accords with their absence in the survey made by Rayle which was small.

At present it is still difficult to solve the problem as to whether the division into long-lived and short-lived lightning is the result of its actual physical properties or is it the result of the difference in the conditions involved in observing essentially one and the same object. We shall return to this question somewhat later in this chapter.

It follows from both the graph and the interpolation formulae obtained (2.5) - (2.7) that the derivative dN/dt decreases monotonically as t increases. The value of $(1/N_O)$ (dN/dt) is equal to the probability density of lightning disintegrating at moment t (in a unit of time): it increases when t \Rightarrow 0.

2.2 Size and shape

It is not surprising that philosophers in centuries past singled out the size and spatial form among all the remaining properties of physical bodies, considering them to be the primary and inseparable properties of matter. In fact, these characteristics of bodies lend themselves particularly well to an objective estimate and depend least of all on the individual qualitities of the observer. Therefore, with regard to the shape and size of ball lightning we can hope to obtain those results which agree best of all. These hopes are being realized. The vast majority of the observers speak of a shape close to a regular sphere, whence the very name of the phenomenon sprang, not only in Russian (i.e. "ball lightning", "ball of fire" in English, "Kugelblitz" in German etc). Thus, the survey carried out by NASA recorded, in 112 incidents a spherical (round) form in 98 cases (87.5%) an elliposidal shape in nine cases (8%), and an annular form in three cases. Approximately 80-90% of the observers reported a spherical form even in the old surveys carried out prior

to the sixties (see, for example, Refs 13 and 14). Unfortunately, neither MacNally's questionnaire nor that appearing in "Nauka i Zhizn" included a question about the shape of the lightning. Nevertheless some letters received contain references to elongated, ellipsoidal lightning, However, these represent no more than a few percent of the total number of observations made. A possible cause of departures from ball lightning having a spherical form will be examined below.

Fig. 2.5 shows a histogram of the size of ball lightning obtained on the basis of 1005 events, reports on which were received in letters addressed to the journal "Nauka i Zhizn". Shown above each column in the histogram is the number of cases where the diameter of the ball lightning was in the given value range, together with the percentage which these cases constitute in the total number of observations, and also the probable limits of random deviations. Just as when distributing the observations according to time intervals, the first and last columns in the histogram, which correspond to diameters of less than 2 cm and greater than 100 cm, include a small number of events and can contain appreciable random and systematic errors.

This histogram can be used to plot the probability density of the lightning having the diameter in question. For this purpose it is necessary to divide the number of events covered by each diameter range in the histogram by this range. This gives the probability density per unit of length of the range, which can then be referred to the mean value of the range. In fig. 2.6 the experimental points are shown by hollow dots. The processed data from the Oak-Ridge and Lewis surveys are shown in similar manner in the form of hollow squares and triangles respectively. The solid lines are smoothed and standardized for a unit of distribution of the probability density. They have a clear maximum in the diameter range of 10-15 cm. Fig. 2.6 also shows that our results and MacNally's data agree satisfactorily. According to Rayle the probability density, whilst having a maximum approximately in the same diameter range, drops considerably more slowly as the diameter is increased

beyond the maximum. This is probably explained by the insufficient statistical selection of samples examined in this survey (a total of 98 events as against 446 dealt with by MacNally, and 1005 in our case). It should be noted that the primary data given by Rayle (Ref. 6) are divided into nine ranges, as a result of which some of them contain very few (less than 10) observations. In order to reduce the effects of random deviations when processing these data we combined adjacent ranges, as a result of which there are only six experimental points on the corresponding curve in fig. 2.6. So as to avoid any misunderstandings it should also be noted that Singer's book (Ref. 2, page 98 - page 66 in english edition) includes a graph, on which the values of a number of observations in the given diameter range are plotted, which are not referred to a range. This graph therefore does not represent the probability density, but instead a histogram of the number of events, the histogram being similar to that in fig. 2.5. This leads to a considerable change in the shape of the curve, in particular to a shift in the maximum into the range of greater dimensions.

The mean values of the diameter of the lightning $\langle \ x \ \rangle$ is determined as

$$\langle x \rangle = \int_{x}^{\infty} x f(x) dx,$$
 (2.8)

where f(x) is the probability density of the distribution according to size, standardized for unit total probability; x is the diameter. The results obtained from determining this value by means of numerical integration are shown in the second column in Table 2.1. The latter also shows the values of the most likely diameter x_{max} , for which the probability density f(x) has a maximum. Although the most likely diameter almost coincides in all three cases, its mean values differ approximately by a factor of 1.5-2, a fact which indicates a noticeable difference in the latitude of probable distributions. The narrowest distribution was obtained in the "Ball Lightning Experiment," whilst the widest was found in the NASA survey. In spite of these differences it can be considered that the results obtained from all three surveys agree satisfactorily with each other. It is to be hoped that unavoidable individual errors on the part

of the observers are compensated fairly well in large statistical samples. (The report contained in Ref. 6 also shows the values of median dimensions, for which half the cases of ball lightning have a smaller diameter. In the case of the data in Ref. 6 this diameter is equal to 35 cm, but 25 cm for MacNally's data and 17.5 cm in the case of the "Ball Lightning Experiment").

The question of an analytical approximation of the distributions obtained now arises. We attempted to use functions of the following form for this purpose

$$f(x) = Ax^n \exp(-x/x_0).$$
 (2.9)

It transpired that the most suitable is a case where n = 1. The constant A is found by standardizing $\int_{-\infty}^{\infty} (x) dx = 1$; as a result we obtain a single formula for describing the results of all three surveys (Ref. 17):

$$f(x) = (x/x^2_0) \exp(-x/x_0).$$
 (2.10)

Parameter x_0 can be determined by plotting on a semi-logarithmic scale the relationship of f(x)/x to x which, in accordance with (2.10), must have the form of a straight line. This has been done in fig. 2.7 (the symbols are the same as those used before). It will be seen from the illustration that all the dots representing the results of observations, with the exception of the first and the last, lie on one straight line with a satisfactory degree of accuracy. Moreover, in all three cases the initial dots, corresponding to fire balls of small diameter (less than 2 and 2.5 cm in the case of the "Ball Lightning Experiment" and for the data in Ref. 5, and less than 5 cm for the data in Ref. 6) lie below the straight line, whilst the final dots, which describe fire balls having a larger diameter are above the line. These differences can be understood if we take into account the fact that observations of fire balls of small diameter are difficult due to their vanishing too quickly. As a rule larger fire balls (of the order of lm and above) are observed at very great distances, thus greatly increasing the likelihood of the size being exaggerated.

From the slope of the curves in fig. 27 we can find the sole distribution parameter (2.10), i.e. x_0 . It is easy to see that the most likely diameter value (i.e. the maximum of f(x)) is $x_{max} = x_0$, and the mean value of the diameter $\langle x \rangle = 2x_0$. The third and fourth columns in Table 2.1 show the values of x_0 obtained in fig. 2.7, and also $\langle x \rangle = 2x_0$. It will be seen that these values agree fairly satisfactorily with their observed values, whilst expression (2.10) approximates the observed distributions of the size of the fire balls with sufficient accuracy.

2.3 Nature of the Movement of Ball Lightning

In spite of the fact that various observers usually do not disagree when determining the trajectory of ball lightning, its movements appear strange and are difficult to describe. The very fact of its free movement in space, the absence of any association with conductors, along which electricity can travel, naturally surprises those witnessing the phenomenon.

Let us first examine the most common characteristics of movement. It follows from the results of our survey obtained on the basis of an analysis of 928 reports that stationary lightning (more precisely lightning covering a distance of less than 1 m) was encountered in 82 cases (9% of the total). The lightning which travelled a distance of from 1 to 10 m accounted for 46.3% of the total (430 cases), i.e. almost one half of the cases observed. This lightning was largely observed inside buildings. However, about 20% of the total number of cases observed (183) involved lightning which travelled a distance of more than 50 m.

Fig. 2.8 shows the standardised probability of the lightning travelling during its life span (strictly speaking during the observation) a distance which does not exceed the value equal to the abscissa of the point. The smooth curve is drawn through the points denoted by hollow dots, which were obtained from 928 observations (the "Ball Lightning Experiment"). Large black dots indicate those points obtained solely from observations in clear weather (134 cases) when the greater part of them were made in the open air. We can see that in the latter case approx. 50% of the cases of lightning occurred when the observation was made at a distance exceeding 50 m. (The crosses denote the results of 155 observations obtained in overcast or rainy weather without thunder-storms; they almost coincide with the first curve). Thus, during its life span, ball lightning can (provided its movement is not restricted by walls in buildings) travel a distance of several dozen and even several hundred metres.

More often than not ball lightning is seen moving horizontally. In our survey this aspect figured in 684 observations, or 75% of the total number of reports containing data on the primary direction of movement. However, it frequently moves downwards (183 observations, i.e. 20%) and only infrequently moves upwards (47 cases, or 5%). In 58 cases (53%) in the NASA survey there is mention of a horizontal movement, in 20 cases (18.5%) vertical movement was involved (unfortunately whether upwards or downwards is not specified) and there was mixed movement in a further 20 cases (18.5%), i.e. both horizontally and vertically.

It frequently happens that a smooth movement is observed (83% of the observations in our survey), rather than uneven movement. The histogram of mean velocities of movement is shown in fig. 2.9, where the number of observations and the proportion they represent of 885 cases examined is shown for each velocity range indicated at the bottom of the columns. The mean velocity was obtained not from estimates by the observers, but by dividing the distance travelled by the lightning by the observation time (this information was contained in the answers to questions in the questionnaire circulated by the journal "Nauka i Zhizn"). It will be seen from the illustration that the vast majority of cases of lightning have a fairly low mean velocity: in 74% of the cases the velocity was less than 2 m/sec. and in 96% it was less than 10 m/sec. Those cases of lightning having a mean velocity of less than 0.1 m/sec., i.e. almost stationary, are also few in number, accounting for approx. 8%. The vast majority of lightning (88%) moves at mean velocities in a range of from 0.1 to 10 m/sec. It is interesting to compare these data with the results of the NASA survey, which revealed not a mean velocity, but a maximum and minimum velocity of the movement of ball lightning. According to these data the maximum velocity proved to be 10 m/sec. in 70% of the observations and less than 30-40 m/sec. in all remaining cases. Thus, statements to the effect that ball lightning can move at a velocity approaching the propagation rate of linear lightning are not

confirmed by statisitcs; the difference between their velocity is 4-5 orders of magnitude.

Thus, ball lightning moves horizontally or falls downwards without acquiring any great velocity. This definitely points to the density of the matter constituting it being almost equal to the density of the ambient air or exceeding it only slightly. Because of this its movement is slightly affected by the force of gravity, namely this fact constitutes one of the reasons for the singularity of these movements: to us they appear just as strange as the movement of objects in a state of weightlessness.

Since the downward movement is observed much more frequently than the movement upward, it is to be expected that the density of the lightning is . nevetheless somewhat greater than the density of the air. Because of this the lightning formed from discharges in the clouds either reaches the ground or stops close to the surface of the ground, where the force of gravity is equalized, and starts to float in the air. The same thing happens with lightning forming close to the surface of the ground, after which it loses the momentum received when being formed. What force equalizes the force of gravity or, more precisely, a small part of it, which is not equalized by Archimedean force? If lightning descends from clouds from sufficient height (300-500 m), this force can again be Archimedean, because the lightning, in so doing, enters denser layers of the atmosphere. Thus, when the height varies by 500 m the density of the air changes by approx. 6% and this can be sufficient for indifferent equilibrium to be established. It is, however, more likely that the small excess of the force of gravity is equalized close to the surface of the Earth by the effects of electric fields. In such cases ball lightning has to carry an electric charge which is of the same sign as that of the surface of the ground. Since the latter is usually positively charged in a thunder-storm, lightning must also have an uncompensated positive charge. After descending, the lightning is in a state of indifferent equilibrium on the equipotential

surface, when it rises and descends above the surface of the ground in a horizontal direction whilst following the contour of the surface. According to eye-witnesses this is what happens when the lightning travels up the slope of a hill, following the relief of the terrain, or when it goes round objects on the surface of the Earth, i.e. houses, tree-tops etc.

In such a suspended state the movement of the lightning depends either on air currents or on small horizontal gradients in the electric field. Therein lies the second cause of its singularity, i.e. "absence of motivation" of the movements. The fact is we do not have organs which would react to the electric field strength. The electric field around us during a thunder-storm can increase by 3-4 orders of magnitude, but nevertheless we are hardly aware of it. Therefore, in everyday life we do not know how the electric fields around us change and, unlike the field of gravity, we are not used to reckoning with them as a possible cause determining the movement of bodies.

It is sometimes stated that ball lightning generally does not sense the movement of air. This is undoubtedly an exaggeration. It is possible to quote many examples when it has moved directly in the direction of the movement of air – both outside and inside of buildings. Let us, for instance, recall a case, described in Chapter 1, where a gust of wind which first opened a door and then slammed it shut, expelled a fire ball out of a building through an aperture in the wall. A pensioner, B.A. Pisarenko, from Eastern Siberia, wrote to us describing a quite fantastic instance where ball lightning was dealt with in an irreverent manner.

In 1915, when still a small boy, he, together with some friends, took refuge from a thunder-storm in a church. After being there a while they noticed a white, luminous ball - the size of a human head - floating at a height of 3 m above the floor. As soon as the ball touched the wall there was a crackling sound and a puff of smoke appeared. The church sidesman, who was also on the spot, did not lose his head, but simply drove the fire ball out of the church

with a broom. Afterwards he, like the other eye-witnesses unfortunately lost all interest in what finally happened to the fire ball.

It is, apparently, more correct to say that ball lightning does not only move under the effects of currents of air. An additional factor determining its movement is an electric field. It is known that ball lightning frequently touches objects, particularly conductors. This can be explained by the fact that, when sufficiently close to an object, it produces in the latter an induced charge. It is possible that this also explains the phenomenon of "guiding", i.e. the movement of ball lightning along a conductor or along any relief feature.

M.T. Dmitriev, for example, reports how ball lightning travelled along a string of rafts running across a river at right angles to the bank (Ref. 18).

Ref. 6 indicates that in approx. 16% of the cases the movement of ball lightning is guided by conductors or other metal objects. In 47% of the cases guiding is observed (we have included in this group cases in which ball lightning simply moves along the surface of the ground). According to Ref. 5 movement along conductors occurred in 20% of the cases. It will be seen from the data that guiding by conductors is not the predominant form of movement of lightning, although it is nevertheless fairly widespread. This process still requires a detailed theoretical explanation. It must be emphasized that, as a rule, guiding occurs without direct contact with a body. Ball lightning moves parallel to a body, whilst remaining some noticeable distance from it, sometimes as much as 2-3 m. Those cases where ball lightning as it were attaches itself to a body or moves along it whilst touching its surface will be examined later on.

A ball lightning charge changes in the course of its movement due to both the exchange with the ambient air and also, to an even greater degree, as a result of colliding with bodies. Because of this the nature of its movement can change unexpectedly. During any variation in the charge the equilibrium of forces is disturbed and the lightning can start to fall or move upwards.

If, in the course of its movement, the lightning completely loses its charge, this still does not mean that an electric field ceases to affect it. At distances equal to the diameter of a fire ball, the difference of the potentials of an electric field arising during a thunder-storm can reach several kilovolts. Under the effects of the field the matter constituting the fire ball will be polarized, so that induced electric charges occur on it. The forces acting on uncharged lightning will move it into an area where the gradients of the potential are less. It is possible that this explains the "stubborn" urge to penetrate closed rooms, even through narrow apertures. After coming into contact with a conductor, a part of the induced charge is neutralized and the lightning thus once again acquires a charge of the same sign.

A number of factors testify to the fact that lightning has a definite mass, although the latter is not great. Let us note that this assumption is not apparent in advance because it permits the lightning to be a self-contained (with regard to exchange between itself and the ambient space) system. From the point of view of the wave theory which regards ball lightning as a focussed electromagnetic wave, it does not make sense to speak of the mass of lightning any more than it does to speak of its energy content. In this case displacement does not mean the movement of heated gas, but instead the displacement of the antinode of a standing electromagnetic wave which heats and ionizes the air at the new location.

In fact, in the movement of ball lightning we are nevertheless probably dealing with the movement of matter. This follows even if only from the fact that at the moment it first occurs and when colliding with objects it can acquire momentum or exchange momentum with surrounding bodies. It suffices to recall that the ball lightning described in the introduction flew in a straight line. The driver of an electric locomotive, L.I. Orlov, reported another case to us.

One night in August 1969 during a thunder-storm accompanied by heavy rain and a wind he saw at a distance of 20-30 m how after a discharge of linear lightning onto the steel support of the overhead power cable a violet coloured luminous ball measuring 10-15 cm across flew out of the point struck and moved in a straight line upwards at great speed at an angle. After travelling about 30 m in a few seconds it disappeared, leaving behind a weak, luminous cloud which quickly dispersed.

It should be noted that this could in no way have been a droplet of molten metal, even if only because, with such a size, it would have weighed between 10 and 40 kg, it would have had to have tremendous momentum and would have moved in a parabola, and not in a straight line. The fact that the ball lightning travelled some distance upwards in a straight line proves not only that its density is close to that of air, but also that it possesses inertia and can acquire momentum under the effects of external forces at the moment when it first occurs.

In conclusion it should be noted that when interpreting the movement of ball lightning we sacrificed the purely objective manner of giving an account, which requires us to confine ourselves to the facts in the interests of a pure description, and not to hold in advance any particular view regarding the nature of ball lightning. It has to be admitted that in the case in question this is a very difficult, almost insurmountable task. The movement of ball lightning is so similar to the movement of a separate body, whose density is approximately equal to that of the ambient air, that to abandon this concept would indeed mean distorting the facts.

It only remains for me to say a few words about the rotation and deformation of ball lightning. According to the results of our survey a rotation of ball lightning was recorded in approximately 30% of the cases observed. The speed of rotation is usually not great and does not have anything in common with those speeds which are assumed in some vortex theories.

The surface of ball lightning can have the form of a solid body (see, for example, description of observation given in Ref. 19), but it is frequently uneven and is constantly deformed. Sometimes this creates the impression of small tongues of fire ("protuberances") or "sparks" being given off. Thus, ball lightning can give off matter from itself and even disintegrate into fragments.

2.4 Estimate of the Energy Contained in Ball Lightning

The energy contained in ball lightning and also the energy flux coming from it are, of course, its most important characteristics. If the lightning does not receive energy from without after its formation, we can speak of a quantity of energy contained in it; on the other hand it is important to know how much energy flows through the lightning during its life span. An estimate of the energy contained in ball lightning can be made from the heating of metal objects, which ball lightning causes; an estimate can also be made from the melting and evaporation of metal. Unfortunately, the reports on these events usually do not contain all the information necessary for making a reliable estimate of the energy. By way of example we can quote the case, described above, where ball lightning moved along a high-voltage line and, after vanishing, heated a section of the conductor to a dark red colour. In spite of the relatively high thermal conductivity ($\simeq 10^{-4}$ m²/sec. for copper), the heat present when the lightning vanished (< l sec.) did not have time to spread any distance. Therefore, the heated section of the conductor must be of the order of magnitude of the radius of the lightning (approx. 10 cm). In order to heat a copper conductor (heat capacity 0.1 cal/ $(g/^{\circ}C)$, density 8 g/cm^{3}) with a diameter of 3 cm and a length of 10 cm to a temperature of 700°C, the conductor must receive approx. 150 kJ. When ball lightning has a diameter of 25 cm, the energy density is thus 18 J/cm^3 .

An interesting case is described by V.V. Lipovetskaya.

Sometime in July or August 1938 after there had been a thunder-storm accompanied by rain, a white fire ball measuring 20-30 cm covered a distance

of 30-50 m vertically. It then exploded in the vicinity of a water pump. The latter consisted of a pipe having a diameter of 5-6 cm and a height of 70-80 cm. After the explosion the pipe was found to be twisted into a loop covered with scale and having the appearance of charred iron, although it had not been made red-hot. All this was observed at a distance of 5 metres.

In order to bend the iron pipe into a loop it was necessary for the section struck by lightning to be heated to a sufficiently high temperature - approximately $600-700\,^{\circ}\text{C}$ (taking into account that there was no glowing). Assuming that the length of the heated section was of the order of the diameter (5 cm), and the wall thickness was 4-5 mm, and allowing for the density (7.8 g/cm³) and heat capacity (0.17 cal/(g/ $^{\circ}\text{C}$) of the iron, we find that the energy content of the lightning was 80-100 kJ. In the case of a diameter of 25 cm this represents an energy density of 10-12 J/cm³.

A student, S.A. Kuznetsov, reported a case he had witnessed in his childhood when a ball of fire with a diameter of approx. 20 cm burnt a 7 cm diameter hole in a metal pipe installed in a factory.

If the thickness of the pipe wall was 0.4-0.5 cm, the energy contained in the lightning must have been approx. 150-200 kJ in order to melt the volume of iron involved.

In the majority of cases ball lightning either melts or evaporates a few grams or fractions of a gram of metal. We shall examine a case described by Ya. V. Berezovskii (see Chapter 1), where a fire ball with a diameter of 10-20 cm evaporated some of the metal in a cleaning rod belonging to a gun. The writer of the letter gave a detailed description of the size of the crater and made special note that there were signs of "spatter" — the metal had evaporated. The crater formed had a diameter of 5 mm and a depth of 3 mm. By taking account of the depression in the form of a paraboloid of revolution, we find that approx. 0.22 g of metal evaporated. The heat capacity of iron is equal to 0.17 cal/(g/°C) in a solid state and 0.2 cal/(g/°C) in a molten state. The

melting and boiling points are equal to 1500 and 2900°C respectively, and the melting heat and the heat of vaporization are 64.4 and 1500 cal/g respectively. As a result it transpires that not less than 2 kJ of heat are required to evaporate 0.22 g of iron. This figure does not represent the entire energy contained in the lightning because, after exploding, it continued to exist, and this made it possible to estimate the lower level of the energy in the lightning.

One case, reported by V.V. Varsonofev and described earlier, involved a fire ball with a diameter of 30-40 cm, which "discharged" into a water heating tank. The writer of the letter notes that a crater measuring 4-5 mm across and approx. 0.5 mm deep appeared on the tank, the metal (approx. 0.08 g of iron) having vanished from the crater. Energy amounting to approx. 700 J is required to evaporate such a quantity of metal.

Given below in brief are a few more reports received by the journal "Nauka i Zhizn".

Lightning with a diameter of 30-50 cm rotated around a post containing wiring for electric lighting.

Lightning measuring 10-15 cm across attached itself to a telephone wire and melted it.

Lightning with a diameter of 25 cm passed along the outside of an IL-14 type aircraft and burnt a number of holes measuring approx. 1-2 cm across (having the size of a thimble) in the fuselage.

Lightning measuring 35-45 cm across exploded near the discharge from a jet engine on an IL-18 type aircraft. There were traces of the metal having melted around the point where the explosion occurred.

Lightning with a diameter of approx. 20 cm appeared out of the socket of a radio set after a linear lightning strike. After touching the partly open door of a stove, the lightning vanished. The edges of the insulator and the socket melted and some of the metal evaporated (unfortunately, the extent of the melting is not mentioned).

As E.I. Bliznyuk reported that in August 1913 a bright white fire ball with a diameter of approx. 20 cm exploded in the boiler-house of a mud-bath establishment in the town of Anapa. This was followed by a large boiler containing sea water for the mud-baths exploding. It is to be assumed that the boiler explosion was caused by the casing being melted as a result of the ball lightning exploding.

In a very large number of cases the explosive or noiseless vanishing of ball lightning after coming into contact with metal objects does not result in their melting, or such cases of melting are so insignificant that eye-witnesses do not even mention them.

Thus, lightning measuring $10-15~\mathrm{cm}$ in diameter "escaped" into the head of an iron bedstead without damaging it.

Lightning measuring 5-10 cm "escaped" into a socket without causing any damage.

There are a number of reports to the effect that small fire balls with a diameter of approx. 5 cm have exploded or "discharged" around electric lamp-holders.

In all these cases the energy transmitted to the metal was, apparently, less than 1 kJ. This, of course, does not mean that the entire initial energy content is exhausted with this value. A considerable part of the energy could be imparted to the ambient air during the life span of the lightning. Moreover, when the explosion occurs some of the energy could be expended to heat the air or it is simply not released when the matter constituting the lighting disintegrates. The estimates described illustrate fairly convincingly that the energy of a "typical" fire ball is confined within limits of from 1 to 100 kJ, whilst the energy density is 1-10 J/cm³.

These results clearly contradict the estimate made by Goodlet, which is repeated in almost all the surveys taken of ball lightning and published during the last forty years (see, for example, Refs. 2, 14 and also 7, in which

the history is given of how the results of this estimate came to be published). As is known, this estimate was based on an outwardly fairly significant case where, according to an eye-witness account, ball lightning "the size of a large orange" struck a small barrel containing 18 litres of water. After being struck, the water "seethed", and some of it - approx. I litre - vanished from the barrel. After assuming that the water had been heated to boiling point and that I litre had evaporated (the latent heat of the evaporation of water at 100° C equals 540 cal(g) we find that the energy imparted to the water is approx. 8 MJ, i.e. something like two orders of magnitude greater than the upper limit obtained from estimates of the melting of metals. If it is assumed that a "large orange" hardly has a diameter of 10 cm, the energy density of the lightning is approx. 15 kJ/cm³, which exceeds by three orders of magnitude the highest energy densities based on the data on melting.

Since the density of the matter constituting lightning is the same as that of air, the number of molecules in 1 cm³ of its matter must also be of the order of 10¹⁹, and at an energy density of 15 kJ/cm³ there will be approx. 10⁴ eV per molecule. This value is three orders of magnitude greater than the ionization potential of any of the known atoms which, in turn, is greater than the bonding energy of chemical compounds. Such energy generally cannot be accumulated in the electron shell because it exceeds the total energy of the bond of all the electrons in the outer shells of light atoms. (The possibility of the energy contained in ball lightning accumulating in nuclear form is extremely unlikely and we shall not be dealing with it.)

Thus, if the Goodlet estimate given above were true, this would unavoidably mean that ball lightning receives energy from an external source. However, it would, nevertheless, remain incomprehensible why an energy flux from without increased in the case in question by several orders of magnitude in comparison with the remaining cases. If energy on such a scale were transmitted during the "discharge" of ball lightning onto a metal object, this would mean

that more than 6 kg of iron or approx. 12 kg of copper would be melted - cases which have never been observed in practice and which cannot be compared in terms of scale with the actual melting caused by ball lightning. Because of these causes we suspect that this estimate is erroneous. In fact, it is not impossible that the "boiling" of the water in the barrel was associated not with the high temperature of the entire mass of the water, but with the formation of bubbles of steam at points where local heat-up occurred (i.e. at those points struck by the matter constituting the lightning) at a low mean water temperature. As far as the missing litre is concerned it may not have evaporated, but simply been spilt onto the ground. It should be noted that the barrel was standing in the street and that any water spilt may not have been noticed. It is true that an eye-witness mentioned how the water was still hot to touch several minutes afterwards. However, these sensations could have been exaggerated, since the actual temperature of the water was not measured.

Let us note that one of the letters received by the journal "Nauka i Zhizn" contained the following.

Between eleven o'clock and noon on a day in June 1962 a thunder-storm broke out over the settlement of Lazovsk in the Moldavian SSR. During the storm an orange fire ball measuring 5-8 cm across flew in through an open door from the street. The fire ball moved downwards at an angle of 45° and, after travelling 3-4 m in 1-3 seconds, it fell into a pail more than half filled with water. Some of the water spilled over the rim because of the violent splash. An eye-witness stated that the water did not become any warmer.

This case was reported to us by V.A. Kuprikova who witnessed the event whilst in the room, into which the lightning penetrated. The colour and size of the fire ball more or less agreed with the case described by Goodlet. This means that there are very serious grounds for doubting the accuracy of a widely used estimate, according to which ball lightning can transmit energy of approx. 10^4 kJ to bodies in its vicinity.

Another method of assessing the order of magnitude of the energy contained in lightning involves investigating the results of its exploding. Observations of a case of ball lightning usually end either with it disappearing from the observer's field of vision or it vanishes in one of the following ways: explosion, disintegration into fragments, quiet extinction. It was found in 413 cases out of 1023, i.e. approx. 40%, that ball lightning disappeared out of the observer's field of vision. Of the remaining 610 cases, 335 terminated in an explosion, 78 in disintegration, and 197 in quite extinction. It must, of course, be borne in mind that the boundary between a weak explosion and disintegration or extinction is arbitrary to some considerable degree, although the sound, usually fairly loud, accompanying an explosion enables us to refer to it in any case. Thus, according to the data received in our survey, lightning explodes in approx. 55% of the cases, disintegrates in 13% and becomes extinguished in 32% of them.

It is reported in Rayle's survey that in 70% of the cases (70 events) the observers saw the end of the existence of a fire ball. This more or less agrees with our data. However, they described only 24 of these events (i.e. approx. 30%) as an explosion, whilst the remainder were described as ending in "quiet extinction". In MacNally's survey 112 (26%) of the 421 cases were classed as slow disintegration, and 309 (74%) involved sudden disintegration. No indication is given regarding the classification of cases where the lightning disappeared from the observer's field of vision. Thus, the difference in terminology, in particular the insufficiently clear determination of the concept "explosion", makes it difficult to compare the data.

In the description of 335 cases involving an explosion, data on which was received by the journal "Nauka i Zhizn", the greater part of which occurred inside rooms, observable effects (excluding cases of melting not always associated with an explosion) were recorded in 34 events only. More often than not this involved splintering of trees or wooden poles (19 cases).

There was a report to the effect that the explosion of a ball of fire destroyed a lightly built week-end bungalow, whilst another case involved the destruction of a transformer booth. In yet another case ball lightning measuring 10-20 cm in diameter caused a crater measuring 2 m in asphalt after exploding near the surface of the ground. A doctor of technical sciences, S.V. Zemblinov, reported that ball lightning measuring 10-15 cm in diameter, glowing like a 100 watt bulb, scattered a pile of stones when it exploded. Three reports have been received which describe how ball lightning penetrated lightly constructed walls or partitions.

The remaining reports speak of less serious damage.

For instance, pieces of porcelain were broken off when ball lightning measuring approx. 50 cm in diameter exploded near a string of insulators on a pole carrying a transmission line. In another case the explosion of a fire ball in a room broke a television aerial stand.

A reserve officer, V.P. Shilnikov, reported how numerous small craters having a diameter of from 5 to 20 mm and a depth of 3-10 mm appeared in the wall of a slag stone house when lightning exploded in its vicinity. A birchwood board above the wall was splintered. The craters in the wall were apparently caused by the material melting at those points struck by the matter constituting the lightning. According to the writer of the same letter a stroke of linear lightning during a storm on 14 July 1974 struck a week-end bungalow, which is surrounded by a garden, breaking a metal stove standing in the latter. When this occurred a small fire ball measuring 5-10 cm in diameter was formed, which flew out onto the verandah (this was witnessed by the owner of the house, N.M. Gavrilov, who was there at the time). After going round someone on the verandah the fire ball rolled across the threshold and down the steps into the street where it exploded. The writer of the letter describing this was nearby and was soon on the scene. He and the owner of the house established the following: 1) a number of panes of glass lying near the wall of the house in the vicinity of the steps were broken; 2) signs of scorching similar to traces

left by arc-welding were found on the bottom of an iron tank intended for water and installed 2 m from the house at a height of 2 m above the ground; 3) two holes measuring about 6 cm across and 2 cm deep were formed in the wall of the house which was covered on the inside with soft cardboard. We shall not dwell on the damage inside the house which was, apparently, associated with a linear lightning strike. It is interesting to note one detail reported by the owner of the house. The ball lightning first struck the panes of glass causing a loud crash, after which it exploded with an equally loud report.

Thus, an explosion (as eye-witnesses have frequently indicated) does not always result in the destruction of a fire ball. Apparently the blast wave can throw ball lightning to one side, after which it still remains intact. Let us quote yet another example of such an event which is also interesting because a case is described where ball lightning penetrated the wall of a house.

A.S. Goloperov, an agriculture worker, relates how some people working in a market garden in July 1936 sought shelter from the rain during a thunderstorm in an old, adobe (i.e. clay block) house in which the office was located. The writer of the letter reporting the incident was in the house at the time. Between twenty-five and thirty people were sitting in the only room in the house on forms arranged along the walls; the doors into the passage and from there into the roadway outside were open. There was suddenly a loud crash and all those present saw how a bright orange ball measuring approx. 10 cm in diameter flew out of the wall in a straight line to a stove opposite. An aperture with roughly the same diameter as the fire ball was left in the clay wall at the point from which the lightning appeared. The lightning travelled in a straight line over a distance of 3-3.5 m in 1-1.5 secs and disappeared into the stove. This was followed by a loud crash in the attic. The stove remainded intact, although a crack appeared in it, but the stove pipe in the attic was destroyed together with 2-2.5m² of tiled roof around the pipe. The person who had been

sitting in the immediate vicinity of that point in the wall where the lightning emerged lay unconscious for 20-30 minutes. He was taken to hospital and was not discharged until three days later. The two people sitting to the right and left of him suffered no harm.

Another letter reports how ball lightning, which had flown out of a telephone hand-set, punched a hole with a diameter of 20 cm in a light, ply-wood partition into a neighbouring room and, after leaving holes in two ply-wood doors, reached the exterior of the building.

However, in the vast majority of cases the effects of ball lightning exploding are insignificant: a broken pane of glass in the case of an explosion near a window, a blackened wall, and a burnt floor. More often than not there is no mention of the effects.

By way of example we can quote a case where ball lightning measuring 20-30 cm in diameter exploded at a distance of less than 5 m from a human. The explosion caused this person to feel a slight wave of air. In another case lightning measuring 15-20 cm in diameter exploded above a table after coming into contact with the metal suspension for a paraffin lamp. Four people were sitting at the table and the lightning was about 0.5 m away from them. There was no report of anyone being injured.

An economist, V.N. Anosov, writes that during a thunder-storm accompanied by heavy rain in July 1952 he felt a sharp blow to the head as he entered a room, causing him to lose consciousness. Other people who were sitting in the room told him later that, at the same time as the heavy clap of thunder occurred, a fire ball measuring 5-7 cm flew out of the lamp socket and fell on his head where it exploded. It transpired that linear lightning had struck electrical wires outside the building. After suffering from concussion he had headaches for two weeks afterwards. As will be seen, the case is very similar to that involving Rikhmanovski, but with a happy ending.

By taking into account that the explosion occurred almost side by side with the person affected, we can definitely say that the force of the explosion was not great.

Because we do not have a truly definite idea of its mechanism it is very difficult to estimate the energy released during an explosion. Let us first turn to those explosions, whose effects were considerable. As was mentioned above, these mostly involved splintered trees or split poles. We shall see below that the matter constituting ball lightning is frequently "drawn into" fissures or porous objects (probably under the effects of electric fields). As a result it is possible to assume that ball lightning can be easily drawn into the pores in timber where, under the changed conditions of heat exchange, it starts to rapidly release heat, resulting in an explosion. If the tree contains a sufficient quantity of water, the latter, by being heated and evaporating, increases the pressure in the pores and this can lead to splintering of the tree (usually along the grain). We shall examine the possible mechanisms involved in splitting. One of them was put forward by Zimmermann (Ref. 20) when estimating the energy of ball lightning observed by Covington (Ref. 21). In a note in the journal "Nature", Covington reports how ball lightning, which had struck a moring post protruding out of the water, split the post along the grain into thin slivers.

We shall designate the strength limit of the wood p_0 . By using the equation of state of an ideal gas we find that in order to produce a pressure p_0 it is necessary to evaporate

$$\mu = p_0 V/(RT) \tag{2.11}$$

gram-molecule of water. For this purpose it is necessary to impart to the water in the pores of the wood a quantity of heat equal to

$$Q = \mu q = \frac{p_{\bullet}V}{RT} q, \qquad (2.12)$$

where q = 46.6 kJ is the quantity of heat which is required for heating and evaporating I g-mole of water from 20 to 100° C (the latent heat of evaporation at the boiling point is assumed to equal 540 cal/g). The volume V occupied by the steam in a layer with thickness h and base radius r is equal to

$$V = \alpha \pi r^2 h, \tag{2.13}$$

where α is the proportion of the volume of the wood occupied by the pores. Let us note that in Zimmermann's calculation, apart from the numerical error, which he permitted when making the calculations, there is no porosity coefficient α . This implies a tacit assumption to the effect that the entire volume of the wood can be filled with water vapour, an assumption which is, of course, incorrect. In fact, the volume of the pores in the wood amounts to a small proportion of its total volume. This value can be estimated on the basis of the reduction in the density of the wood during drying, or the quantity of liquid which can be forced under pressure into the wood, for instance when impregnating it with various solutions. Such estimates yield $\alpha \approx 0.1$.

Thus, the quantity of heat which has to be transmitted to the wood sufficient to cause cracking along the grain is equal to

$$Q = 46,6 \frac{\rho_{,\pi}r^{2}h}{RT} \alpha (kJ) \qquad (2.14)$$

The stress at which the wood fibres break lies, for the various kinds of wood, between 2,000 and $10,000 \text{ n/cm}^2$ (200-1000 atm) (Ref. 22). Unfortunately, however, the value of p_0 , which corresponds to cracking along the grain, is not given in any works of reference. It is natural to expect that this value is lower by an order of magnitude at least. The thickness of the layer of wood

h, into which the matter constituting the ball lightning penetrates, must be of an order of magnitude of the radius of the lightning. The radius of a log, r, is assumed to equal 25 cm. By assuming h = 10 cm, $p_0 = 30-40$ atm and T = 380°K (the boiling point of water), we find that

$$Q = 90 \div 120 \quad (k\mathcal{T}) \tag{2.15}$$

In the case of lightning with a diameter of 20-25 cm this gives an energy density of approx. $10-15 \text{ J/cm}^3$.

The calculation given above corresponds to a case where the pores in the wood contain a small amount of water in terms of volume: approx. 40-50 g at a total pore volume in the layer of wood under examination of about 2 litres. Thus, the pores are considered almost empty. In the case of the post standing in the water, or a living tree, the other extreme case when almost all the pores in the wood are filled with water is more likely. Moreover, by being drawn in through a small number of free pores into the inside of the wood and by releasing its energy there, the matter constituting the lightning rapidly heats the water contained in the pores. As a result the pressure within the wood increases sharply and this can lead to splitting. This mechanism is examined in Ref. 17.

By differentiating the equation of state

$$dV = (\partial V / \partial P)_T dP + (\partial V / \partial T)_B dT$$

and assuming dV = 0, we find that

$$\left(\frac{dp}{dT}\right)_{V} = -\frac{(1/V)\left(\frac{\partial V}{\partial T}\right)_{P}}{(1/V)\left(\frac{\partial V}{\partial \rho}\right)_{T}}.$$
 (2.16)

The coefficient of the volumetric expansion of water $(1/V) \times (\partial V/\partial T)p$ at a temperature of 20-40°C is equal to $3 \times 10^{-4} (°K)^{-1}$ (Ref. 23), whilst the compressibility coefficient of water in the same temperature range at a pressure

of 1-100 atm is 4.5×10^{-5} (atm)⁻¹ (Ref. 23), whence it follows that dp/dT = 6.6 atm/°K. The quantity of water in the pores is equal to $\alpha \pi r^2 hp$ (ρ is the density of the water). This water has to be heated to a temperature of p_0 (dp/dT)_V, for which it is necessary to impart to the water a quantity of heat equal to

$$Q = \alpha \pi r^2 h \rho c_p \frac{\rho_u}{(d \, p/dT)_V}, \qquad (2.17)$$

where c_p is the heat capacity of the water. It is easy to see that, when the water is heated by 6-10° the pressure in the pores increases to 40-70 atm and this, apparently, is sufficient for the wood to fracture along the grain. For this purpose, when r=25 cm, h=10 cm, $\alpha=0.1$, it is necessary to impart 50-80 kJ to the water, which corresponds to an energy density of 6-10 J/cm³ (the lightning having a radius of R=25 cm). These results are in accordance with the estimates for melting. Both estimates give an upper limit for the energy necessary for splitting a tree, because it is assumed in these estimates that—the matter constituting lightning is distributed uniformly over the entire volume of the layer under consideration. This might lead to fracturing into thin fibres. In fact, more often than not the trees split at one point and, consequently, it is to be expected that the heat is released in a considerably lower volume. Moreover, the values, obtained above, for the necessary energy release must decrease considerably.

As was already mentioned above, in the vast majority of cases the effect of ball lightning exploding is insignificant. Consequently, we should not draw too hasty conclusions about the energy of ball lightning. The fact is that ball lightning does not have a firm shell and is probably a weakly connected agglomeration of matter. Therefore, even during the earliest stages of the explosion the matter can fly apart and become diffused in the atmosphere without releasing any internal energy contained in it. That is

probably the reason why the explosion of ball lightning usually produces a loud report (often compared with that of a rifle or pistol), although there are frequently no other effects.

It can, therefore, happen that no more than a few percent of the lightning's energy is released when the explosion occurs in a free space. (A completely different situation arises in the case of poles, trees or other object being split, when the matter constituting the lightning is drawn into pores or cracks before the explosion takes place). Even in this case Goodlet's estimate appears to be highly exaggerated. In fact, according to this estimate, 1% of the energy amounts to approx. 100 eV per particle, a figure which corresponds to the heating of the matter in the volume of the lightning to a temperature of approx. 1 million degrees. The release of such energy would be accompanied by a flash greatly exceeding in brightness the linear lightning channel and comparable with the brightness of a nuclear explosion. Eye-witnesses do not report anything of this nature.

Lightning measuring 20 cm across has a volume of approx. 500 cm^3 and contains about 0.5×10^{22} of molecules if its density corresponds to the density of gas at a temperature of $500-700^{\circ}\text{K}$. The release of 3-4 kJ of energy during an explosion can heat such a quantity of matter to a temperature of a few thousand degrees (with allowance for radiation losses). If this energy amounts to 5-10% of the entire energy of ball lightning, the latter can be equal to several dozen kilojoules. Thus, the energy of ball lightning must be within a range of several units to several hundred kilojoules, whilst the energy density is $1-10 \text{ J/cm}^3$ respectively.

2.5 Radiation and colour of ball lightning

Impressions of the colour of ball lightning are, of course, of a more subjective nature than data on its size, shape and trajectory. Nevertheless we find here as well satisfactory agreement between the descriptions given. The difficulties involved are not solely due to various people retaining varying impressions of the colour of one and the same object. The fact is that a fire ball can possess a variety of colours and shades. The situation is similar to that arising when describing the nature of movement. It is often difficult to attribute one particular colour to ball lightning. All the colours in the rainbow frequently occur in descriptions of it. In other cases mention is made of shades which are at opposite ends of the spectrum, e.g. reddish-blue, bluishorange etc. A change in colour with time is observed in a few cases, if not many. For instance, in a case described in Chapter 1, where a group of tourists observed a fire ball, its colour varied during the observation time from white to dark red. Moreover, various parts of the lightning can have a different colour. Eye-witnesses very often speak of ball lightning having a halo and a nucleus, which can vary greatly in colour. The case described by M.T. Dmitriev (Ref. 18) can be quoted as one example.

Nevertheless the vast majority of people writing to us mentioned one particular colour in the spectrum. Table 2.2 shows the results obtained. In those cases where there was mention of mixed colours relating to adjacent regions of the spectrum, for instance red-orange and yellow-green, we referred the colour alternately first to one region of the spectrum, and then to the other. MacNally's and Rayle's data are given in the same table. The former include a total of 216 observations, because there was no mention of the colour in 202 cases. Moreover, two colours were noted in 57 cases, and three colours in 28 cases (the actual colours were not mentioned). On the other hand, Rayle's survey (Ref. 6) resulted in the following: 152 replies involving 109 observations (in three cases there was no mention of the colour), because all

two-colour shades appeared in both columns. Since it was not possible to reproduce the initial material we standardized the distribution according to colours for 152 cases. Finally, the last two columns were taken from Charmen's article (Ref. 10).

Red, orange, yellow, white and pale blue are the most common colours in all the cases mentioned. It is worth noting that green is almost completely absent: it amounted to no more than 1.3% in our survey, and 1.4% in MacNally's. In surveys based on a smaller number of events the proportion of green is slightly greater, although still not high: 6.6% in Rayle's survey, and 4.4% in Charmen's. If we draw a boundary between adjacent colours in the spectrum, for instance red and orange or orange and yellow, it is more convenient to compare the results by arranging the colours in three groups. We shall include red, orange and yellow in the group for the red end of the spectrum, green, pale blue, darker blue and violet in the second group, and white in the third group. In this case we obtain the result given in Table 2.3. The results now agree fairly well with each other. White lightning accounts for 20-25%. The red end of the spectrum includes the vast majority - 60% in all three groups, and from 12 to 20% is accounted for by the blue end of the spectrum. It follows from this that, although the lightning at the blue end of the spectrum is also the least widespread group of all, it does, nevertheless, represent an appreciable proportion. There is, therefore, no reason to agree with the opinion expressed by Barry (Ref. 14) to the effect that both pale blue and darker blue lightning are taken only erroneously for ball lightning. We shall see below that, even in terms of a number of other properties, lightning of this colour does not differ from the remaining colours.

Among the remaining replies, given in Table 2.2, to our survey we received reports of 26 cases of a "mat" colour and four cases involving grey.

The question regarding burns left by ball lightning merits special examination. As a rule these burns occur when lightning comes into direct contact with an object and they can be caused either by chemical reaction with the matter constituting the lightning, or by ultraviolet radiation from the latter. Such short-wave ultraviolet radiation can also explain the occurrence of a halo around the lightning. It is possible that this halo is the result of the air molecules absorbing this radiation and luminescing. It is reported in the letters received by us that ball lightning had, on occasions, "burned someone's trousers", "burned someone's neck and singed their hair", "left a burnt stripe on a table", "burned a hole in a carpet" etc.

Data on the physiological effects of ball lightning are very conflicting. We have received not a few letters, from which it follows that ball lightning can seriously injure or kill humans.

Our post-bag included letters giving accounts of five cases involving fatalities. In one of them, however, someone was killed with a fragment of flying glass, which resulted from ball lightning exploding, and which entered the victim's heart. In another case lightning struck someone riding on a motor-cycle pillion. Ball lightning has sometimes caused serious injuries. It has caused a burn in the form of a red stripe, another in the form of the letter Z on someone's back etc. The effects of lightning sometimes caused a slight fainting fit, and there are cases on record where the victim spent some days or even weeks in hospital. In one case the patient was in a pre-infarct state with pains in the heart and burns on the chest, and a pattern resembling blood vessels was formed on the body. Ball lightning caused a thirteen year old to suffer from a burn running from her neck to the middle of her back. A number of letters speak of cases involving the death of animals (sheep and horses) caused by ball lightning.

But sometimes even direct contact with lightning did not have any serious effects.

On one occasion a fire ball, which penetrated a house, rolled off a table, fell onto the knee of someone sitting at the table, rolled down their calves and disappeared into the floor. This left a red, contusion type mark on the leg, although there was no sensation of pain. In another case ball lightning struck someone on the legs, but did not cause any burns or leave any marks. There is also an account of ball lightning measuring 10-15 cm across striking someone on the shoulder and disintegrating without leaving any burns. One letter describes how ball lightning with a diameter of 5 cm, which travelled downwards, struck someone sitting at a table on the right arm above the wrist, then fell to the ground and disappeared. The point struck was painful for two weeks, but there was no mention of burns. Likewise there was no sensation similar to that involving an electric shock. All the observer felt was a blow of the same strength as if he had been struck with a stick, although the lightning travelled downwards only slowly. In conclusion we would like to recall an account given by Dr. V.A. Latunna, which we also mentioned in Chapter I. The burn described by her was caused by a splash of the matter constituting the lightning striking the victim directly (and not indirectly by the air being heated by this splash of matter).

The brightness of the light from ball lightning is considerably less than the brightness of a linear lightning channel. Its brightness is usually compared with that of an electric light bulb having a wattage of from 10-20 to 100-200 W. Of the 110 eye-witnesses participating in the NASA survey (Ref. 6), only 12, or approx. 11%, consider that ball lightning is as bright as linear lightning (it is possible that these observers had in mind the brightness of the explosion). Twenty-three people, i.e. 21%, stated that the ball lightning had been bright enough to illuminate surrounding objects. The majority however (66 reports, i.e. 60% of the total number) state that the ball lightning had been bright enough to be visible in daylight. Finally, nine people (8.2%) consider that it had been hardly visible in daylight.

The most surprising aspect of ball lightning is not that it emits light, but that, although it emits light, it emits hardly any heat.

By way of example we can refer to the sighting made by V.V. Varsonovyev (see Chapter 1). He was sitting on a chair, under which a fire ball rolled. For a moment his feet had been surrounded by a luminous, vapour-like mass, but he received no burns and did not sense any heat.

It has long been known that only a small percentage of observers report a sensation of heat coming from ball lightning. It is interesting to estimate just how many people witnessing ball lightning sufficiently close to them sensed heat. This question was answered in the affirmative by thirty-five of the people writing to the journal "Nauka i Zhizn". Of these, fourteen had been at a distance of less than l m, fifteen at a distance of l-5 m, whilst the remainder had been more than 5 m away from the ball lightning observed. Leaving aside the last group of replies, since the sensation of heat at such a distance could arise only as a result of the senses being deceived, we shall focus our attention on the first two groups. In 158 cases the lightning was observed at a distance of less than 1 m, the emitted heat being sensed by only 9% of the observers. Observations at a distance of up to 5 m accounted for one half of the cases, i.e. approx. 500 sitings, and the proportion of observers being aware of heat decreased to 6%. This means that the majority of the eye-witenesses in this group saw the lightning at a distance of 1 m, rather than 5 m. According to Rayle, only four of the eye-witnesses mentioned any awareness of heat, as against 100 who did not. Unfortunately, we have no evidence in writing regarding the distance from the points where the eye-witnesses were standing to the actual lightning. It was mentioned earlier that the distribution of cases of lightning according to distance from the sitings selected by Rayle was approximately the same as in our data. It can then be expected that approx. 15-20% of the observers, i.e. 20-25 people, witnessed the lightning at a distance of approx. 1 m or less. If the four people mentioned above are included in the

group numbering 20-25, the figure then amounts to 15-20%. In summing up it can be said that approx. only 10% of the observers witnessing the lightning at close range (≈ 1 m and less) sensed heat from it.

These data testify convincingly to the fact that the temperature of ball lightning cannot be high. Not only is any mention of 10-15 thousand degrees, quoted sometimes by authors of reports (Refs. 2, 18), out of the question, but a temperature in excess of 1000°K can also be ruled out. Objects with which the lightning comes into close contact do not as a rule suffer damage and this fact indicates that its surface temperature is relatively low. In order to avoid any misunderstanding it should be noted that the majority of cases involving the melting or evaporation of metal occur during explosions, which we shall not be examining at this point.

One interesting feature of ball lightning is its transparency established in the work described in Refs. 24 and 25. At 9.30 in the evening on 9 July 1958 during a thunder-storm an interesting photograph was taken at the Karabad meteorological station in the Gurev region by V.M. Deryugin of the path of a fire ball caused by lightning, a report on which, together with the photograph, was published considerably later in the journal "Priroda" (Nature) (Ref. 26). As will be seen from the photograph, the intensity of the radiation from the lightning changed considerably in the course of its movement. On one of the sections the path is missing altogether. Ref. 24 gives the results of the photometric measurement of the path of the lightning on the photograph taken by M.T. Dmitriev and G.A. Kalinkevich. The change in the degree of blackening of the film both along the path and in three of its cross-sections was examined. Here we shall be interested solely in the results of photometric measurement of the cross-section. Fig. 2.10 shows that results of these measurements taken from Ref. 25. The hollow dots, squares and triangles represent the relative intensity of luminescence, obtained in three cross-sections, at the point in question in the path.

If the visible light emitted by ball lightning were absorbed by the matter constituting the latter, the distribution of the intensity of luminescence and of the degree of blackening in the cross-section would be represented by the dashed line in fig. 2.10. In an opposite case, where the light leaves the inside of the lightning freely, the degree of blackening must gradually decrease as the distance from the centre of the path increases in proportion (in the absence of any non-uniformity) to the length of the chord lying on the trajectory of the ray in ball lightning. In this case the intensity of luminescence must vary according to the law represented in the illustration by a solid line. It can be seen that the test points lie along this line with a satisfactory degree of accuracy; this indicates that ball lightning is transparent where visible light is concerned. Hence an important conclusion can be drawn regarding the fact that there cannot be a large quantity of free electrons in the lightning and, apparently, the latter cannot have a high temperature. One argument against the matter constituting the lightning having a high temperature is also its weight: if the temperature of ball lightning were to reach a few thousand degrees, it would be considerably lighter, not heavier than the ambient air.

We cannot help noting, however, that a number of causes makes it difficult for heat from ball lightning to be removed to the ambient air. The main cause resides in the matter constituting the lightning not mixing with the ambient air. On the strength of a number of factors, which will be discussed later, the matter constituting ball lightning does not mix with the medium in which it finds itself. Moreover, convection, as a rule, is a considerably more effective method of heat transfer than is thermal conductivity. Heat from combustion products is transmitted to surrounding objects more easily than can be expected in the case of ball lightning.

The main channel for the transfer of heat from lightning to the ambient air must be thermal infra-red radiation. If it is assumed that, in the infra-red region of the spectrum, lightning emits as a black body, the balance of energy from ball lightning is determined by the following equation

$$(4/3)\pi R^3 \omega = 4\pi R^2 \sigma T^4 \tau, \qquad (2.18)$$

where w is the energy density of ball lightning; \mathcal{T} is its life span; $\mathcal{S} = 5.7 \times 10^{12} \; \text{W/(cm}^2/\,^{\circ}\text{K})^4$ is the Stefan-Boltzmann constant. This equation determines the temperature of the lightning

$$T = (\omega R / 3\tau \sigma)^{1/4}$$
. (2.19)

In the case of lightning of average size R \approx 10 cm, assuming that w \approx 5J/cm³, we find that when $10\lesssim \tau \lesssim$ 50 sec. the temperature is in the range

According to Wien's law the maximum of the spectral density at a temperature of 600° K relates to a wave-length of 5 μ m, and approx. 70% of the energy radiated is contained within a wave-length range of from 2 to 10 μ m.

The total energy flux from ball lightning in the case of the typical parameter values adopted above and when $\mathcal{C}\approx 25$ sec is approx. 0.8 kW. At a distance of 1 m this gives approx. 60 W/m², which may explain the absence of any awareness of heat on the part of eye-witnesses at such a distance. Let us note that an increase in the temperature of ball lightning to $1000-1100\,^{\circ}\text{K}$ increases the radiation flux from it by an order of magnitude, which would make a sensation of heat unavoidable at a distance of approx. 1 m or even more. In view of the fact that the extinction of lightning, resulting in de-excitation of the energy, is not the only cause of its disappearing (more than two thirds of

fire balls vanish due to an explosion and disintegration), the life span would decrease to an even greater degree. This clearly conflicts with the results of the observations. A reduction in temperature to below 500°K greatly reduces the thermal flux and results in only an insignificant part of the energy contained in the lightning being able to escape during the life span of the fire ball. In such a case it would be difficult to understand the correlation between the size and life span of ball lightning, an aspect which will be examined at the end of this chapter.

It can be thought that a considerable part of the heat emitted by infrared radiation falls in the absorption bands and is retained close to the fire ball in a thin layer of moist air. The solution to the heat conductivity equation is

$$\frac{1}{r^2} \frac{d}{dr} \left(r^2 \lambda \frac{dT}{dr} \right) = 0, \quad T(r) = \frac{Q_T}{4\pi\lambda} \frac{1}{r} + T_{\infty}, \quad (2.20)$$

where Q_T is the heat flux; T_∞ is the temperature of cold air at considerable distances from the lightning. When $r \approx R$ we obtain from (2.20)

$$Q_T = hS(T - T_{\infty}), \qquad (2.21)$$

where T = T (r = R) is the air temperature at the interface with the ball lightning; S = $4\pi R^2$; h = λ/R is the convective heat transfer. By assuming the heat conductivity coefficient of the air to be $5 \times 10^{-2} \text{W/(m x °K)}$ (this more or less corresponds to a temperature of 600°K), we find, when R = 10 cm, T ≈ 600 °C, $T_{\infty} = 300$ °K, that the heat flux removed by thermal conductivity is small (approx. 20 W) in comparison with the heat emitted by radiation. This confirms the justification of ignoring the heat flux due to thermal conductivity when calculating the heat radiated by ball lightning.

However, convective flows and turbulent heat conductivity occur outside the confines of ball lightning, in the heated air. Under these conditions the convective heat transfer coefficient h_c increases by more than an order of magnitude. After assuming in (2.21) that $h = h_{\uparrow} \approx 10\text{--}20 \text{ W/(m}^2/\text{°K})$, we find that the heat flux removed by convection must be of the order of 400-800 W, a value which more or less corresponds with the energy emitted through the surface of ball lightning by radiation. Moreover, the thickness of the heated layer of air proves to be small, i.e. less than the radius of the fire ball.

The radiation power of ball lightning in the visible and ultra-violet regions amounts to a few watts because its luminous flux corresponds in the case in question to the luminous flux of an ordinary 100 W electric light bulb. The power of this radiation in the total energy balance of the lightning is not significant, although it exceeds by several times its equilibrium value in the temperature range being examined.

There are also facts indicating that ball lightning is a fairly intensive source of radio-frequency radiation.

For instance, this is what M.T. Dmitriev writes in the journal "Priroda" (Ref. 18). The event described occurred on 23 August 1965 around eight o'clock in the evening on the river Onega in the Archangel district. The eyewitness was in a tent on the bank of the river. There was a loud crack in a radio set, which had been working properly up to that moment, accompanied by a close clap of thunder. The lightning, as it transpired, struck the river bank 70 m from the tent. This is how the author of the article describes the events which followed. "For a few seconds all remained quiet, then a rustling sound started, which grew louder and louder, finally reaching a humming noise. It became necessary to switch the radio off, but a hissing sound, accompanied by sharp crackling, now came from the direction of the river." Upon looking out of the tent Mr. Dmitriev saw, above the river, a fire ball, which was moving slowly towards the tent.

Analysing data on forty-five cases of ball lightning collected by him and described in Ref. 26, Mr. Dmitriev reports that, in six cases, ball lightning affected radio reception.

The post-bag of the journal "Nauka i Zhizn" also included accounts of a number of cases where interference to radio reception caused by ball lightning was recorded. We have not taken account of reports, according to which the occurrence of ball lightning caused fuses to melt and damaged telephone, electrical and radio equipment. It should be borne in mind that these effects produced during a thunder-storm could have been caused by ordinary linear lightning discharged not far from the point where the ball lightning occurred.

Information on actual radio interference is given in three letters, one of which reports that the loudspeaker started crackling when the ball lightning disappeared. Another letter mentioned that a deafening report was heard on a telephone when a fire ball exploded at a distance of 40-50 m. However, the most interesting report was received from V.I. Stepanov who lives in Leningrad.

In July 1965 he was working in the settlement of Itat in the Komarovo district of the Krasnoyar region. A thunder-storm was blowing up and he went into the office housed in a trailer, in order to use the telephone. As he started to dial the number a crackling sound, which grew louder and louder, was audible on the telephone. This was followed by a pale yellow fire ball measuring 8-10 cm across entering through the open door of the office. The lightning moved horizontally along the walls of the room at a distance of 20-30 cm, curving smoothly inside the corners. One other person was in the room at the time. A diagram of the room sent by the eye-witness, showing the trajectory of the ball lightning is given in fig. 2.11. We can now leave it to Mr. Stepanov to tell what happened. "When the ball lightning entered the room the crackling noise on the telephone became deafening and reached its maximum

when the fire ball was closest to the telephone. The lightning moved all around the trailer, following the walls at a height of 1 m from the floor, and left by the same door, through which it had entered. Moreover, the crackling noise on the telephone continued for some minutes before gradually dying away. Silence was thus restored."

The quite clear correlation of the noise level as the distance to the ball lightning varies, as reported in this letter, shows convincingly that ball lightning was, in fact, the cause of radio interference. The radio-frequency radiation of lightning must be of an essentially non-equilibrium nature, since the intensity of black body radiation in the radio frequency range when $T\approx 600\,^{\circ}\text{C} \text{ is very small.}$

2.6 Surface tension of the matter constituting ball lightning

The spherical shape of lightning already indicates that the matter constituting it has surface tension. However, the most striking proof of this resides in the fact that ball lightning can pass through narrow apertures whose width is considerably less than the diameter of the lightning. Moreover, after passing through such an aperture the shape of the lightning is restored. This characteristic of ball lightning is mentioned in both past as well as more recent surveys (Ref. 2). Rayle's survey (Ref. 6) mentions twenty-four cases where ball lightning passed through narrow apertures, such cases accounting for approx. 24% of the total number of observations. Neither our survey, nor that conducted by MacNally contained a special question about lightning passing through fissures or narrow apertures. Nevertheless we also received descriptions of such events in at least 31 letters. One or two examples are given below in brief.

A teacher, N.G. Gornostayeva, writes that during a thunder-storm sometime in 1949 a fire ball measuring 20-30 cm across, which appeared after a sharp clap of thunder, entered a room through an aperture in the wall intended for an earth wire.

Another teacher, S.B. Sergieva, saw how during a thunder-storm sometime in 1943 ball lightning measuring 10 cm across passed through a 1 cm gap in a window frame and emerged "sausage shaped".

N.K. Kulishova related how ball lightning witnessed by her during a thunder-storm in June 1951 entered and departed through a crack in a window pane. The fire ball had a diameter of 10-20 cm.

In June 1956 during a thunder-storm an engineer, R.Sh. Akhmerov, observed how ball lightning measuring 30-50 cm across entered in the form of a "yellow thread" through a small hole (1-1.5 cm wide) in a window pane (the corner of which was missing). After describing several circles around the room the fire ball exploded some 20 or 30 seconds later.

Another engineer, R.S. Kozlov, reports that some time in 1968-69 ball lightning measuring 5-10 cm across "entered like a snake" through a partially open push-out window during a thunder-storm, after which it formed a fire ball. After travelling a distance of 5-10 m through the room in 20-30 seconds the fire ball disappeared near the light switch without exploding.

I.I. Tsarev from Vladivostok writes that during a heavy thunder-storm in 1962 ball lightning measuring 15-20 cm entered the house through a gap between planks near the chimney. The plank affected was blackened and a fire started.

In 1966 a mechanic, J.F. Yaroshenko, from the town of Toliatti .
witnessed how ball lightning measuring 10-20 cm across passed through an 8 mm opening in the window.

An electrical engineer, N.B. Tyurina, reports how ball lightning "the size of a tennis ball" passed through a closed window, a pane in which had a crack.

We cannot list here all the cases, and for the sake of brevity we are not reporting all the data on ball lightning given in the letters, from which we have quoted excerpts. We shall only note that, in other respects, lightning which had passed through apertures and fissures did not differ in its characteristics and behaviour from other fire balls caused by lightning. Some letters contain a fairly detailed description of the actual process of such passages through windows etc.

For instance, Yu. M. Agarkov witnessed at a distance of 15-20 cm how a yellow ball the size of a large orange passed through a fissure in a wall. He defined it as "having, more precisely, flowed through the aperture".

K.K. Poters from Nizhneudinsk in Siberia saw how ball lightning entered a room through an opening in the window after flattening itself, its size being larger than that of the hole. This is what he writes: "The fire

ball was only 10-15 cm from our faces and we plainly saw how it started to pass through the aperture, taking on the form of a musk melon. The fire ball became elongated, its diameter less, and it passed through. As it was passing through the aperture the fire ball became smaller and seemed to quiver all the time, and it appeared to consist of a gelatine-like substance. Blue rays some 1.5 cm long came from its surface and bursts of sparks were to be seen at the ends of the rays".

Thus, it is not the middle of lightning, which is small in diameter, which penetrates a fissure, as is sometimes assumed, but instead the entire matter constituting the lightning gradually flows into a fissure. The reason why lightning is forced to pass through narrow apertures, especially through fissures, can, it appears, be sought solely in electric fields, and this confirms yet again that electric fields play an important part in the movement of lightning. The persistent urge on the part of lightning to restore its shape is also found when it disintegrates into fragments, which again become spherical. This can also be confirmed by some actual data obtained by us.

Naturally, the question arises as to why the shape of the lightning in some cases is not spherical. An elongated form or the shape of a pear is frequently mentioned in such cases. Pear-shaped lightning can occur when its surface tension is too small and the capillary constant is of an order of magnitude of the radius of the lightning. It should be remembered that the magnitude (2.22) is referred to as the capillary constant (Ref. 27, p. 285)

$$a = \sqrt{2\sigma/(g|\rho - \rho_{\rm o}|)}, \qquad (2.22)$$

which has the dimension of the length; σ = surface tension coefficient; σ = free fall acceleration, ρ and ρ = density of the matter constituting the lightning and of the air. When σ R a droplet of such matter in the air

will be spherical (R is the radius of the ball), but when $\alpha \approx R$ the lightning must be pear-shaped with a widening towards the bottom. As was already noted above, analysis shows that $|\rho - \rho_0| \ll \rho_0$. By assuming that $|\rho - \rho_0| \ll \rho_0 \approx 10^{-4} \, \text{g/cm}^3$ we obtain, when $\alpha \approx R \approx 10$ cm, an estimate of the surface tension, $\delta = 5 \, \text{erg/cm}^2$.

In the majority of cases the velocities of ball lightning are too low to explain the occurrence of elongated, ellipsoidal ball lightning by its movement. Moreover, it follows from the observations that ball lightning frequently becomes extended in a direction other than that in which it is moving. For instance, M.T. Dmitriev (Ref. 18) notes that the ball lightning (more precisely its middle part, which is surrounded by a pale blue halo) was a sphere extended along the vertical diameter, the sphere moving horizontally at a low speed. A number of other eye-witnesses also report the elongation of lightning along the vertical diameter. This elongation is occasionally fairly considerable, but in the majority of cases it is small. A sufficiently natural explanation of this deformation is provided by the polarization of the matter constituting the lightning in an electric field, as a result of which charges of the opposite sign, produced by induction, are accumulated at opposing ends of the lightning.

This results in the lightning being deformed, and since an electric field on the surface of the Earth is generally directed vertically, deformation must occur more often that not in that direction.

The most weighty proof that ball lightning is a gaseous medium stems, of course, from observations of the nature of its movement, which indicate that its density is approximately equal to that of air. However, it transpires that lightning has not only been the object of observations, but also of experiments.

V.A. Bobrin, a lecturer from Khabarovsk, encountered ball lightning one evening in July 1954 before a thunder-storm when he was going hunting. The white fire ball measuring 20-25 cm in diameter was moving horizontally, following the relief contour of the terrain. When it was passing at a distance of 15 m he fired at it with his shot-gun. This had no real effect; all the fire ball did was to waver slighly. Within approx. 40 seconds the lightning had passed out of the observer's field of vision, having travelled some 40 m. The pellets thus pased through the matter constituting the lightning without imparting to it any noticeable momentum.

It is known that ordinary gases, whose molecules interact only in the case of collisions, do not possess surface tension. However, a plasma whose particles are connected by long-range Coulomb forces, behaves differently. Spherical plasma formations frequently occur in experiments involving a gas discharge (see, for example, Refs. 28, 29, 30 (p. 290) and 31). These formations were (and still are) frequently adopted erroneously for laboratory models of ball lightning. In actual fact any similarity here is purely external, since the plasma spheres disappear when the discharge ceases and are observed only in the fairly narrow inter-electrode spaces. Nevertheless, the fact that a plasma can assume stable, spherical shapes and, apparently, possesses surface energy remains without doubt. Let us also add that other media consisting of charged particles, for instance liquid metals and electrolytes, also have an anomalous, high surface tension. Thus, the surface tension coefficient of metals is equal to 500-1000 erg/cm², whereas it is $10-20 \text{ erg/cm}^2$ for organic liquids (Refs. 23, 32). In spite of the fact that water, as a polar liquid, has a relatively high ϕ value (pprox 80 erg/cm²), the surface tension coefficient of strong electrolytes is greater than that of pure water, and increases as the concentration of the electrolyte is increased.

Let us dwell once more on an interesting characteristic of ball lightning, to which no attention has been paid in known surveys, but which contrasts sharply with the behaviour of ordinary gases. We are speaking of the stability of lightning when it moves. It is a well known fact that when two fluids or gases are moving in relationship to each other the so-called Kelvin-Helmholtz instability occurs (Ref. 33, p. 96). This leads to a rapid blurring of the boundary on which a break in the tangetial (i.e. tangential to the boundary) velocity component occurs, and to the two gases mixing with each other. Waves on the surface of a body of water are one of the cases where such instability manifests itself. If the densities of the media involved . differ very considerably one from the other, the instability becomes stabilized by the force of gravity and the process is confined to the choppiness of the surface waves. However, if the densities on either side of the boundary are of the same order of magnitude, these media must mix with each other due to the development of the instability, the mixing rate being some orders of magnitude higher than the molecular diffusion rate. This would have to result in ball lightning vanishing rapidly - within fractions of a second. However, ball lightning can exist for dozens of seconds and cover distances intact, which exceed the radius of the fire ball by thousands of times.

The surface tension leads to stabilization of short-wave perturbations occurring during the development of this instability. In the case of a plane interface we find that the boundary of the wave stability with wave number k is determined by the condition (Ref. 27, p. 295)

 $u < \sqrt{2 \sigma k / \rho},$ (2.23)

where μ is the velocity of movement; the density of two adjoining media can be assumed to be identical and equal to $\rho \approx 1.3 \times 10^{-3} \text{ g/cm}^2$ (allowance for the small difference in densities leads to small corrections to formula (2.23) in the case in question). Since, on the surface of the ball, the maximum wave-length is of the order of R, the minimum k value is of the order of $2\pi/R$. By assuming that R = 5-10 cm and the velocity is $u \approx 1$ m/sec, we find that, in order to stabilize the waves occurring on the surface of ball lightning, a surface tension of $\delta \approx 10$ erg/cm² is required, a value which coincides in terms of the order of magnitude with the estimate obtained above. It is impossible to claim better coincidence in view of the very approximate nature of such an estimate, and also the use of a formula applicable solely to a plane interface.

Another instability which also develops on the interface of two media is referred to as convective instability or the Rayleigh-Taylor instability. It develops in the gravitational field when a denser medium is above a less dense one. Such instability can be stabilized by surface tension. This question will be examined in greater detail in the last chapter of this book. For the present we shall only note that, in order to stabilize the convective instability, approximately the same surface tension is required $(0 \approx 1-10)$ erg/cm²). Moreover, an examination of this instability shows that the density of the matter constituting ball lightning must, in fact, differ only very slightly from the density of the surrounding medium, especially for fire balls with a large radius (R \approx 50 cm). In cases to the contrary the development of convective instability must lead to the unavoidable disintegration of lightning and to the matter constituting it becoming mixed with the air.

Surface tension indicates that the matter constituting the ball lightning will form in the air a separate phase differing from the gas surrounding it. Such a possibility was recently referred to (Ref. 34). At the end of its existence, ball lightning, which is filled with products

resulting from its matter disintegrating and with air diffused into the lightning, is transformed into a cluster of droplets, thereby losing its clear outline and shape. This causes eye-witnesses to speak of a "puff of vapour or splashes". The same can occur at the outset, i.e. before the formation of ball lightning (see Section 4.6). However, during the major part of its life span ball lightning has a fairly clearly defined boundary which can, apparently, be regarded as a phase boundary.

Let us note in conclusion that the movement of lightning along conductors involving its coming into contact with them (a fact which is sometimes reported by eye-witnesses) is, possibly, also associated with surface tension forces arising under such circumstances on the boundary with the metal and finally resulting in a reduction in the surface energy at the point where this contact occurs.

2.7 The origin of ball lightning

First of all it is interesting to establish whether ball lightning occurs when linear lightning is discharged or whether it occurs independently of this. According to the account by MacNally, almost all cases of ball lightning in the Oak Ridge Survey (Ref. 5) occurred after a linear lightning strike (376 cases out of 444, i.e. approx. 85%). According to the NASA survey (Ref. 6), ball lighting occurred after a linear lightning strike in 73% of the cases (62 cases after discharge to the earth, and 7 after discharge between clouds, from a total number of 95 events, for which a reply had been received to this particular question). Our questionnaire did not contain a special question as to Whether the occurrence of ball lightning was preceded by a . discharge of linear lightning. Nevertheless, it follows from the letters received that it was so in at least 25% of the cases. It should be noted that the occurrence of ball lightning not associated with a specific lightning strike does not refute the assumption that ball lightning is nevertheless associated with linear lightning. Ball lightning can travel a considerable distance from the point where it first occurs. In particular ball lightning can occur during discharges in clouds, after which it can descend to earth.

According to the results obtained from our survey, cases where the observer witnessed how ball lightning actually arose are fairly rare (151 answers in the affirmative from 1060 cases observed) and account for approx. only 14% of the observations. An essentially definite result was obtained in the NASA survey. There, in 48 cases out of 112, the observers stated that they had witnessed how the ball lightning had arisen. The Oak Ridge questionnaire did not include a question on this point.

It is difficult to say what the explanation is for such a difference. It is possible that this is due to a different interpretation of the terms "origin". Some of the letters show that an answer in the affirmative is sometimes given to this question by people who, in actual fact, witnessed not

the process of the ball lightning arising, but instead a process by which the lightning appeared in a room or in the observer's field of vision. Therefore, we shall nevertheless consider that an observation of how ball lightning comes into being is a fairly rare occurrence (in comparison with a simple observation of ball lightning).

Unfortunately, a considerable proportion of the letters answering this question in the affirmative do not contain any further observations. In all we received a total of 67 letters, in which the process involving the origin of the ball lightning observed is described more or less in full. Approximately half of them (31 letters) state that ball lightning occurs in the immediate vicinity of a linear lightning channel. In the other half (29 letters) the eye-witnesses report that they saw how lightning arose out of various metal objects and instruments: radio sets, electrical plugs, telephone hand-sets, aerials etc. Finally, a further seven letters describe the sudden occurrence of lightning "as if out of nothing", "occurring in thin air" etc.

Since the conditions involving the observation of a linear lightning channel are more difficult than those where the observation concerns ordinary metal objects, an identical number of letters does not necessarily mean an identical frequency of occurrence. Therefore, let us first examine a case where ball lightning arises out of (or close to) the discharge channel of linear lightning. It is sometimes stated that ball lightning arises at a point where the channel branches.

Thus, U.G. Isatulov describes how an oak tree, which he was passing in a horse-drawn cart, was struck "from two sides" by lightning. This was followed by a bright red ball measuring 50-70 cm across travelling down the tree and then rolling down the slope of a hill. The horses (unlike the untroubled cows in New Zealand, described in Chapter 1) reared up on their hind legs and pulled in different directions. The lightning occurred at a distance of 70-100 m from the observer and disappeared within 5-10 seconds after rolling down the hill. This took place in daylight in May 1926.

A student of chemistry, A.Yu. Sazanov, witnessed how three bright white fire balls detached themselves from the middle of a linear lightning channel and started to descend slowly. Their diameter was estimated as being 30-50 cm, and the distance to them as in excess of 100 m.

In a number of cases the observations of how ball lightning actually arose were made at fairly close range: 20-30 m and less.

In 1953 P.F. Grishchenkov from the town of Murom witnessed at a distance of approx 10 m how a bright yellow fire ball measuring 30-40 cm across sprang out of the ground at a point struck by linear lightning. After rising to a height of 6-8 m the lightning started to move horizontally. During this time it pulsated, acquiring first a spherical shape, and then an ellipsoidal one. After covering 50-70 m in 1-1.5 minutes it collided with a fir tree and exploded.

One incident, described earlier and reported by L.I. Orlov, involved ball lightning which occurred after linear lightning had struck a transmission line support.

At the end of May 1950 a teacher, V.I. Balina, witnessed at a distance of 30 m how a bright mauve luminous ball measuring 30-40 cm across bounced down a hill after linear lightning had struck a poplar tree. The fire ball disappeared from the observer's field of vision after 30-40 seconds.

A worker at the Volga Automobile Works (in the town of Toliatti),

A.M. Polistruyev, was approaching his house when he saw how linear lightning
struck a tree a short distance away. At that very moment he saw an elongated
luminous object which, after splitting into two spheres, quickly fell to the
ground. This was followed by one of them penetrating a room where it exploded
after "going round" the corner of a divan.

A very detailed description of the occurrence of ball lightning was sent to us by a high-school teacher, A.S. Timoshuk, from the town of Gatchina. This occurred one morning in April 1946 in the town of Belaya Tserkov in the Kiev district. At a distance of 20-30 m he saw from a window how linear lightning struck conductor wires not far from the pole supporting them. was followed by a yellowish-green "flash" and then burning on a conductor near the pole. The flash gave rise to a fire ball measuring approx 15 cm across, which started to roll slowly along the sagging conductor, gathering momentum as it did. The fire ball gradually became red. After travelling the $4-5~\mathrm{m}$ to the point of maximum sag it dropped onto the lower conductor and then rolled a further half metre before falling onto the branches of a poplar tree close by. There was a loud report accompanied by flying sparks and a number of small fire balls (a little larger than a tennis ball) rolled along the branches of the poplar. For a moment or so the fire ball itself was hidden by the small branches, but it then appeared once more near one of the lower branches; by then its diameter had decreased considerably. The fire ball fell onto the road, showering sparks around, and then started to bounce along the road like a ball, jumping up 10-15 cm as it did. After a few bounds it disintegrated into fragments, which immediately became extinguished. All this took place within the space of 10-20 seconds and was observed by someone else as well.

Another interesting incident was described by N.D. Trushaev, an engineer, from Sebastopol. During daylight on 16 May 1938 the writer of the letter witnessed how, after linear lightning had struck a ploughed field, spurts of flame seemed to run across the field, and he had the impression that the ground had "caught fire". Within 3-5 seconds the "spurts" of flame had gathered into a clump, forming a white fire ball measuring 50-70 cm in diameter. The fire ball detached itself from the furrows, rose to a height of 2 m above the surface of the ground and started to move horizontally. The surface

of the fire ball seemed to seethe and appeared to be "shaggy", the shaggy appendages being longer on one side than on the other. The fire ball moved towards the wall of a court-yard, running alongside the ploughed land, near which the writer of the letter was standing, together with his father. When it was within 1.5-2 m of the wall the fire ball changed direction sharply, at an angle of 90° , after which it changed direction yet again before coming into contact with a pile of straw which it set on fire. This incident was witnessed by two people (the writer of the letter and his father). It continued for 30-50 seconds. During this time the minimum distance to the lightning was less than 5 m, and the total distance travelled by it was about 400 m.

Let us note an interesting case from the point of view of the cluster theory (see Chapter 4) where ball lightning was formed when linear lightning struck a body of water. I.A. Gulidov from Kharkov described what happened.

One day in July 1963 during a thunder-storm accompanied by rain in the hours of daylight a lake was struck by linear lightning. A fire ball flew out of the water at the point struck. It had a diameter of 10-20 cm and was orange in colour. After reaching a height of 30-50 cm it started to move horizontally, rising and falling above the surface of the water. After travelling 20-30 m in 10-20 seconds it dropped onto the water and disappeared with a loud noise, forming a vapour cloud as it did. This event was observed by two people standing on the bank (at a distance of 50-70 m).

We shall now examine the second group of replies, according to which ball lightning arose out of (or close to) metal objects. Let it be noted first of all that errors were possible in a number of cases. The fact is that, as was mentioned above, ball lightning can pentrate rooms through small apertures and cracks whose diameter is several times smaller than the diameter of the lightning itself. It can, therefore, enter a room at that point where an electric wire or aerial is led in, thus creating the illusion of its appearing out of plugs or wires.

In a letter written by I.D. Vologdin we read how ball lightning measuring approx 10 cm across occurring during a thunder-storm travelled along a conductor to the point where it entered a barracks. It was then seen by two eye-witnesses in one of the barrack rooms.

However, the number of sightings associating the occurrence of ball lightning with telephone hand-sets, electrical plugs, aerials etc is too large for all this to be attributed to errors and inaccuracies in the observations. We shall quote some of these.

A.P. Solovei, a pensioner from the town of Brotslava in the Vinnitsa district (Ukraine), relates how lightning measuring 20-30 cm across came out of a telephone hand-set hanging on the wall, passed through two rooms at a height of 1.5 m above the floor and left within 6-7 seconds via a push-out window. The letter includes a diagram of the rooms, the path of movement of the lightning, and also the positions where people in the room were located. This occurred in 1940 (Ref. 9).

In 1943 N.V. Martynov, a meteorologist, observed how ball lightning measuring 10 cm across flew out of the casing of a telephone hanging on the wall, from which the cover was also removed. This happened after a discharge of linear lightning. The fire ball rolled across the floor and exploded with a loud report, waking up a number of people sleeping in the room, none of whom suffered any harm.

V.V. Mosharov reports in his letter that ball lightning occurred after linear lightning had struck the television aerial.

Yu. V. Kolganov from the town of Kolomna (in the Moscow district)
reports that ball lightning occurred around a panel with a meter and instruments
when a discharge of linear lightning occurred.

A few letters contain accounts of cases where small fire balls (approx. 5 cm in diameter) have flown out of an empty bulb socket in an electric lamp. There are reports to the effect that ball lightning can appear out of electrical and radio sockets, an aerial wire, a loudspeaker etc.

Thus, one of the people writing in, I.V. Mochalov, described in detail an incident which occurred in daylight in August 1956 in the town of Nizhny Tagil in the Sverdlovsk district. During a thunder-storm he noticed how a pale blue ball the size of a pea appeared on the handle of a tap belonging to a water heater. The ball swelled up "like a soap bubble". The ball started to glow more brightly and, after reaching 4-5 cm in diameter and detaching itself from the tap, it passed under a table without touching the floor. It stopped near a pile of nails lying on a chair (sparks were flying out of the ball), rebounded upwards, and once more floated under the table where it burst with a report ("like that of a pistol shot") and vanished. All this was observed at a distance of 1-2 m by the writer of the letter and his two children for about one minute. Attached to the letter was a diagram showing the positions of people and objects in the room, as well as the path followed by the lightning (Ref. 9).

In conclusion let us dwell in brief on those relatively few occasions when ball lightning arose as it were "out of nothing".

For instance, one of the letters describes how ball lightning suddenly appeared a few metres from the observer "as if someone had switched on an electric torch". The fire ball then started to drop. Another letter describes how in May 1975 after a thunder-storm a small fire ball mesuring 5-10 cm across suddenly appeared above the road near a trolley-bus stop and then slowly came lower. The fire ball appeared to be semi-transpareent and emitted a pale blue light. For 5-10 seconds the fire ball was hidden from view by the bus shelter, after which it vanished. Similar cases involving the sudden appearance of ball lightning (it should be noted that the author of the last letter answered in the affirmative the question about whether the lightning had been seen to actually form) can be explained by its descending after being formed during the discharge of lightning in clouds. In such cases the lightning suddenly appears in the observer's field of vision, attracting his or her attention and creating the impression that the lightning arose "out of thin

air".

In summing up we are, unfortunately, faced with accepting that we still cannot definitely indicate just how and under what conditions ball lightning arises. It is apparent that the discharge of linear lightning is a necessary condition for its occurrence. Ball lightning frequently occurs in the immediate vicinity of a linear lightning channel or near a spot struck by linear lightning. In the event of ball lightning forming near conductors or equipment, the energy necessary for its creation can be transmitted along conductors over some considerable distance from the point struck by ordinary lightning. It is also interesting to note that, as will be seen from the descriptions given above, a time of the order of one second is required for the formation of ball lightning, and this is long in comparison with the duration of a discharge of linear lightning. We shall have the opportunity of again returning to this question in the final chapter of this book.

2.8 Correlation of the properties of ball lightning and their variation in time

An examination of the results obtained from the NASA survey did not reveal any appreciable correlation in the groups or types of ball lightning as regards properties, nor any change in these properties with time in keeping with the laws governing them. In particular, no systematic changes in the properties of the lightning were found, for instance in the colour or degree of luminescence at the end of the life span of a fire ball. If this is actually so, it would be a serious argument against a certain reserve of energy being accumulated in the lightning at the moment when it first arises. A similar conclusion was also drawn by Rayle (Ref. 6), who considers that this argument is in favour of the theories which assume that ball lightning receives energy from without. It should be noted that such an assumption is justified only if ball lightning does in fact disintegrate due to a lack of energy, and not for any other reasons, for instance, because of instability. Moreover, the data contained in the replies to the NASA survey is too limited - not more than 112 observations - to make it possible to establish sufficiently reliable correlations between the properties, or a change in these properties in time.

In some surveys, particularly that conducted by Barry (Ref. 14), which was based on extremely non-uniform historical material, we find confirmation of numerous correlations, which, however, are far from always being supported by factual data. In other replies we find reference, for instance, to ball lightning not being pale or dark blue, and statements that some phenonomena with this colour taken for ball lightning are in fact St. Elmo's fire. As was already mentioned, the blue end of the spectrum is, in fact, encountered in the observations considerably less often than the red end and, for this reason, it was natural to first verify this statement with the aid of data obtained by us.

In terms of colour all cases of ball lightning were divided into three groups: the first group covers white lightning, the second red, orange and yellow, which, in the interests of brevity we shall call "red", and the third group covers "pale blue" lightning, which includes green, dark blue, pale blue and violet. It should be noted that the pale blue lightning predominates in the last named group, since, as will be seen from Table 2.2, green, dark blue and violet did not account for more than 30% of this group. The distribution in terms of life span and size in each group was examined. In order to reduce the rôle of random deviations, three groups of diameters were distinguished: 0-10 cm, 10-30 cm, and over 30 cm, together with three ranges of life span: 0-10seconds, 10-50 seconds, and over 50 seconds. Tables 2.4 - 2.5 show the results characterising the distribution of lightning according to these groups. The upper figure indicates the number of cases of lightning in the corresponding group, and the low figure indicates the proportion it represents of the total number of cases of white, red or pale blue lighting. The figure in brackets indicates the probable random deviations \sqrt{n}/n (in percentages), where n is the average number of events constituting the group indicated. The last column gives (for purposes of comparison) the results of the distribution of diameters or life spans for the same groups. These results were obtained from an overall histogram including all cases of lightning (see figs 2.5 and 2.1).

The bottom line shows the total number of cases which refer to the cases of lightning in the group in question. Naturally, the total number of cases of white, red and pale blue lightning was somewhat less in the total than the total number of cases of lightning given in the last column, because not all the questionnaires seeking data on the size and life span included a question about the colour as well. It will be seen from the tables that there is a slightly higher proportion of cases of white ball lightning with a brief life span (48% of white fire balls survive for less than 10 seconds as compared with

42% in the remaining groups). Small diameters are encountered somewhat less frequently among cases of red lightning than in the remaining groups (20% of fire balls have a diameter of less than 10 cm as compared with 25% of white ones and 30% of pale blue ones). On the other hand, a small diameter is encountered somewhat more often than usual among pale blue fire balls. Medium size ball lightning (10-30 cm) represents a somewhat smaller proportion of blue lightning (47% as against approx. 55% in the remaining groups). The deviations, on which all the assumptions quoted are based, lie on the boundary of permissible errors, and for this reasons it is generally possible to drawn a conclusion about there being no appreciable differences in the distribution in terms of the size and life span of lightning of different colour. There is no reason to make a distinction, as Barry does, regarding pale blue lightning, considering it to differ somehow in nature from the remaining colours. This is also indicated by the distribution of this lightning according to the distances the lightning travels during the observation. Moreover, the proportion of cases of "fixed" pale blue lightning also does not differ appreciably from that for the remainder. In the case of St. Elmo's fire it would be natural to expect an increase in this proportion.

We have already had the opportunity of seeing that a noticeable number observations were not associated with a thunder-storm. These included 130 cases where the lightning occurred in clear weather. There were also 150 observations where the eye-witnesses stated that there was no thunder-storm at the time, although the weather was overcast and rain was possibly falling. Although these cases amount to a relatively small proportion (approx 25%) of the observations, their number is nevertheless great enough to make a statistical examination of their properties worthwhile. Fig. 2.8 gives data on the distances travelled by the lightning in this group during the observation time. Small crosses indicate the proportion of cases of lightning travelling a given (or shorter) distance (corresponding to the abscissa of the points) in the case of observations in

overcast weather without a thunder-storm, and the black dots indicate the corresponding value for lightning in clear weather. It can be seen from the illustration that the first group of observations does not differ from the average results obtained for all the observations (hollow dots), although ball lightning occurring in clear weather travels considerably greater distances than ball lightning occurring under other circumstances. Thus, approximately one half of these fire balls travel a distance in excess of 50 m; a distance of less than 10 m (which corresponds approximately to the cases involving observations in rooms) is travelled not by 55%, but by no more than about 30% of fire balls. It can be thought that such a difference is a natural result of the difference in the observation conditions: in clear weather ball lightning is much more frequently observed outside rooms, where it covers considerable distances.

Let us now turn our attention to some other properties of lightning observed. Table 2.6 gives data on the colour of lightning, all the colours in the spectrum again being divided into three groups: white, red (red, orange and yellow) and pale blue (green, pale blue, dark blue and violet). The upper figure indicates the number of observations in the corresponding group, and the lower figure represents the percentage of the total number of cases of lightning of a given type indicated by the bottom line in the table. The figures in brackets indicate the limits of random errors inversely proportional to the root of the number of observations in the group in question. For comparison purposes the last column gives data for all the cases of lightning taken from Table 2.3.

It will be seen from Table 2.6 that, among the cases of lightning observed in clear weather, there is a somewhat greater proportion of pale blue lightning (17% as against the usual figure of 12%) and a somewhat smaller proportion of cases of red lightning (54% as against 60%). However, these differences also lie on the boundary of possible random deviations. Lightning in clear weather does not differ in colour from other lightning.

Tables 2.7 and 2.8 give the distributions of lightning according to size and observation time. These distributions are likewise divided into three groups so as to reduce statistical errors. The distribution of the life span of lightning seen in clear weather is the same as for all remaining cases. Among the cases of lightning occurring in clear weather, a considerable proportion consists of fire balls with a long life span (34% instead of 18% for a life span of more than 50 seconds); a considerably smaller proprotion involves short-lived ones (25% as against 42% for a life span of less than 10 seconds).

Both groups, particularly the one observed in clear weather, contains a somewhat greater number of cases of ball lightning with a large diameter (37 and 30% as against 21% on average for a diameter exceeding 30 cm). On the other hand, ball lightning with a diameter of less than 10 cm, which, on average, accounts for 24%, amounts to 12-14% in the groups examined. These deviations are noticeably outside the limits for statistical erros. However, it is not impossible that these deviations are explained simply by the difference in the conditions under which the observations are made. If the lightning occurring in clear weather is more often observed outside buildings at considerable distances, it is natural that the duration of observation is longer and there is a tendency to overestimate the diameter of such fire balls (a luminous object seen at a distance appears larger than it actually is).

In summing up it can be said that there are noticeable differences between fire balls occurring during a thunder-storm and those occurring in clear weather. The latter are considerably larger and are observed over a longer time span. However, these differences are not great enough for an appreciably different nature, as compared with "ordinary" ball lightning, to be attributed to them. The future will show whether these differences are associated only with the observation conditions or whether they testify to ball lightning having a certain difference in origin and properties.

We shall now turn our attention to the question as to whether lightning changes during its life span. Neither our survey nor the Oak Ridge questionnaire included questions about the change in the shape of ball lightning. Such questions were included in the more comprehensive NASA questionnaire. 86% of eye-witnesses writing in stated that the size of ball lightning remained invariable, and approximately as many speak of the absence of any change in the brightness. Approximately 76% of the eye-witnesses describe the lightning as homogeneous. However, some letters we received contained a fairly detailed description of the structure of lightning and changes in its appearance during its life span. It will suffice to recall a description of lightning observed in a forest near Moscow by a party of tourists (see Chapter 1).

Let us quote a further account received by us from A.A. Lenska from the town of Yaroslavl. At two o'clock in the afternoon one day in June 1974 a violent thunder-storm broke out which was accompanied by torrential rain. The ball lightning flew in through an open push-out window of a kitchen on the second floor of a five-storey building. This was a homogeneous yellow fire ball measuring 20 cm across. According to the letter written by an eye-witness: "The ball moved slowly and smoothly in a horizontal line, descending slightly as it travelled about 1 metre. It floated in the air as a body floats in a liquid." The ball was an arm's length away from the eye-witness. The latter stepped back, and left the kitchen, closing the door behind her, but continuing to observe through the glass panel what happened to the fire ball. "Channels", i.e. thin strips directed downwards and having an irregular zig-zag shape, formed within the ball. The matter constituting the lightning became red around the channels. The ball thus because inhomogeneous and started to appear greyish. It then started to disintegrate into fragments, and silently disappeared without falling. The eye-witness then returned to the kitchen immediately, but there was no sign of the ball lightning: neither heat nor droplets of liquid. The observation lasted about 30 seconds.

Another way in which ball lightning came to an end was described by M.T. Dmitriev (Ref. 18). This involved a case which occurred on the river Onega (on 23 August 1965). We have already heard how after a lightning strike above a river a fire ball appeared and made its presence felt by disturbances to reception in a transistor radio set. This fire ball travelled across a string of pontoons on the river to the bank in 30-40 seconds, passing within 3 m of a tent, and then entered a wood. What happened than is described by Dmitriev as follows. "At that moment sparks started to fly out, first on one side, and then on the other. This was accompanined by an additional and more steady crackling sound, turning the whole scene into something very reminiscent of arc welding. This happened six or seven times, with the fire ball rebounding each time in the opposite direction before a fresh burst of sparks was emitted. The colour then changed from white to bright red before the fire ball became extinguished. All this took place within 60-65 seconds.

Judging by the recoil of the fire ball, the "sparks" were small fragments of its matter, which were given off, probably due to increasing instability.

Photographs obtained from photometric measurements of the track of lightning, which was mentioned earlier, also enabled us to detect changes in the state of the lightning with time - periodic ones in this case. The photograh taken by V.M. Deryugin (Ref. 24) even shows that the light intensity of lightning changes periodically and sometimes the luminescence is completely absent. Longitudinal photometric measurements of the track showed the distribution of the extent of blackening along it; this distribution is shown in fig. 2.12. The distance travelled by the lightning from the initial point in the track is plotted along the horizontal axis, its radius (i.e. half the width of the track) being used as a unit of measurement. It will be seen that the light intensity changed dozens of times (its maximum value is taken

arbitrarily as 100, whereas it is equal to 1 for the background in the photograph). Such pronounced changes in the degree of blackening can hardly be attributed solely to the change in the velocity of the lightning; apparently, the light intensity did in fact change periodically. If we assume that the radius of the ball lightning was approx. 10 cm, and the velocity of the lightning lm/sec, the time between consecutive maxima is of the order of 1 sec.

At the beginning of this chapter we saw how, according to the observation time (and, possibly, also according to the law of disintegration), ball lightning can be divided into two groups: short-lived fire balls with a characteristic time of $\widetilde{l_1} = 11$ sec, and long-lived fire balls ($\widetilde{l_2} = 54$ sec). In the entire range of observations made by us, the two groups were represented in almost identical quantities (57% and 43% respectively), whereas short-lived fire balls predominated in the American data. Naturally, in the course of time the ratio between the two groups must change in favour of long-lived fire balls. For this reason it is necessary to examine whether the properties observed in the range of fire balls examined by us vary with time.

If, at a certain moment in time, which we shall assume for each case of ball lightning as the initial moment (this being the point in time when the eye-witness first saw the lightning), 57% of the sightings among the total examined by us involved short-lived fire balls and 43% long-lived ones, then within 20 seconds, as is easy to calculate from their disintegration times \mathcal{T}_1 and \mathcal{T}_2 , the fire balls remaining at that moment will comprise 76% long-lived, and not more than 24% short-lived ones, whilst within 50 seconds only long-lived fire balls (96.5%) will remain. Moreover, of the 1,000 cases of lightning which we had at the initial moment, 380 will still remain after 20 seconds, and 175 after 50 seconds - totals which are large enough for statistical processing.

Let us first examine how the distribution according to colour varies (and whether it varies at all) as the proportion of long-lived lightning in the total number of cases increases. We shall once more divide the lightning into three groups according to colour: white, red (red-yellow) and pale blue (green-violet) and determine what proportion of these groups has a life span of more than 20 seconds and of more than 50 seconds. These results, and also (for comparison purposes) the distribution of all cases of lightning according to groups ($t \ge 0$) are given in Table 2.9.

As in the tables given earlier, each figure against the colour indicates the total number of cases of lightning in each group, and the figure in brackets represents the proportion in the total number of cases of lightning examined in the column in question, and the limits to the possible random deviations from the average value. Let us note that the total number of cases of lightning $t \ge 0$, from which the distribution is compiled (see bottom line in the table) is somewhat less than 1,000, since this table can contain only those cases of lightning for which the colour, in addition to the life span, is indicated. In all, there were 894 cases of such lightning (whereas the total number of cases where the life span is indicated was 980). For an observation time of $t \ge 20$ sec and $t \ge 50$ sec there were 357 and 166 respectively; the total number of cases of lightning, where the observation time exceeded 20-50 sec, was 380 and 175, in full agreement with formula (2.5).

It will be seen from Table 2.9 that, within the limits of statistical errors, the distribution according to colour does not vary, i.e. long-lived lightning does not, an average, vary in terms of colour.

Let us now examine the distribution according to size as shown in Table 2.10.

The first column was obtained from fig 2.5, where the histogram of distribution according to diameters was compiled from 1,005 observations. In

the case in question we find a strong correlation between the type of lightning (i.e. the life span) and its size. The proportion of small sizes (diameter of up to 10 cm) decreases from 25% for all cases of lightning to 15% for lightning with a life span in excess of 20 secs, and to 11% in the case of lightning with a life span of over 50 sec. On the other hand, for larger sizes (\geqslant 30 cm) this proportion increases from 21 ato 33% for t \geqslant 20 secs and reaches 40% when t \geqslant 50 sec.

Considering that by the time t = 50 sec only long-lived lightning remains, and by applying its law of disintegration, it is easy to calculate the assumed number of cases of long-lived lightning at the initial moment in time in each group of sizes. Since the total number of cases of lightning at the initial moment is known in each group, it is also possible to find the total number of cases of lightning with a short life span. The results are given in Table 2.11.

Thus, at the outset, observations of lightning with a short life span amounted to 80% of the cases of ball lightning with a small diameter (up to 10 cm), and only 20% of fire balls with a larger diameter (over 30 cm).

Naturally, the commencement of the observation does not always coincide closely with the moment when the lightning occurs (in the same manner as the end does not always coincide closely with the moment when the lightning ceases to exist), and it can be stated that lightning which is small in size exists on average for a shorter time, and vice versa.

In the calculation just given we applied the exponential law of disintegration derived for all types of lightning as a whole to each separate group of fire balls differing in diameter. The validty of this is, of course, not self-evident, since deviations from this conformity to the relevant laws in one group can be compensated by opposite deviations in another group. In order to prove that this is, in fact, not so, we shall apply the exponential

law with two life spans for the purpose of calculating the number of cases of lightning in each group diameter when t=20 sec, using the initial number of short-lived and long-lived fire balls shown in Table 2.11. The results obtained can be compared with the actual number of fire balls of such a diameter with a life span of $t \ge 20$ sec (Table 2.12).

Thus, a formula of type (2.5) can, apparently, be used when calculating the disintegration of lightning in each size group (if the number of events examined is large enough to counterbalance random deviations).

Let us now return once more to cases of ball lightning observed in clear weather. Does not this lightning belong to the group consisting of long-lived lightning? If this were so, its quantity within 10 seconds should decrease by 17% and not by 24.6% as was the case in reality (see Table 2.8).

Thus, lightning observed in clear weather is not always long-lived.

Table 2.13 shows that statements contradicting this are also true.

In fact, lightning with a life span exceeding 50 seconds almost always falls in the long-lived group, but, as will be seen from Table 2.13, only about 30% of these cases were observed in clear weather. Although this is more noticeable than for all types of lightning (13%), the majority of the "long-lived" lightning - over 50% - occurs during a thunder-storm.

Is there any difference between the end of long-lived and short-lived lightning? When examining lightning observed for more than 50 seconds, we find that a somewhat greater proportion, i.e. 46% (\pm 5%) instead of 40.4% (\pm 2%), in all cases, disappears from the field of vision. This seems perfectly natural, but the increase is not great and lies within the limits of statistical errors. If we examine only lightning whose end is observed by the eye-witness, it transpires that 42% (\pm 7%) of long-lived lightning exploded (in comparison with 54.9% (\pm 3%) of all types of lightning, 19% (\pm 4%) disintegrated (as against 12.8% (\pm 1.4%)) and 39% (\pm 6%) became extinguished (32.3% (\pm 2.3%) for all types of lightning). Thus, all three types of end of the lightning are

typical of long-lived lightning. However, there is a somewhat smaller proportion of explosions and a somewhat greater proportion of disintegrations and extinctions in the case of lightning with a long life span.

It is natural to ask why no traces of any correlation between the life span and the diameter were revealed in the NASA survey (this correlation was not examined in MacNally's survey).

We have already seen at the beginning of the chapter that this survey contains only short-lived lightning with a disintegration time of 13 seconds, whilst long-lived lightning, which amounted to approx. 14% in the more extensive survey conducted by MacNally, is almost absent. That is probably the reason why Rayle's survey did not reveal any correlation betwen the size and life span of ball lightning.

2.9 Results obtained from processing observations

In summing up our current knowledge of the properties of ball lightning we cannot help feeling a little disappointed. It appears at a first glance that statistical questionnaires addressed to the population did not yield anything new in comparison with what people already knew about lightning in Arago's time. A luminous ball measuring 10-20 cm across, existing for approx. 10 seconds and moving along an odd sort of trajectory was, in essence, known more than one hundred years ago. However, the fact is that information obtained from isolated, random observations is very unreliable. It is necessary to gather a considerable quantity of statistics for this information to be actually regarded as scientifically substantiated data. There are now such statistics, at least for such readily perceptible properties as the shape, size and, perhaps, the life span.

Let us formulate those basic properties of ball lightning which have been established in this chapter.

The number of fire balls (N(E)) distintegrating during observation time t is determined by the following expression:

$$N(t) = N_0 [1 - \alpha_1 \exp(-t/\tau_1) - \alpha_2 \exp(-t/\tau_2)],$$
 (2.24)

where $\alpha_1 + \alpha_2 = 1$, $\mathcal{T}_1 = 5 - 10$ sec, $\mathcal{T}_2 \approx 50$ sec, N_0 is the number of fire balls at the beginning of the observation ($\ell = 0$). The proportions of short-lived (α_1) and long-lived (α_2) lightning at the commencement of the observation varies in different statistical samples. They more or less coincide ($\alpha_1 = 0.57$, $\alpha_2 = 0.43$) in the case of the data obtained by the journal "Nauka i Zhizn". Short-lived lightning predominated in surveys conducted in the USA ($\alpha_1 \simeq 0.86$ in the Oak Ridge survey (Ref. 5), and $\alpha_1 = 1$ in the NASA survey (Ref. 6).

2. The most probable diameter of ball lightning is equal to 10-15 cm, whilst the average is 20-30 cm. The distribution of the dimensions of ball lightning is described by formula

$$f(x) = (x/x^2_0) \exp(-x/x_0), \qquad (2.25)$$

where f(x) is the probability density of an observation of ball lightning with diameter x; $x_0 = 11$ cm in the case of data obtained by the journal "Nauka i Zhizn" and $x_0=16$ cm in the case of the Oak Ridge survey.

- 3. The density of the matter constituting ball lightning almost coincides with the density of air and normally exceeds it only slightly, i.e. it amounts to (1-2) 10^{-3} g/cm³.
- 4. The temperature of ball lightning probably lies in the $500-700^{\circ}$ K range (not including the moment when a fire ball explodes).
- 5. Ball lightning carries a considerable <u>electrical charge</u> and the movement of the lightning under indifferent equilibrium conditions, when the force of gravity is balanced by an Archimedian force, is determined by electric fields (and the movement of air).
- The reserve of energy in ball lightning ranges from a few kilojoules to a few dozen kilojoules, and in some cases (especially where large fire balls are concerned) it is possible for the reserve of energy to reach a value of the order of several hundred kilojoules. The energy density is $1-10 \text{ J/cm}^3$.
- 7. The matter constituting the lightning has considerable <u>surface tension</u>
 (1-10 erg/cm²). The small departures from a spherical shape are probably caused by polarization in an external electric field.

- 8. A well pronounced correlation between the life span and size of the lightning is observed. Long-lived lightning (\mathcal{T}_2 = 50 sec) is, in the main, large (according to the data received by the journal "Nauka i Zhizn" it amounts to 80% in cases of fire balls having a diameter exceeding 30 cm and only 20% among fire balls with a diameter of less than 10 cm). On the other hand, short-lived lightning ($\mathcal{T}_1 \approx 10$ sec) is of small diameter (80% of fire balls have a diameter of less than 10 cm, and 20% have a diameter of more than 30 cm). Further investigations will show whether the division of short-lived and long-lived lightning is associated with the observation conditions or with the nature of the lightning itself.
- 9. Lightning diappears as a result of an explosion ($\approx 55\%$ according to data obtained by the journal "Nauka i Zhizn") or due to the development of instabilities leading to the scattering of matter ($\approx 13\%$) and also because of an insufficient reserve of energy accumulated within the lightning (quiet extinction accounts for the end of 32% of the fire balls).
- 10. The majority of fire balls (approx 60%) emit visible light at the red end of the spectrum (red, orange or yellow). Approximately 15% emit light in the short-wave, pale blue region of the spectrum (pale blue, more rarely dark blue, violet and green). Finally, the lightning is white in approx. 25% of the cases. The power of light emitted is of the order of a few watts. Since the temperature of the lightning is not high, its visible radiation is of a non-equilibrium nature. It is possible that the lightning also emits a certain quantity of ultraviolet radiation, the absorption of which may explain the pale blue halo around the lightning.
- The heat-exchange between lightning and the surrounding atmosphere takes place via the emission of a considerable quantity of infrared radiation. At a temperature of 600°K the power of the equilibrium thermal radiation for fire balls of average diameter (≈ 20 cm) is of the order of 1 kW, and the maximum of the radiation lies in the $\lambda \simeq 5-10~\mu m$ range. These estimates agree with the radius and life span of the lightning.

12. In addition to infrared, visible and ultraviolet radiation, ball lightning is probably also a source of fairly strong non-equilibrium radio-frequency radiation.

Information Source	Xmax, cm	(χ) cm	X _O , cm	(χ) acc. to (2.10) cm
Data obtained by journal "Nauka i Zhizn"	12.5	22.5	11	22
Oak-Ridge Survey (Ref. 5) NASA Survey (Ref. 6)	14 12	32.7 45.4	16 18.5	32 37

Table 2.2

Colour	Data obta by journa "Nauka i	1	MacNally (Ref. 5)		Rayle (Ref. 6)	,	Charmen (Ref. 10)
of ball	Number	%	Number	%	Number	%	Number of	%
lightning	of observati	l .	of observation	1	of observation	1	l oi bservatio	
	0.001.00							
White	244	26.1	44	20.4	27	17.8	10	22.2
Red	180	19.2	40	18.6	7	4.6	4	8.9
Orange	113	12.1	50	23.1	46	30.3	5	11.1
Yellow	246	26.3	38	17.6	37	24.3	16	35.6
Green	12	1.3	3	1.4	10	6.6	2	4.4
Pale Blue	83	8.8	39	18	16	10.5	8	17.8
Darker Blue	15	1.6	_	-	4	2.6	_	-
Violet	13	1.4	2	0.9	5	3.3	-	-
Other Colours	30	3.2	_	-	-	-	_	-
Total	936	100.0	216	100.0	152	100.0	45	100.0

Table 2.3

Colour	Data obtai by journal "Nauka i Z		MacNally's data (Ref.		Rayle's d (Ref. 6)	ata	Charmen's	
of ball lightning	Number of observatio	%	Number of observation	% .s	Number of observatio	% ns o	Number of bservation	% s
White	244	27.3 (<u>+</u> 1.7)	44	20.7 (<u>+</u> 3.1)	27	19.0 (<u>+</u> 3.6)	10	23.3 (<u>+</u> 7.3)
Red/Yellow	539	60.3 (<u>+</u> 2.6)	128	60.1 (<u>+</u> 3.3)	90	63.4 (<u>+</u> 6.7)	25	58.1 (<u>+</u> 11.6)
Pale Blue- violet	111	12.4 (<u>+</u> 1.2)	41	19.2 (<u>+</u> 3.0)	25	17.6 (<u>+</u> 3.5)	8	18.6 (<u>+</u> 6.6)
Total	894		213		142		43	

Table 2.4

	Colour					
Size	White	Red	Pale Blue	All lightning		
0-10 cm	73	106	37	246		
	25.8%(<u>+</u> 2.8)	20%(<u>+</u> 1.9)	30.6%(<u>+</u> 4.9)	24.5%(<u>+</u> 1.5)		
10-30 cm	152	296	57	548		
	53.7%(<u>+</u> 4.2)	55.8%(<u>+</u> 3.2)	47.1%(<u>+</u> 5.8)	54.5%(<u>+</u> 2.3)		
Over 30 cm	58	128	27	211		
	20.5%(<u>+</u> 2.5)	24.2%(<u>+</u> 2.0)	22.3%(<u>+</u> 4.1)	21.0%(<u>+</u> 1.4)		
Total number of observations	283	530	121	1005		

Table 2.5

Observation	Colour					
time	White	Red	Pale Blue	All lightning		
0-10 secs	137	220	49	410		
	48.4%(<u>+</u> 4.2)	41.7%(<u>+</u> 2.8)	41.2%(<u>+</u> 5.9)	41.8%(<u>+</u> 2.0)		
10-50 secs	100	223	47	394		
	35.3%(<u>+</u> 3.5)	42.2%(<u>+</u> 2.8)	39.5%(<u>+</u> 5.9)	40.2%(<u>+</u> 2.0)		
Over 50 secs	46	85	23	176		
	16.3%(<u>+</u> 2.4)	16.1%(<u>+</u> 1.7)	19.3%(<u>+</u> 4.0)	17.9%(<u>+</u> 1.3)		
Total number of observation	283 s	528	119	980		

Table 2.6

		Type of lightning	
Colour	Lightning in	Lightning in	All types
	clear weather	overcast weather	of lighning
White	38	44	244
	29.0%(<u>+</u> 4.7)	28.8%(±4.3)	27.3%(±1.7)
Red	71	93 :	539
	54.2%(+6.4)	60.7%(±6.3)	60.3%(±2.6)
Pale Blue	22	16 .	111
	16.8%(±3.6)	10.5%(±2.6)	12.4%(<u>+</u> 1.2)
Total number	131	153	894
of observations			

Table 2.7

	Γ	Type of lightning	
Size	Lightning in overcast weather	Lightning in clear weather	All types of lightning
0-10 cm	19	19	246
	12.2%(<u>+</u> 2.8)	14.2%(<u>+</u> 3.2)	24.5%(<u>+</u> 1.5)
10-30 cm	90	66	548
	57.7%(<u>+</u> 6.1)	49.2%(<u>+</u> 6.1)	54.5%(<u>+</u> 2.3)
Over 30 cm	47	49	211
	30.1%(<u>+</u> 4.4)	36.6%(<u>+</u> 5.2)	21.0%(<u>+</u> 1.4)
Total number of observations	156	134	1005

Table 2.8

		Type of lightning	
Observation	Lightning in	Lightning in	All types of
time	overcast weather	clear weather	lightning
0-10 secs	62	33	410
	40.5%(<u>+</u> 5.1)	24.6%(±4.3)	41.8%(±2.1)
10-50 secs	63	55	394
	41.2%(±5.2)	41.0%(±5.5)	40.2%(±2.0)
Over 50 secs	28	46	176
	18.3%(±3.4)	34.3%(±5.1)	17.9%(±1.3)
Total number	153	134	980
of observations			

Table 2.9

	Observation time					
Colour	t <u>></u> 0	t > 20 secs	t. <u>></u> .50.secs			
White	244 27.3%(<u>+</u> 1.3)	102 28.6%(<u>+</u> 2.8)	49 29.5%(<u>+</u> 4.2)			
Red	539 60.3%(<u>+</u> 2.6)	207, 58.0%(±4.0)	92 55.4%(<u>+</u> 5.8)	:		
Pale Blue	111 12.4%(<u>+</u> 1.2)	48 13.4%(<u>+</u> 1.9)	25 15.1%(<u>+</u> 3.0)			
Total number of lightning strokes	894	357	166			

	Observation time				
Diameter	t <u>></u> 0	t ≥ 20 secs	t > 50 secs		
0-10 cm	246	55	20		
	24.5%(<u>+</u> 1.5)	14.7%(<u>+</u> 2.0)	11.4%(<u>+</u> 2.5)		
10-30 cm	548	195	87		
	54.5%(<u>+</u> 2.3)	52.3%(<u>+</u> 3.7)	49.7%(<u>+</u> 5.3)		
Over 30 cm	211	123	68		
	21.0%(<u>+</u> 1.4)	33.0%(<u>+</u> 3.0)	38.9%(<u>+</u> 4.7)		
Total number of lightning strokes	1005	373	175		

Table 2.11

		Size		
Type of lightning	0-10 cm	10-30 cm	Over 30 cm	
Short-lived	198 80%	336 61%	45 21%	
Long-lived	48 20%	212 39%	166 79%	
Total number of lightning strokes	246	548	211	

Table 2.12

Number of lightning strokes where t > 20 secs	Computed	Observed
Diameter 0-10 cm Diameter 10-30 cm Diameter exceeding 30 cm	55 200 122	55 195 123

Table 2.13

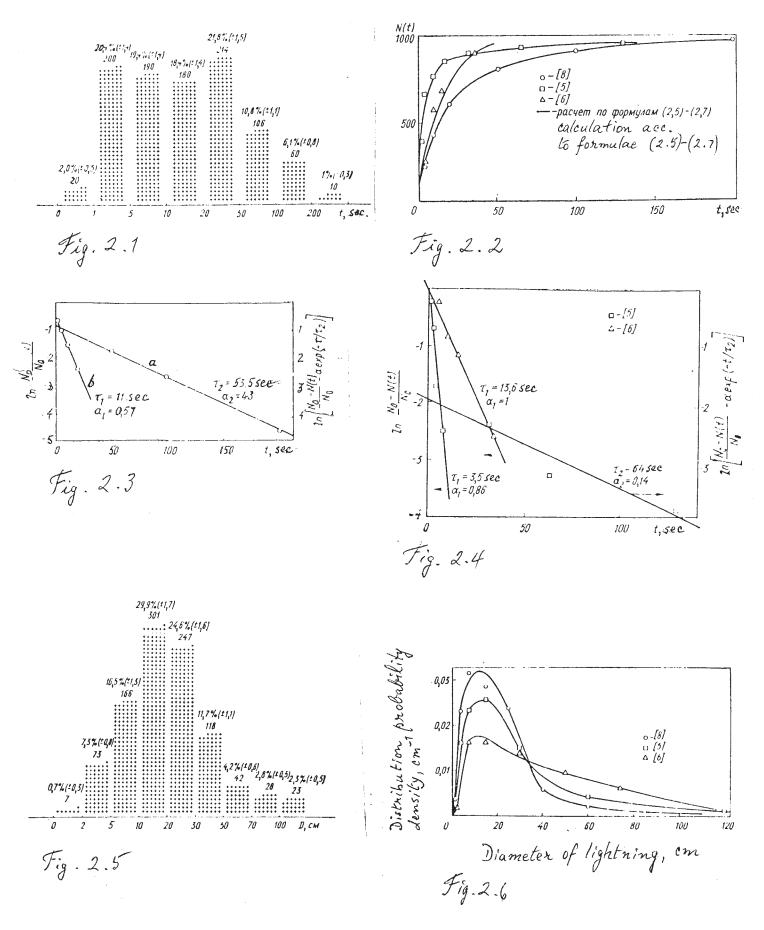
	Observation conditions		
Type of lightning	Thunder-storm	Overcast	Clear
Lightning with a life-span exceeding 50 seconds	86 52.8%(<u>+</u> 5.7)	30 18.4%(<u>+</u> 3.4)	47 28.8%(<u>+</u> 4.2)
All types of lightning	699 69.5%(<u>+</u> 2.6)	173 17.2%(<u>+</u> 1.3)	134 13.3%(<u>+</u> 1.1)

FIGURE CAPTIONS

- Fig. 2.1. Histogram of the distribution of the time during which cases of ball lightning were observed (based on 980 reports obtained by the journal "Nauk i Zhizn"). The figures in brackets indicate the probable random deviations in percentages.
- Fig. 2.2 The law of "disintegration" of a total of 1,000 fire balls resulting from ball lightning.
- Fig. 2.3. The law of "disintegration" on a semi-logarithmic scale for data received by the journal "Nauka i Zhizn".
- Fig. 2.4. The law of "disintegration" on a semi-logarithmic scale based on the data in Ref. 5 (hollow squares) and Ref. 6 (hollow triangles).
- Fig. 2.5. Histogram of the distribution of cases of ball lightning according to diameter ranges (based on the results of 1005 reports received by the journal "Nauka i Zhizn"). The figures in brackets are the probable random deviation in percentages.
- Fig. 2.6. Probability density of the distribution of cases of ball lightning according to diameter, standardized to unit total probability.

 (The solid lines are drawn so as to approximate the results of the observations).
- Fig. 2.7. Relationship of lnf(x)/x to x (f(x) is the probability density of observations of the diameter x). (The arrows indicate the direction in which the first and last dots must shift so as to lie on straight lines).
 - A. Diameter of lightning
- Fig. 2.8. Distribution of cases of lightning according to the distances travelled (data from the journal "Nauka i Zhizn"). (The ordinate of the point indicates the probability of ball lightning travelling a

- distance which is less than or equal to the value of the abscissa):
- O based on 928 observations
- + 155 observations during overcast weather without a thunderstorm
- - 134 observations in clear weather
- for 120 observations made of lightning at the blue end of the spectrum.
- A distance travelled by the lightning.
- Fig. 2.9. Histogram of the mean velocities of ball lightning compiled from 885 reports received by the journal "Nauka i Zhizn".
- Fig. 2.10. Results of a transverse photometric measurment of a trace of ball lightning taken by V.M. Deryuginim on 9 June 1958 at the Karabad Meteorological station (Ref. 24)
 - 1. Relative intensity of blackening
 - 2. Distance from centre of lightning
- Fig. 2.11. Trajectory of ball lightning (settlement of Itat in the Krasnoyarsk region diagram sent by V.I. Stepanov), which caused crackling on the telephone which increased as the fire ball approached, and decreased as it moved away.
 - 1 place where the writer of the letter was standing
 - 2 place where the second observer was standing
 - 3 tables
 - 4 clothes rack on wall
 - 5 telephone
- Fig. 2.12. Results of a longitudinal photometric measurement of a trace of ball lightning (Ref. 24). The arrows indicate the cross-section, in which a transverse photometric measurment of the trace was taken (see fig. 2.10)
 - A. Relative intensity
 - B. Relative distance along the trace.



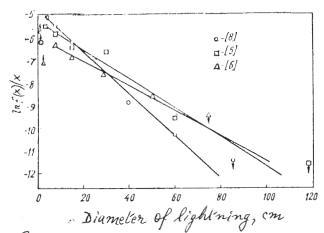
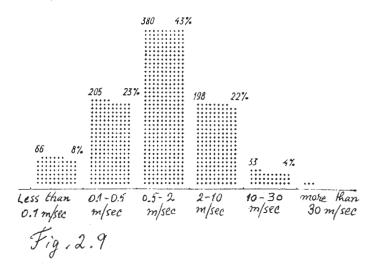


Fig. 2.7



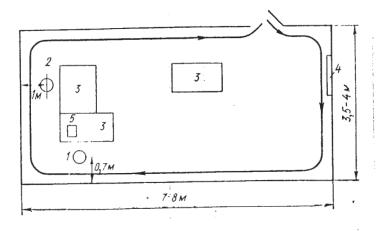
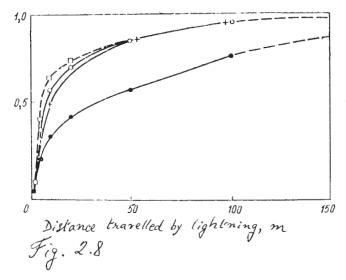
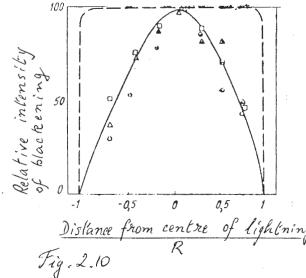
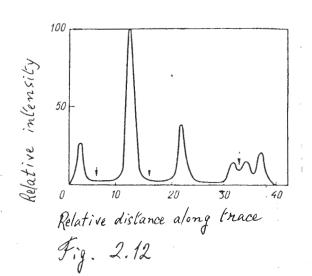


Fig. 2.11







3. BRIEF REVIEW OF THE HYPOTHESES REGARDING THE NATURE OF BALL LIGHTNING

3.1 What should the hypothesis explain

Ball lightning possesses a number of surprising properties which have been attracting man's attention for ages past. Attempts to explain this phenomenon are notable for their wide (considerably wider than one would wish) variety which, perhaps, has hardly any equal in terms of explanations of physical phenomena. Before proceeding to give a very cursory survey of these attempts, let us briefly sum up those aspects of the phenomenon, which should find an explanation in the hypotheses.

- 1. Ball lightning emits energy continuously and, in addition, can liberate considerable energy when it explodes. It is first of all necessary to explain where this energy comes from. The assumed source must maintain a constant energy flux for a sufficiently long space of time (several dozen seconds).
- 2. It is necessary to explain the mass and movement of ball lightning. The fact that the density of the matter constituting it is approximately equal to the density of the air does not at a first glance impose any great limitations on the range of hypotheses suggesting themselves, but these limitations are nevertheless still very appreciable. In fact, it is clear on the one hand that, in terms of density, ball lightning is very similar to a gas, and not to condensed media. On the other hand it should be understood why this gas bubble, which, even if it is not very hot, does not float upwards in the cold air surrounding it.
- 3. It is necessary to explain the shape and size of ball lightning. The spherical shape causes us to think of surface tension, which, as is known, ordinary gases do not possess. However, lightning stubbornly persists in maintaining its shape, a fact which is explained by cases involving its passage through narrow apertures or its disintegration into fragments, after which it

once again acquires its original spherical shape. Even an explosion does not always destroy a fire ball, sometimes the explosion wave simply deflects it to one side.

- 4. It is necessary for us to understand the reason why ball lightning is resistant to the tangential jump in the velocity and to the development of convective instability. The movement of lightning, and also the very slight differences between the density of the matter constituting it and that of the ambient air should result in the development of instability leading first to an increase in perturbations on its surface and then to rapid (within fractions of a second) disintegration of the lightning causing it to mix with the air.
- 5. It is necessary to indicate the mechanism of the radiation emitted by ball lightning. In the first instance this involves visible light. Since the temperature of the lightning is probably not high, it is necessary to explain the cause of the radiation at a low temperature. In addition, the lightning is, apparently, also the source of radio-frequency radiation.
- 6. It is necessary to understand why ball lightning can explode under certain conditions, which are so far not fully known. Moreover, the energy accumulated in the lightning is released rapidly.

These six points have to be explained first of all without using more independent hypotheses than absolutely necessary.

3.2 Ball lightning which receives energy from without

The work by P.L. Kapitsa, published in 1955 (Ref. 35), contains an interesting comparison between ball lightning and a red hot cloud of ionizing gas forming as a result of a nuclear explosion. This cloud had a diameter of approx. 150 m and luminesced for several seconds. The energy content of a completely ionized gas depends only slightly on the nature of the gas and, because of this, it is proportional to the volume of the cloud ($V R^3$), and the heat transfer rate through radiation is proportional to its surface area ($S R^2$). (The latter applies if the object is optically opaque.)

Therefore, as the volume of the ionized gas decreases, its de-excitation time must diminish in proportion to its radius. Consequently, the fully ionized gas in a sphere with a diameter of 10-15 cm must cool down one thousand times more rapidly than the cloud from a nuclear explosion, i.e. in a space of time of the order of 10 msec, which is approx. 1,000 times less than the actual life span of ball lightning.

Such reasoning can be a weighty argument against ball lightning having a high temperature. If this is not so, it proves that it must receive energy from without. In other words, if ball lightning is a cloud of ionized gas heated to a high temperature, it cannot maintain itself in this state by its own internal energy for 10 seconds. The fact is that the density of the energy which can be stored in an electron shell is limited, and this energy cannot exceed the ionization energy of the atoms of the matter constituting the lightning. Another argument in favour of the existence of an external source supplying the lightning with energy is that the intensity of luminescence hardly decreases during its life span, as would be the case if the lightning gradually became extinguished due to a lack of energy.

The hypotheses based on an external energy source can be divided into two groups. In one of them it is assumed that the energy is supplied by the radiation of electromagnetic waves along a wave-guide channel connecting the ball lightning to a cloud; the second group examines the supply of energy by an electric current via a conducting channel. We shall refer to them as the wave-guide and current hypotheses respectively. In the first group the best known hypothesis is that put forward by P.L. Kapitsa (Ref. 35), in which it is assumed that ball lightning arises in the antinode of the electric field of a standing electromagnetic wave. The random occurrence of a small quantity of free electrons leads, in the case of a sufficiently high field strength, to avalanche ionization and to the appearance of a highly ionized plasma in a region having a diameter of the order of one quarter of the wave length. When the diameter

increases further, the electric field drops and the ionization rate decreases, whilst the heat transfer rises as the surface increases and this restricts the growth of the ionization region. By taking account of the size of ball lightning usually encountered, we find that the wave length of the radiation ionizing the air must fall within the decimeter radio-wave range (40-80 cm).

When reflected from metal surfaces the antinode of the electric field (i.e. the centre of the fire ball) is at a distance of one quarter of the wave length from the surface and, consequently, the edge must be at a distance from it equal to the radius of the lightning. The lightning mainly moves along the surface of the ground due to the movement of the radiating region (presumably the cloud). Therefore, its movement need not depend on the weather. On the basis of this hypothesis it is easy to explain how lightning passes through solid screens into enclosed rooms. If, for some reason, the radiation frequency flux ceases, the heated air cools rapidly (within ≈ 0.01 sec) and becomes compressed. This results in a loud report which is interpreted as an explosion. From this aspect an explosion is not associated with the release of energy at all. Beaded lightning is regarded as a chain of fire balls forming in a number of crests of a standing electromagnetic wave.

Let us now turn to the hypotheses, in which ball lightning is connected to an external energy source by a current conducting channel. In this case we are dealing with a discharge, gigantic in size, connecting the cloud to the Earth. Assumptions to the effect that ball lightning is a variety of gas discharge were already being expressed in the last century, and also in the first half of this century (Ref. 2, page 145). In particular, Tepler regarded it as a brush and spray discharge (Ref. 2, page 153). We are so used to these hypotheses that some monographs have introduced them into the actual definition of the phenomenon being examined. Thus, in the book by R.A. Leonov, "The riddle of ball lightning" (Ref. 36), containing a reference to the monograph by I.S. Stekolnikov — (Ref. 37), we find the following: "Ball

lightning is a spherical (less frequently pear-shaped) electric discharge of long duration occurring during a thunder-storm". Here it is taken as a proven fact (though proof is still required) that ball lightning is in reality a variety of gas discharge.

The work by Finkelstein and Rubinstein (Ref. 38) contains an interesting idea regarding ball lightning being associated with the non-linear nature of the conductivity of gases in a strong electric field. It is known that, in a gas discharge, the volt-ampere characteristic, i.e. the relationship of the current to the voltage applied, unlike the simple Ohm's law for metals, usually has a complex and non-linear form. It consists of a number of branches, so that a number of different current values, sometimes differing by an order of magnitude, can correspond to one and the same voltage. This is encountered in particular in the ignition of a glow discharge instead of a dark one, the glow discharge accompanied by luminescence being associated with relatively high current density values. Two sections of the volt-ampere characteristic corresponding to these two types of discharge are connected by a third section, on which the current increases as the voltage applied is decreased, thus causing the entire characteristic to acquire the shape of a letter S. Both types of discharge can exist at the same time on this intermediate section, part of the inter-electrode space being occupied by a luminous, glow discharge, whilst the other parts remain dark. The glow discharge plasma sometimes accumulates in the middle of the inter-electrode space in the form of a luminous sphere which does not have any contacts with the electrodes. The density of the plasma and the temperatures of the electrons, and also the potential within this sphere are considerably higher than in the surrounding space (Refs. 30, 31).

The idea expressed in the work listed as Ref. 38 is to the effect that ball lightning is an intermediate, transient form of dark and glow discharges.

Moreover, a discharge occurs within the lightning, which has a high plasma concentration, and a high temperature and current density, whilst outside of

the lightning there is a dark discharge with low parameter values. This idea is further developed in Ref. 39, which contains detailed calculations for a ball lightning model. The basis used for the model was the joint solution of a system of equations consisting of a steady-state heat transfer equation (with allowance for the Joule heat-up) and a discharge transfer equation (likewise steady-state). Account is taken of the relationship of the electrical conductivity and heat conductivity to the temperature. An elementary sphericalsymmetrical case is examined. The temperature in the centre of the ball is assumed to equal approx. 5000°K, whilst on the perimeter, at a distance of 10-15 cm, it is approx. 3000°K. The current flowing through ball lightning measuring 20 cm across amounts to a few dozen amperes. The calorific power released in the lightning is equal to approx. 10 kW, and approximately the same power is formed in the external, non-luminous part of the lightning where the temperature falls to that of the atmospheric air. The power of the light radiated is of the order of 100 W. The dark current-conducting channel, along which the current reaches the ball lightning, has a diameter which is considerably greater than the diameter of the lightning. The current density in this channel is of the order of $10^{-2}\alpha/\text{cm}^2$, and the electric field is 10^2 - 10^{4}V/cm .

From this aspect, ball lightning can occur in the following manner. After a linear lightning strike a small part of its channel remains, which is heated to a high temperature. The current does not cease at the end of this discharge. The bright, spark discharge is now replaced by a dark, non-luminous discharge, in which the current flows along the extinguished linear lightning channel. The air here contains an increased quantity of ions which have not had time to re-combine. The conductivity of this column of air filled with ions, whose width is assumed to be considerably greater than the original diameter of the lightning channel, is assumed to be of the order of 10^{-3} - 10^{4} m⁻¹0hm⁻¹. The movement of ball lightning is due to the effect of the magnetic field

on the same current when the cylindrical symmetry is disturbed. An explosion is regarded as a collapse resulting from the current ceasing.

"The Achilles heel" of all the theories assuming external energy sources is the movement of ball lightning. The lightning moves as a self-contained body not connected by any current-conducting or wave-guide channels. We shall not dwell yet again on the complex nature of its movement; this was described in detail in Chapter 2. We shall leave it to the reader to judge just how little the theories agree with the ideas of lightning, which is the whole time at the end of an invisible guide, which either draws the lightning behind it or moves with it. It is not true that the movement of ball lightning does not depend on the wind, as would be the case if it were in fact the crest of a standing radio-wave. In reality ball lightning is more reminiscent of a child's toy balloon filled with a gas which is slightly heavier than air. As will be seen from the observations described above, ball lightning possesses inertia. However, its movement is affected not only by metal objects, as was, for example, the case when it was expelled from a room by an ordinary broom.

Yet another question arises. Why, as a rule, does only one fire ball occur at a time? Why do plasma bunches not occur in the neighbouring crests of a standing electromagnetic wave? After all, the appearance of slight seeding ionization is hardly a rare thing during a thunder-storm. Finally, a certain number of discharges can come from ball lightning and strike neighbouring points, thus giving rise to fresh cases of lightning. Why then does this not happen? The reference to beaded lightning (it is not by chance that all hypotheses of this type strive to include also this phenomenon - it is a natural result of such a view of ball lightning) does, in fact, speak against theories involving an external energy source. In fact, beaded lightning is encountered so rarely in comparison with ball lightning that there are no grounds for associating these two phenomena. The relative rarity of beaded lightning was already mentioned in Chapter 1. Let us also add that the very nature of these

phenomena is completely different; for instance, the diameters of individual links in beaded lightning are, judging by the photographs, many times larger than the diameters of ordinary ball lightning. The nature of its movement also differs greatly, as does the brightness, since beaded lightning is only ever observed at great distances.

The explosion of ball lightning is not only a report resulting from the compression of hot air being rapidly cooled. A considerable quantity of energy can be released by an explosion. The wave from an explosion is directed away from the lightning, and not into it, as would happen in the case of collapse. Some observers speak of feeling a wave around them; on one occasion lightning which had landed in a camp-fire scattered it in all directions, and on another occasion lightning which had exploded above the ground swept the dirt out of a space measuring approx. 2 m across. The weak effect of the explosion is simply explained by the fact that ball lightning does not have a firm shell and the matter constituting it is scattered in the initial stages of the explosion before it has time to react.

In order to compensate losses it is necessary for a very considerable quantity of energy - approx. 100 W per square centimetre - to be fed via the wave-guide or current channel to the volume occupied by the plasma. In the case of the wave mechanism it is necessary for this energy to be concentrated in a narrow part of the spectrum close to frequencies of 400-500 mHz, because the condition of resonance with the plasma volume will otherwise be destroyed. The most intensive radio-frequency radiation forming during a discharge of linear lightning lies in a range of some dozens of kHz, and even in this range its intensity is lower by several orders of magnitude than that required for forming and maintaining a volume of plasma of appropriate size in a heated state. As the radiation frequency rises, its intensity decreases inversely proportional to the frequency.

Turning to the theory of the current-conducting channel, we note that the formation, and particularly the survival of such a channel for several dozen seconds is very unlikely. In fact, the current, with a strength of $10^{-2}\,a$ involving a potential difference of 10^2V/cm in the dark part of the channel results in a heat release of 1 W/cm^3 . If this heat were not removed by intensive convection, then, as the authors of Ref. 39 point out, it would result in an increase in temperature of 2000° K within 1 second. The convection can, of course, remove the desired quantity of heat, but why does it then not destroy the channel? After all, it must lead to a rapid dispersal of the ions. And this applies all the more to the actual volume of ball lightning, in which. considerably greater power is released. How does lightning preserve itself and resist convection for several seconds during such intensive heat release? should be noted that the transient state of the discharge, during which some of the inter-electrode space is occupied by the plasma from a glow or arc discharge, whilst the remainder remains dark, is highly unstable. It is possible to stabilize it in a very narrow pressure, current and inter-electrode spacing range. (Moreover, the distance between the electrodes is of the order of 1 cm and is comparable with the diameter of the luminous sphere.)

However, actual ball lightning occurs, as a rule, during a thunderstorm, not infrequently when a strong wind is blowing. It is reasonable to ask,
how is it possible under such conditions for a channel connecting a cloud to

Earth to be preserved for dozens of seconds. This implies a channel having a

length of some hundreds of metres, which follows the extremely complex movements
of the ball lightning and which consists of ordinary air, with a small admixture
of ions. A linear lightning channel is renewed by an arrow-shaped leader every
30-40 msec, and it does not last for more than 0.1-0.2 sec.

The main objection to this resides in the fact that ball lightning does not have that high a temperature, the maintenance of which means relying on an external energy source. The hypothesis regarding an external energy source is

simply superfluous. It was created for the purpose of explaining a property which, in fact, does not exist. We have just seen that the calculation made by Uman and Helstrom is based on the assumption that the temperature in the centre of the lightning reaches 5000°K; even on its boundary the temperature still remains at a level of $3000^{\circ}\,\mathrm{K}$. Approximately $10^{4}\,\mathrm{watts}$ are released within the lightning and an equal quantity outside its boundaries (mainly at a distance of the order of the radius where the current density is the maximum). A strong convective stream of hot air is required to remove such a quantity of heat. Moreover, a powerful stream of thermal infra-red radiation would come from the lightning at such temperatures. Is it possible that no heat was sensed at a distance of less than 1 m from the centre of lightning of this kind? However, this was so in 144 cases out of 158 (see Chapter 2). Finally, the luminous flux, as was mentioned above, also amounts in this calculation to approx. 100 watts, which is equivalent (in the case of an efficiency equal to a few percent) to an electric lamp of a few thousand candle power. This greatly exceeds the luminous flux inferred by the descriptions given by eye-witnesses.

Thus, the assumption that ball lightning is a discharge connected by a current channel to an external energy source is not justified. At the end of Ref. 4, to which we have referred more than once, Humphreys (after enumerating eleven different forms of phenomena which can be taken for ball lightning) raises the question: "Is there then nothing of this nature that could be called ball lightning?" And then answers: "I do not know. I know only that many things can be referred to as ball lightning but are, in fact, something else. It is possible that a 100 foot long wire, or longer if necessary, suspended more or less vertically in free air will, when the potential gradient is very great, produce on its end a brush and spray discharge, the brighter part of which will be noticeable and can be taken for ball lightning. This will be a rare event, of course, but so will ball lightning be - if it exists at all." Throughout this book I have had occasion to argue with Humphreys so many times that I am

now pleased to note that our views coincide (although to a very limited degree only). It is hardly likely that another current channel exists, apart from the one mentioned above, which could effectively supply ball lightning with energy from without. Humphreys concludes his article with the words: "The idea frequently put forward that ball lightning is a balloon of luminous gas without walls does not appear to have made any progress towards being accepted scientifically". We shall now be turning our attention to theories of this type.

3.3 Plasma and chemical theories of ball lightning

Because of the progress in work on the problem of controlled thermonuclear sythesis, our knowledge of the properties and laws of retaining a high-temperature plasma has increased considerably. It is not surprising that this progress has led to fresh attempts to explain the physical nature of ball lightning. The idea behind these attempts resides in imagining ball lightning as a plasmoid, i.e. a volume filled with high-temperature plasma retained by its own magnetic field. This same magnetic field, which prevents the plasma particles from flying apart, can isolate it from the ambient air and prevent rapid dispersion of its energy.

Such plasmoids with a magnetic field frozen into them have been obtained in experiments (Refs. 40, 41). The magnetic field is produced by current flowing in the actual plasma and, naturally, the entire system can exist only if the plasma particles do not collide with each other. Such collisions cause the current to cease, and lead to rapid dissipation of the magnetic field. Fortunately, in a fully ionized plasma there is always the possibility of lengthening the free path of the particles by increasing their temperature. However, investigations into the theory of stability (Ref. 42) showed that there are important limitations on the plasma parameters, which have to be reckoned with. First of all it transpired that a system retained by its own magnetic field (in contrast to a system with a field imposed from without, to which,

for example, Tokamaks belong) is stable only when there is external pressure, i.e. the plasmoid must be in a gaseous atmosphere. Furthermore, the virial theorem (Ref. 38) states that the full energy of the plasmoid, comprising kinetic energy involving both ordered and random movement of its particles and magnetic field energy, cannot exceed 3pV, where V is the volume occupied by the plasma, and p is the external pressure of the surrounding gas. This greatly limits the energy of ball lightning, leaving it at a level of one thousand joules (with p = 1 atm and a radius of approx. 10 cm). No allowance is made here for the energy expended on ionization, although, as will be seen later, this energy is negligibly small because of the high temperature and the low density of the plasma.

The pressure of the plasma in the plasmoid need not differ greatly from the pressure of the gas outside it, i.e. from p=1 atm in the case of ball lightning. Moreover, as was already mentioned, the life span of a plasmoid is restricted to the free path time of its particles. It can be demonstrated (Ref. 38) that, in order for this time to be of the order of 1 second or more, the plasma temperature must exceed 10^{50} K and, consequently, its density (when p=1 atm) must be some hundreds of times less than the density of the air. A plasmoid of this kind will float upwards, and will not sink in the atmosphere. The upper limit of the temperature can be obtained by taking account of the synchrotron radiation of the electrons in the magnetic field. It is natural that, as a result of this radiation, the lightning need not lose the energy stored in it within less than a few seconds. Moreover, it transpires that the plasma temperature must be restricted to a value of approx. 10^{70} K (Ref. 38).

As was indicated in the work by Finkelstein and Rubinstein (Ref. 38), fresh difficulties arise when this hot plasma becomes combined with the cold air surrounding it. A strong, variable magnetic field preventing the plasma from coming into direct contact with the air must exist on the boundary. The layers of air in the vicinity must also be ionized (otherwise the cold, neutral

molecules will pass freely through the magnetic field into the inside of the lightning), but they (these layers of air) must already have a considerably lower temperature than the plasma in the nucleus of the ball lightning.

Let ω be the characteristic frequency of the oscillations of the variable magnetic field retaining the plasma. The magnitude of this field can be estimated from the relationship $H^2/4\pi \simeq p$. When p=1 atm the field must be of the order of 3000 erg. The magnetic field passes through the layer of air surrounding the lightning and ionized to the depth of the skin layer, i.e. to a distance of

$$\Delta R = c/\sqrt{4\pi\omega\sigma},\tag{3.1}$$

where \vec{G} is the the conductivity of the air. The current arising in the layer (which results in the magnetic field vanishing as the distance from the boundary of the lightning increases), has density:

$$j = \frac{c}{4\pi} \frac{H}{\Delta R}.$$
 (3.2)

The joule losses in the skin layer equal

$$\frac{J^2\Delta V}{\sigma} = \frac{c^2}{4\pi} \frac{H^2 R^2}{\sigma \Delta R} = \frac{c^2 p R^2}{\sigma \Delta R},$$
 (3.3)

where $\Delta V = 4\pi R^2 \Delta R$ is the volume of the skin layer. This expression determines the dissipation rate of the magnetic field energy of ball lightning in the ambient air. If W is the energy of the lightning, its life span \mathcal{T} , determined by the dissipation of this energy in the skin layer, is equal to

$$\tau = \frac{W\sigma}{f^2\Delta V} \leqslant \frac{2V\pi RV\sigma}{cV\omega}.$$
 (3.4)

When deriving (3.4) use was made of the relationship (3.3) and the expression (3.1) for ΔR , and also of the virial theorem, according to which W<3pV, where $V = (4/3) \pi R^3$ is the volume of the plasmoid. It follows from (3.4) that, in order to obtain lightning with a sufficiently long life span \mathcal{T} , it is necessary for

$$\omega \leqslant 4\pi R^2 \sigma / (c^2 \tau^2). \tag{3.5}$$

However, the thickness of the skin layer must, in any case, be less than the radius of the lightning $\Delta R \gtrsim R$, whence, according to (3.1), it follows that

$$\omega \gtrsim c^2/\left(4\pi\sigma R^2\right). \tag{3.6}$$

By taking account of the fact that the conductivity of the ionized air at relatively moderate temperatures is limited, we find that it is impossible to satisfy the two inequalities (3.5) and (3.6) simultaneously. In fact, for this it is necessary that

$$(4\pi\sigma R^2) > c^2\tau. \tag{3.7}$$

Because $\delta=e^2n/(mv)$, then, assuming that $n=10^{18}cm^{-3}$ and the collision frequency is $v\simeq 10^{12}~{\rm sec}^{-1}$, we find that $\delta\approx 2.5~{\rm x}~10^{14}{\rm sec}^{-1}$. It should be noted that an assessment of the heat flux removed by the air indicates an air temperature in the skin layer of equal to 10^4 K. Bearing in mind the value of δ we find that, when $R=10~{\rm cm}$, $T\gtrsim 1~{\rm sec}$, instead of (3.7) the inverse inequality is fulfilled with a margin of almost four orders of magnitude.

It will be seen from formula (3.3) that the smaller the thickness of the skin layer ΔR , the greater the heat released in it. By using this as a basis it is possible to consider the maximum life span of the lightning when $\Delta R \simeq R$:

$$\tau_{max} = W\sigma/(c^2 pR) < 3pV\sigma/c^2 pR) = 4\pi R^2 \sigma/c^2.$$
 (3.8)

When R = 10 cm and \mathcal{T}_{max} = 10 sec we obtain $\mathbf{6}$ = 0.7 x 10^{19} sec⁻¹. This conductivity value exceeds by several orders that which can be permitted in the plasma at not excessively high temperatures; this value corresponds to the density of the number of charge carriers 2.7 x 10^{22} cm⁻³ (v = 10^{12} sec⁻¹). When $\mathbf{6}$ = 2.5 x 10^{14} sec⁻¹, we obtain from (3.8) $\mathcal{T}_{max} \lesssim 0.35$ x 10^{-3} sec, i.e. the plasma must be cooled within a period of time of less than 1 msec.

Thus, a model based on high-temperature collision-free plasma does not bear criticism, and the problem of ball lightning does not, unfortunately, have anything in common with effecting controlled thermonuclear synthesis. However, the preparation of ball lightning from ordinary low-temperature plasma is in no way easier due to the recombination of ions during collisions. At temperatures which are not very high the atomic ions are transformed into molecular ions by colliding with molecules. For instance $N^+ + N_2 \rightarrow N^+_2 + N$ or

 $0^+ + 0_2 \rightarrow 0_2^+ + 0$. The rate constants of these reactions are equal to

 10^{-11} and 6 x 10^{-10} cm³/sec and, consequently, at a molecule concentration of the order of 10^{19} cm³ all the atomic ions of the oxygen are transformed into molecular ions during a time period of the order of 10^{-8} sec. The molecular ions rapidly recombine as a result of dissociative recombination (Ref. 43):

$$O + e \rightarrow O + O$$
; $N + 2 + e \rightarrow N + N$. (3.9)

The recombination coefficient α for these processes is of the order of $2 \times 10^{-7} \text{cm}^3/\text{sec}$. In order to simplify the assessment we shall assume that there is only one sort of ion. The densities of the electrons and ions is then, of course, equal and, by designating them as n, we obtain

$$dn/dt = \alpha n^2$$
, $(n_0 - n)/n_0 n = \alpha t$, (3.10)

where n_0 is the density of the plasma at the initial moment in time. When t=1 we find that

$$n_0 u / (n_0 - n) \approx n = 1 / (\alpha t) \approx 0.5 \cdot 10^7 (c M^{-3}),$$
 (3.11)

i.e. irrespective of the initial density of the plasma n there remains a negligible number of unrecombined charged particles already by the end of the first second.

It is true that, at low temperatures, the plasma should not contain free electrons which adhere to the molecules, thus forming negative ions:

$$e + 2O_2 \longrightarrow O_2 + O_2.$$
 (3.12)

The rate constant of this reaction is $k=3 \times 10^{30} {\rm cm}^6 {\rm sec}^{-1}$, and when ${\rm n_{o_2}} \simeq 10^{19} {\rm cm}^{-3}$ the characteristic time for the formation of negative ions $1/({\rm kn^2_{o_2}})$ is of the order of 10^{-8} sec. However, the positive ions recombine with the negative ions just as rapidly as with the electrons.

Ball lightning must not be represented as excitation of the $\mathbf{0}_2$ or \mathbf{N}_2 molecules to the metastable levels because, at atmospheric pressure, deexcitation due to collisions takes place extremely rapidly (Ref. 43).

Thus, ball lightning must consist of natural molecules in an unexcited state. We arrive at the so-called chemical hypotheses of ball lightning. Arago is sometimes called their creator, and there are, without doubt, sufficient grounds for this assertion. For instance, Arago stated that ball lightning consists of nitrogen oxides and ozone, and is impregnated with "lightning matter". However, Arago's views on the matter constituting the lightning were formulated in such a general manner that any hypothesis on ball lightning which is based on an autonomous energy source can also, if needs be, derive its origin from Arago's works. Hypotheses on the chemical nature of ball lightning have been put forward by N.A. Gesehus (Ref. 44), Thornton (Ref. 2, p. 121), Ya. I. Frenkel (Ref. 45, p. 140), by Barry (Ref. 46) relatively recently, and by other authors as well. It is assumed in these works that ball lightning contains a certain chemical compound (usually referred to as ozone or nitrogen oxides; hydrocarbons are involved in Barry's case), which forms during an electrical discharge and by some means or other (as an explanation of how the main point of the hypothesis should stand) reaches a considerable concentration in a relatively small volume. This hypothesis is developed most fully in those of B.M. Smirnov's works which have appeared in most recent years (Refs. 43, 47-It is on these results that we shall dwell in somewhat greater detail,

referring readers who are interested in the history of the problem to existing surveys (Ref. 2, for example).

Smirnov assumes that the energy of the lightning is contained in the ozone and is released when it disintegrates. The atomic oxygen, which is obtained in large quantities in a linear lightning channel when molecular oxygen decomposes can, as it transpires, be transformed into ozone under certain conditions. Usually atomic oxygen recombines according to formula.

$$2O + X_2 \rightarrow O_2 + X_2,$$
 (3.13)

 $\rm X_2=0_2$, $\rm N_2$, the reaction rate constant being $\rm k_1=3\times10^{-33}~cm^6/sec$ at a temperature of 400 K. The number of elementary acts comprising this reaction in a unit of time and in a unit of volume is equal to $\rm k_1^2 n^2 0^n 0_2$, and the time taken to combine the oxygen atoms when $\rm n_{O_2}^{} + \rm n_{N_2}^{} \approx 3\times10^{19}~cm^{-3}$ is (in seconds)

$$\tau_1 = [kn_O(n_{O_A} - | -n_N)]^{-1} = 10^{13}/n_O$$
 (3.14)

Moreover, ozone forms in accordance with the following formula:

$$O + O_2 + X_2 \rightarrow O_3 + X_2$$
 (3.15)

with a rate constant of $k_2 = 6 \times 10^{-34} \text{cm}^6/\text{sec}$. If atomic oxygen constitutes a small admixture to the 0_2 and N_2 molecules, the rate of the last reaction, which is proportional to n_0 , and not to n_0^2 , can be considerably greater than the first. In fact, the time taken for the absorption of the oxygen atom, accompanied by the formation of ozone (in seconds) is

$$s_2 = [k_2 n_{O_4} (n_{O_4} + n_{N_2})]^{-1} = 10^{-6}$$
 (3.16)

where n = 0.6 x 10^{19}cm^{-3} , $n_{\text{N}_2} \approx 2.4 \times 10^{19} \text{cm}^{-3}$, $n_{\text{O}} \ll 10^{18} \text{cm}^{-3}$ (i.e. at an atomic oxygen concentration of the order of or less than 1%), $\mathcal{T}_2 \ll \mathcal{T}_1$ and almost the entire atomic oxygen is transformed in 10^{-5} seconds into ozone.

Furthermore, ozone starts to decompose during interaction with the residues of atomic oxygen. The fact is that the reaction (3.15) is reversible, although the bimolecular reaction, which is the reverse of (3.15)

$$O_3 + X_2 \rightarrow O_2 + O + X_2$$
 (3.17)

takes place very slowly (its rate constant is $k_3 = 2 \times 10^{22} \text{cm}^3/\text{sec}$). As a result the mixture with the ozone always contains a certain, even if very small quantity of 0 atoms (approx. $0.5 \times 10^{-7} \text{ n}_{03}$). By interacting with the ozone this oxygen gradually transforms it into molecular oxygen $0_3 + 0 \rightarrow 20$ (the rate constant is $6 \times 10^{14} \text{cm}^3/\text{sec}$). However, the process takes place very slowly due to the low equilibrium concentration of atomic oxygen. If nitrogen oxides are present in the mixture, the ozone decomposes considerably more rapidly due to further oxidation of these oxides

$$NO + O_3 \rightarrow NO_2 + O_2;$$
 (3.18)

$$NO_2 + O_3 - NO_3 + O_2$$
. (3.19)

It is precisely these reactions which usually determine the life span of the ozone which is formed. The rate constants depend to a large extent on the temperature [for instance, for the last reaction $k = 7 \times 10^{12} exp$ (-3520/T)], so that at a temperature exceeding 400-500-K the decomposition time is brief in comparison with the life span of ball lightning.

When viewed from the aspect under examination, the formation of ball lightning from a linear lightning channel is represented in the following manner. A certain quantity of hot, dissociated air, which is ejected by the shock wave from the linear lightning channel, mixes with the ambient cold air and is cooled so rapidly that a small amount of the atomic oxygen in it does not have time to re-combine. According to the considerations set out above, this oxygen must be transformed into ozone within 10^{-5} seconds. The permissible quantity of hot air in the mixture forming is greatly restricted because the temperature of the mixture must not exceed 400°K, otherwise the ozone forming will rapidly decompose. This limits the quantity of ozone in the mixture to a value of the order of 0.5-1% (Ref. 47). In order to obtain higher ozone concentrations the author of Ref. 49 examined the excitation of oxygen by lightning current. The author comes to the conclusion that this can lead to the occurrence of a mixture containing up to 2.6% ozone. Thus, in this case the discharge of lightning actually enters into the process as a necessary detail of the picture. This favourably distinguishes the hypothesis under examination from certain other chemical hypotheses, where the actual discharge does not, at a first glance, play any part, any the reason why ball lightning is so closely associated with a thunder-storm remains unexplained.

The ball lightning obtained in this manner must consist of ordinary air which has a temperature approximately 100° K higher than that of the surrounding atmosphere and must contain about 1% ozone (and also a certain quantity of nitrogen oxides). The time during which the ozone will decompose is calculated in Ref. 49. Account must be taken of the fact that the decomposition of ozone is accompanied by the release of heat, which, in turn, leads to an increase in temperature and, consequently, in the reaction rate. If we ignore the heat removal, the decomposition of 1% of the ozone leads to a 50° K increase in the temperature of the mixture. Because of this the decomposition rate increases sharply with time. The half-lives of ozone calculated in Ref. 49 were equal to

1.4 and 0.4 secs at 1 and 3% ozone respectively. The initial temperature of the mixture was taken to equal 400°K, whilst the concentration of nitrogen nuclei contained in the oxides amounted to 10% of the ozone concentration. In the absence of nitrogen oxides the decomposition time under the same conditions was 15 and 2 seconds.

The reduced ozone decomposition times coincide in order of magnitude with the life span of ball lightning. During the decomposition of 1% of 0_3 contained in the air at atmospheric pressure, approx. 300 joules are released. In this way the energy of ball lightning in the model described is between 0.3 and $1~\rm kJ$.

Without doubt, the hypothesis set out belongs to those worked out in the greatest detail and most thoroughly substantiated. However, it too is not free from the short-comings which are inherent in all chemical hypotheses. First of all, they are not capable of explaining the form of the lightning and its stability in the case of movement. A cloud of neutral gas cannot be preserved under these conditions. The references to experiments with burning, which are sometimes quoted (Ref. 2, page 124; Ref. 48), are not convincing because the scales and conditions, under which these experiments were conducted, and are not in accordance with the conditions under which ball lightning is observed. Ball lightning travels hundreds of metres in a turbulent atmosphere, it can penetrate narrow apertures and cracks, and then re-form after so doing, and can also survive an explosion, rebounding to one side and once more acquiring its original shape. It is very difficult to imagine that all this is possible solely on the strength of the "temperature field symmetry", as B.M. Smirnov assumes (Ref. 49). The temperature field will not simply be symmetrical due to the convective flows arising in the gravitational field. Surface tension can be expected only in the case of a medium with the density of gas, where its molecules are charged and interact in accordance with Coulomb's law.

Furthermore, the energy of ball lightning in the model examined above is too low. Its scale is always several hundred joules, whilst it can be seen from the examples dealt with in Chapter 2 that it must be of the order of several dozen, and in some cases even hundreds of kilojoules are possible. An energy of 1 kJ is insufficient to melt, let alone evaporate a few grams of metal. It is necessary also to take account of the energy losses due to radiation during the life span of ball lightning and to a final explosion. The assumption that ball lightning is divided into high-energy and low-energy lightning is hardly justified, and attempts to increase the ozone concentration outside the limits of 1-3% encounter fundamental difficulties (Refs. 47, 49).

Among not the least of the difficulties is also the problem of the mass of lightning. We saw above that ball lightning has a density exceeding that of atmospheric air. However, a mixture containing less than 3% ozone and heated from the very outset to 400°K must be lighter than air. As the ozone decomposes, the temperature of the mixture increases to approximately 500°K and its density becomes almost one half of that of air at room temperature. This means that the lightning consisting of a mixture of ozone and air must float upwards, and not sink in the Earth's atmosphere.

Likewise, the chemical hypothesis does not explain the glowing of lightning. The hopes of associating this with the formation of excited nitrogen dioxide molecules during the oxidation of NO with ozone were not realized because, at atmospheric pressure, the extinction of excited states by collisions takes place more rapidly than does de-excitation (Ref. 49).

Finally, it is not apparent in principle how to explain on the basis of the chemical hypothesis the radio-frequency radiation from ball lightning, which manifests itself as radio interference. The neutral molecules do not radiate radio waves. Only charged particles can produce noticeable radio-frequency radiation. Therefore, at the end of this chapter we shall once again return to those hypotheses, in which ball lightning consists of charged particles. In the case in question we shall be dealing with molecular ions and particles of dust.

Hypotheses of this kind were put forward by Ya. I. Frenkel (Ref. 45), and most recently of all by E.L. Hill (Ref. 50). (The hypothesis set out in Ref. 51 also deals with ball lightning consisting of ions, but in essence, it attracts an external energy source.)

Let us dwell in somewhat greater detail on Hill's hypothesis. Here he assumes that lightning is a region filled with ions of the same sign or with clouds of ions of opposite sign separated from each other. Thus, it carries greater spatial charges. It is largely molecular ions obtained during the ionization of complex organic molecules, which are examined. According to Hill this space can, in addition to molecules, also contain a large quantity of charged dust particles. The re-combination which, in the case of complex molecular ions, takes place even more rapidly than in the case of simple ions, is retarded by the ions of different sign being separate, and also by a considerable part of the charges being associated with low-mobility dust particles. Glowing occurs as a result of break-down and the formation of discharges between oppositely charged ionic clouds, and also as a result of dust particle corona.

No serious quantitative calculations are quoted to support the views expressed. The main difficulty immediately encountered when attempting to define precisely this point of view in a quantitative sense resides in the enormous magnitude of the Coulomb forces acting between the discharge clouds. These forces lead to a rapid mixing of the clouds of ions of different sign and to their re-combination or, if the entire lightning consists of ions of the same sign, to its rapid (within fractions of a second) disintegration and dispersion in the air.

Dust particles are worthy of particular examination. For the density of the lightning to be comparable with the density of air, the concentation of dust particles must not be too great. Let N be the number of charged dust particles in 1 cm 3 and r be their average radius, and ρ the density of their substance. Then

$$(4/3) \pi r^3 \rho \mathcal{N} \leq \rho_0, \tag{3.20}$$

where ρ_0 is the density of the air. When calculating the inequality (3.20) the density of the lightning (with due allowance for the air and dust particles contained in it) is no more than twice as great as the density of pure air. The energy contained in 1 cm³ is equal to

$$w = ZE_i N, \tag{3.21}$$

where E_i is the ionization energy; Z is the average number of elementary charges per dust particle. In comparison with \boldsymbol{w} , the electrostatic energy of the dust particles can be ignored (when r $\leq 10^{-3}$ cm).

In order to determine Z we calculate the maximum charge which can be accumulated on a particle. Let us use \mathcal{E}_{o} to designate the field strength, at which the break-down of air occurs: $\mathcal{E}_{o}=3\times10^{4}\text{V/cm}$ (10² in the CGS system). It is apparent that

$$Ze/r^2 \leqslant \mathcal{E}_0$$
 (3.22)

(e is the electron charge). From this we can determine Z. Let us note that the value of Z found in this manner and, consequently, also the energy \boldsymbol{w} are excessive because, in fact, the charge starts to leak from a dust particle due to corona long before the field strength on its surface reaches $\boldsymbol{\mathcal{E}}_{o}$. By determining Z from (3.22) and N from (3.20) and by substituting these values into (3.21), we find that

$$w \leq E_{I} \frac{3\%_{o}}{4\pi e} \frac{\rho_{o}}{\rho} \frac{1}{I}. \tag{3.23}$$

By assuming that $\rho_{\rm o}/\rho \approx 10^{-3}$, E = 10 eV \approx 1.6 x 10^{-18} J, we obtain (in J/cm³)

$$\omega \leq 0.8 \cdot 10^{-10}/r.$$
 (3.24)

We saw in Chapter 2 how the density of the energy contained in ball lightning must be of the order of 1-10 J/cm³. For this the radius of the dust particles, which is expressed in centimetres in formula (3.24) must be of the order of the radius of the atom or less. If we restrict ourselves to sizes which are usual for dust particles, i.e. $r \approx 10^{-4}$ cm, the energy density accumulated in them (given a reasonable value for the mass of the lightning) is negligible: of the order of 10^{-6} J/cm³, which, for lightning measuring 10 cm in diameter, represents a reserve of energy equal to no more than 4 x 10^{-3} J. An even lower value is obtained for large particles whose radius exceeds 10 μ m (in this case the bulk of the energy is accumulated in the electrostatic field of the charged dust particles).

It is also easy to obtain an estimate of the upper limit of the value of the electrostatic energy of dust particles by using (3.20) and (3.22):

$$\omega^{1} = N \frac{z^{2} e^{2}}{2r} \leq \frac{\rho_{0}}{\rho} \frac{3}{4\pi r^{1}} \frac{E^{2} e^{r^{4}}}{2r} = 3 \frac{\rho_{0}}{\rho} \frac{E^{2} e^{0}}{8\pi}.$$

Hence, when $e_0/e \simeq 10^{-3}$, $E_0 = 100$ (in the CGS system) we find $\omega' \lesssim 1.2 \times 10^{-7} \text{J/cm}^3$.

Thus, the reserve of energy which can be accumulated in ball lightning consisting of dust is negligibly small.

- 4. BALL LIGHTNING COMPRISING CLUSTER IONS
- 4.1 The cluster hypothesis

It should be noted the dipole molecules are attracted to ions, the bonding energy of which can be very considerable. Thus, the water molecule has a dipole moment of $p=1.83 \times 10^{-18}$ (in the CGS system) and, as is easy to calculate, its bonding energy with a singly charged ion is approx. 1 eV if the distance r between the ion and centre of the dipole is $2 \cdot 2 \cdot 5 \times 10^{-8}$ cm. It must be emphasized that in the case in question we are dealing solely with electrostatic energy equal to pe/r^2 (e is the electron charge). This energy is high enough for the ion and dipole molecule to form a strong bond at not very high temperatures. In the presence of a large quantity of such molecules a stable solvation sheath can occur around the ion (fig. 4.1). The ion, together with its sheath actually constitutes one large molecule, i.e. a solvated ion, also referred to as a cluster ion or simply a cluster. We shall examine a cluster as a firmly bonded compound comprising a positive or negative ion with a sheath of neutral particles.

In hydrated ions or hydrates the cluster sheath consisting of 3-5 water molecules has a bonding energy of approx. 4 eV and it should not be destroyed by collisions at temperatures below 1000°K. It is natural to suppose that such a sheath can disturb recombination. Let us suppose that ball lightning consists of cluster ions. This hypothesis was expressed by the author of this book in the article listed as Ref. 52. At the low temperatures which are characteristic of ball lightning, the free electrons combine with neutral atoms or molecules, thus forming a negative ion, which is then solvated. In order to fulfill the quasi-neutrality conditions, the quantity of positive and negative ions must, naturally, be approximately identical. Apart from the cluster ions, lightning must contain in a free state a certain quantity of molecules which constitute the cluster sheath. Since water, which is widely

distributed in the natural world, is firmly retained by ions, water molecules and hydrated ions may, more likely than not, be involved here. If cluster sheaths can in fact, retard recombination, this may explain why ball lightning survives for some considerable time. Moreover, by recombining, it releases the ionization energy contained inside it.

This energy can be estimated approximately. Approximately 10-15 eV are released when the ions recombine. Moreover, a further 3-5 eV are usually released during the subsequent chemical reactions. Thus the recombination of 0+ and 0 ions results in the formation of two 0 atoms, which then combine into an O2 molecule, thereby releasing 5 eV. In precisely the same manner, after neutralization, the N⁺ and O⁻ ions form the NO molecule or molecular nitrogen and oxygen. As a result the energy being finally released during the neutralization of the pair of ions is 15-20 eV. The energy expenditure must be as follows: firstly, approx. 6-8 eV should be expended on the destruction of the cluster sheaths of the two ions; secondly, a further 1-2eV must be expended on the dissociation of the negative ion producing an electron and atom. of this, each pair of cluster ions can give 5-10 eV during recombination. there are approx. 0.5×10^{19} pairs of ions in the matter constituting the lightning, the density of the energy contained in it is $5-10 \text{ J/cm}^3$. In such a case the lightning with the most likely diameter (20cm) carries in it energy equal to 20-40 kJ. This energy can amount to several hundred kilojoules in the case of lightning with a larger diameter (pprox 50 cm). These values agree with the estimates given in Chapter 2.

A very important advantage of the view-point expressed is the simple solution of the problem concerning the mass of ball lightning. The solvation sheaths make the cluster ions very heavy and this compensates the reduction in density due to the rise in temperature. The hydration sheath consisting of four water molecules has a molecular weight equal to 72, to which the mass of the ion

itself has to be added as well. Because of this, even at a temperature which is twice as high as that of the ambient air and also in cases where the content of free water molecules is considerable, the density of the matter constituting the lightning can still be greater than that of the air under ordinary conditions.

In addition, plasma media, whose particles interact in accordance with Coulomb's law, reveal properties which are similar to the surface tension of liquids. The degree of ionization of the matter being examined by us is very considerable because the major part of the neutral molecules in it are combined in cluster sheaths. At distances which greatly exceed the radius of a cluster ion its electric field is the same as in the case of an ordinary ion. As was already mentioned, the surface tension makes it possible to explain some of the properties of ball lightning, starting with its shape and ending with its stability.

It is not difficult to also form a rough qualitative picture of the radiation from ball lightning. When the matter constituting the lightning is at a comparatively high temperature (500-700°K), the vibrations of the molecules in the hydration sheaths of ion clusters must be noticeably excited. Because of this, black radiation in the infrared region of the spectrum ($\lambda \approx 5$ - 10 μ m, transition energy 0.1 - 1 eV) should be expected. However, the visible radiation from the lightning is of a non-equilibrium nature. This radiation probably arises during the recombination of two cluster ions, which is accompanied by the release of approx. 10 eV. At first the energy released is distributed to approx. 10 molecules constituting two clusters. Until this excess energy is transmitted to the surrounding particles via collisions, the matter constituting the recombined clusters will be heated to a very high temperature 10^4 °K (on average approx. 1 eV per particle). Several dozen collisions with cold molecules caused by the insignificant number of particles involved in the process are required to cool this matter. It can be assumed

that, in such a state, a certain (even if, on average, very small) amount of the energy will be removed in the form of visible or even ultraviolet radiation.

As far as radio-frequency radiation is concerned, it can occur during the movement of ions in the matter constituting the lightning. Dipole radiation of a particle carrying a charge e and moving with acceleration α is, as is known (Ref. 53, p. 213), determined by the formula

$$J = 2e^2a^2/(3c^3) (4.1)$$

The acceleration of an ion in the field of another ion is equal to

$$a = e^2/(Mr^2) \tag{4.2}$$

By assuming the mass of a cluster to be M \simeq 80x1.6x10⁻²⁴ g., and the distance r to be equal to the mean distance between ions (at a charged particle density of $10^{19} {\rm cm}^3$, r \approx 5 x 10^{-7} cm), we find that the dipole radiation power from 1 cm³ is equal to (in W/cm³)

$$10^{19} \text{ J} = 3 \times 10^{-7}$$
 (4.3)

Lightning with a diameter of 20 cm should radiate approx. 10^{-3} W of energy. The frequency of this radiation ν can be assessed by equating the acceleration α (4.2) to the centritripetal acceleration $4\pi^2\nu^2r$; hence we obtain $\nu \simeq 20$ GHz. This corresponds to the radiation of radio-waves in the centimetre range. The power calculated from formula (4.3) exceeds by some orders of magnitude the power of equilibrium radio frequency radiation at a temperature of 600°K. At a distance of lm the lightning produces the same radiation flux density as a 100 kW radiostation at a distance of 10 km. It can, therefore, be expected that the radio frequency radiation of lightning will exert noticeable influence on systems with a poor selective capacity in terms of frequency, telephone lines being one example.

It will also be seen from the formulae given that ball lightning need not contain any appreciable quantity of free electrons. Indeed, because of the small mass the acceleration of the electron is 1.5×10^5 times greater than the

acceleration of the hydrated ion, whilst the power radiated is, accordingly, 2 x 10^{10} times greater. Moreover, ball lightning with a diameter of 20 cm would radiate approx. 10 MW or approx. 2 kW/cm³ (at an electron concentration of 0.5 x 10^{19} cm⁻³). This would lead to de-excitation of the entire energy of the lightning approx. within 10^{-3} sec.

In order to explain the causes of ball lightning exploding, it is possible to postulate the possibility of two different paths for the recombination of cluster plasma. In one of them the recombination rate depends very largely on the temperature; this rate increases rapidly as the temperature rises. In the other one this relationship is considerably less. At the fairly low temperatures, which are usual for the matter constituting the lightning (presumably 500-700°K), the first path is "suppressed" and recombination largely takes place in the second. This leads to a steady state being established, in which the heat being released in the volume of the lightning, succeeds in escaping from it. Such a state is stable in a particular temperature range, as a result of which ball lightning exists until its energy reserve is exhausted or until the conditions ensuring its integrity as a single body cease to exist (conditions for the decay by surface vibrations). In the first case the lightning is quietly extinguished, whilst in the second case it collapses, scattering sparks as it does.

However, as the temperature rises, the role of the first path in the recombination process increases sharply. Because the recombination rate is dependent to a very considerable degree on the temperature in this route the state becomes unstable because the heat does not have time to be removed. As a result, the temperature rises and this, in turn, increases the recombination rate. This is followed by a chain reaction which ends in an explosion. Given below is a description of the specific recombination mechanisms with the corresponding properties which can be present in a plasma comprising cluster ions.

4.2 Clusters and cluster sheaths

What grounds are there for thinking that cluster type sheaths, in particular hydration sheaths of ions can retard their recombination. Since the theory of electrolytic dissociation came into being, it has been known that this also occurs in solutions if the solvation heat exceeds the energy released during the recombination of ions. However, it is not the solutions which interest us, but the gaseous state of matter. It has been known for some considerable time that sheaths consisting of neutral molecules can form around ions in the gas phase as well. More than half a century ago Langevin and J.J. Thomson discovered the anomalously low mobility of ions in air, attributing this to the fact that they are covered with a "fur-coat" of neutral particles, which is firmly bonded to the ions. The term "cluster" was first introduced as a result (Ref. 54).

In the 1960's clusters of type $H^+(H_2O)_n$ and $NO^-3(H_2O)_n$, $CO^-3(H_2O)_n$ (n = 1-3) and a number of others were found in large quantities in the D layer of the ionosphere (Ref. 55). It is interesting to note that this happened at heights where water vapour is almost absent: it freezes out due to the low temperature in the stratosphere and rises higher than an altitude of 20-30 km in very small quantities only. Therefore, it was first assumed that the results of mass-spectrographic investigations of the ion composition, obtained by rockets, were erroneous. Water might be carried up to such an altitude in the form of combustion products from rocket fuel. However, it was later found that such was not the case. It was finally established that $H^+(H_2O)_n$ type ions are the most widely distributed ones in the ionosphere below heights of 80-85 km, whilst negative hydrated ions predominate over the concentration of free electrons, starting from heights of approx. 70 km (and below).

One question is natural: how do $\mathrm{H}^+(\mathrm{H}_2\mathrm{O})_n$ ions form out of primary O^+ and NO^+ ions occurring as a result of ionization by solar radiation of atoms of the main neutral components at these heights? This question had been answered

by the beginning of the 1970's. It transpired that, as a result of a series of ion-molecular reactions, the 0^+ and $N0^+$ ions must in fact be transformed into $H^+(H_2O)_{\rm II}$, such ions as $0^+2_{\rm I}O_{\rm II}$, $N0^+N_{\rm II}$ etc. being formed during the intermediate stages. We shall not dwell on this problem, but only note that the experimental investigations carried out when solving it are extremely important for us, because it was precisely through them that the energy of hydration of the ions was determined, as were the equilibrium constants and those of the hydration reaction rate at various temperatures.

Let us now return to the question as to whether a cluster sheath can disturb the recombination of ions in the gas phase. This appears to us as being self-evident, at least in those cases where the ion hydration energy exceeds the energy being released during their recombination. The fact that this can occur in the gas phase can be seen from Table 4.1, which shows the water molecule binding energies measured in the hydration sheaths of H₃O⁺ and OH⁻ ions (Refs 56 and 57). Let us note that the H₃O⁺ ion, the so-called oxonium ion, is essentially the product of the hydration of the proton by one water molecule:

$$H^+ + H_2O \rightarrow H_3O^+.$$
 (4.4)

However, the binding energy released during this reaction (7.18 eV) is so great in comparison with the binding energy of the subsequent water molecules that it is more convenient to talk of the hydration of the $\rm H_3O^+$ ion, and not of the proton. In accordance with this we shall frequently write formulae of ion hydrates in the form $\rm H_3O^+(H_2O)_n$, and not $\rm H^+(H_2O)_n$.

Table 4.1 shows the enthalpy $(\Delta H)_n$ -1, n of reactions.

$$H_3O^+(H_2O)_{n-1} + H_2O \rightarrow H_3O^+(H_2O)_n;$$
 (4.5)

$$OH^{-}(H_{2}O)_{n-1} + H_{2}O \rightarrow OH^{-}(H_{2}O)_{n}.$$
 (4.6)

It will be seen from the table that the binding energy of a hydration sheath comprising seven water molecules of the $\rm H_3O^+(H_2O)_7$ ion is approx. 5.4 eV. The energy for forming the hydration sheath of the $\rm OH^-(H_2O)_7$ ion must be almost the same (approx. 4.5 eV). It is true that the hydration heat of this ion, n=6, 7, was not measured, but it can be seen that it is close to the $\Delta \rm H$

values for the oxonium ion hydrate ${\rm H_3O^+(H_2O)}_{\rm n}$ at an identical value of n. By taking account of the binding energy of H⁺ and H₂O in the oxonium ion (7.18 eV), and also the relationship of the electron to the OH radical (1.7 eV), we find that an energy of 18.8 eV is required for the decomposition of two cluster ions ${\rm H_3O^+(H_2O)}_{7}$ and ${\rm OH^-(H_2O)}_{7}$ to H⁺, OH, the electron and fifteen molecules. At the same time, no more than 13.5 eV is released during the recombination of the proton and electron. Even when allowing for the fact that the hydrogen atom formed as a result can combine with an OH group, after forming a further water molecule and releasing approx. 5 eV, we obtain 18.5 eV. Recombination under these conditions would lead to an increase in the internal energy. As will be shown below, at atmospheric pressure and a temperature of less than 500°K, it is those clusters with n \approx 7 which predominate in a mixture of ions and water vapour.

Thus, in the gas phase, it would appear that conditions can occur where the recombination of ions is unfavourable in terms of energy in a manner similar to what occurs in electrolyte solutions. However, the essence of the hypothesis which we are now discussing does not reside in this. In the case examined above, the system of hydrated ions is stable in terms of energy. It cannot serve as an energy source. We are interested in conditions where recombination, in spite of the fact that its occurrence is accompanied by the release of energy, is retarded, i.e. cases where the system is in a metastable non-equilibrium state. Unfortunately, there is still no confirmation of this fact based on experiments. Only the cross-sections of the recombination of positive hydrated oxonium ions and the free electron were measured (Ref. 58). The coefficient of recombination with the electron is high, and it increases with an increase in the number of molecules in the hydration sheath of clusters from 10^{-6} for $\mathrm{H_3O^+}$ to 10^{-5} cm³/sec for $\mathrm{H_3O^+}(\mathrm{H_2O})_5$. This was what was to be expected due to the increase in their geometric dimensions. However, the recombination coefficients of positive and negative hydrated ions when n = 3-5

were not measured. This difficulty is further aggravated by not knowing in advance what types of ions are resistant to recombination.

The appearance in advance of such metastable states for systems comprising cluster ions in the gas phase is aided by the fact that, unlike solutions, ions of different signs are not constantly in direct contact with each other here. Of course, in the case of non-elastic collisions it is possible for neutral clusters to form, in which oppositely charged ions, separated by the sheaths, are combined into one particle (see fig. 4.1). However, the bonding energy of such large formations is, apparently, not great and they probably disintegrate easily at an elevated temperature.

In order to answer the question regarding the extent to which the cluster sheaths disturb the direct contact of ions, it is important to understand to what extent our ideas of ions as charged spheres of a particular radius are in keeping with reality. The structure of the oxonium ion is reminiscent of a water molecule (fig. 4.2, a,d): their diameters are very similar to each other and amount to approx. 2×10^{-8} cm. If a completely filled first hydration sheath consists, as is usual to consider, of 3 or 4 water molecules densely packed around the ion, the diameter of such a cluster must be approx. 6 x 10^{-8} cm, and the collision cross-section of two clusters is πD^2 = 10⁻⁴ cm². To some extent this is confirmed experimentally in work on studying the scattering of ${\rm H_30^+(H_20)}_{\rm n}$ ions with an energy of 10-60 eV by He atoms (Refs 59-61). Unfortunately this work involved measuring only the relative crosssection of the scattering of clusters with various n values. During the transition of H_30^+ ion to $H_30^+(H_20)_3$ and from the OH^- ion to $OH^-(H_20)_3$ the transverse cross-section increases approximately sixfold, indicating a 2.5 increase in the diameter. The OH^- and H_3O^+ ions have almost identical diameters, which are equal to the diameter of the water molecule (2 x 10^{-8} cm).

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By taking account of the sizes indicated it is possible to calculate the energy of bonding the water molecule with the ion as the energy of interaction between the point charge and the dipole. It is, of course, necessary to also take account of the geometry of the arrangement of the dipoles in the water molecule (the positive end of the dipole is further from the centre of the molecule than the negative end). Such a calculation shows fairly good agreement between the bonding energy calculated and the experimental values. When n > 3 or 4 the next hydration sheath starts to fill up; in addition, the interactions between the molecules in the sheaths become noticeable. Of course, the true structure of hydrated ions can only be given by quantum mechanics, but the corresponding quantum mechanics calculations are very complex and so far rather few in number (Ref. 62).

Apart from the bonding energy it is important to know also the structure of the ion and the distribution of the charge in it. Is the ion charge really locked inside a cluster sheath, and is it not possible for it to emerge onto the surface of the ion? Although it would appear to be energetically advantageous to have the charge within the cluster surrounded by dipoles, the analogy with a charged conducting sphere can infer that the ion charge is distributed over the surface of the hydration sheath.

Unfortunately, the structure of the hydrated ions has not yet been established. Even in the case of clusters with a small n value, various structure formulae are proposed for instance, in the case of H_50^+2 it is possible to draw both a chain (fig. 4.2, b) and an annular (fig. 4.3, d) structure. As far as more complex clusters are concerned, the number of possibilities increases here. Thus, a chain model (fig 4.2, e), a protoncentered model (fig.3, b) and an oxonium model (fig. 4.3, c) are proposed for $H_90^+_4=H^+(H_20)_4=H_30^+(H_20)_3$. In similar manner there is a chain structure (fig. 4.2, c) and a proton-centered structure (fig. 4.3, a) for $H_70^+_3=H^+(H_20)_3$

as well. The proton-centered structure is based on the fact that in the centre of a cluster ion is a proton which is surrounded on all sides by water molecules, the negative ends of whose dipoles face the proton. Such a structure does not correspond to the assumption regarding the hydration of the oxonium ion. However, in a number of works (see, for example, Ref. 56) the authors consider that the oxonium structure with a central oxygen atom exists solely for H₃0⁺ during further hydration all the water molecules are in an equally justified position with regard to the primary proton. In contrast to this, fig. 4.

3,c shows a structure with an oxonium ion in the centre, which has been hydrated by three water molecules, arranged symmetrically around it. In this case the ion formula can, of course, be written in the form H₃0⁺(H₂0)₃, whereas H⁺(H₂0)₄ is more suitable for the proton-centered structure.

Yet a further possibility are chain structures (see fig. 4.2, b,c,e). In these we are dealing with a recurrent OH group, the O atoms of which are arranged along the chain and linked together by hydrogen atoms, whilst the H atoms are turned almost at right angles to the chain. As the quantum mechanics calculations showed, the maximum (in terms of absolute value) bonding energy for H70⁺3 is found in the chain structure (Ref. 63). In the case of H90⁺4 the chain and oxonium structures are identically advantageous from an energy aspect, whilst the proton-centered model has a somewhat lower bonding energy. It is true that the energy gain is not great (less than 1 eV) and, possibly, lies within the accuracy limits of the approximated calculation methods. As will be seen from figs. 4.2 and 4.3 the chain structures are not drawn out in a straight line, but instead reveal a tendency towards twisting, which will probably manifest itself to a greater degree in more complex clusters.

The same work (Ref. 63) contains calculations for the H and O atom charges for both chain and oxonium models of clusters. These are shown in figs 4.2 and 4.3 (in electron charge units, e). It should be remembered that in a

water molecule model two protonss carry charges of + 0.13 e, whilst the oxygen atom carries a charge of -0.26 e. As will be seen from fig. 4.2, in the chain structure of an H₉0₄⁺ cluster, the lateral hydrogen atoms arranged along a chain have a charge which is close to the hydrogen atom charge in a neutral water molecule (+ 0.21 e instead of + 0.13 e). The end water molecules (oxygen and two hydrogen atoms) have a total charge of no more than 0.15 e, i.e. one seventh of the ordinary ion charge. The main ion charge is concentrated in the hydrogen atoms arranged along the centre line of the molecule. This charge is partially bonded with noticeable negative charges of 0 atoms on the centre line. In the oxonium structure (see fig. 4.3, c) the end water molecules have small charges (+ 0.15 e); the main part of the positive charge is inside the cluster in the oxonium ion, where it is partially bonded by the negative oxygen charge.

Thus, in ${\rm Hg0}_{\begin{subarray}{c} 4}^{\begin{subarray}{c} 4}$ clusters, there is a tendency towards bonding of the ion charge in the inside of a cluster. It can be expected that the proton-centered structure leads to the maximum charge concentration in the centre of the ion. Similar structures also occur in the case of ${\rm OH^-(H_2O)}_n$ clusters (Ref. 63), which, in many respects are reminiscent of the hydrated oxonium ion. It is not impossible that some of the cluster isomers are stable with regard to recombination and can form a metastable ion plasma, whilst the others are not.

What are examined above are largely hydration clusters, the sheaths of which consist of water molecules. The hydrated ions, just like aqueous solutions of electrolytes, are encountered most frequently in nature and have been better investigated experimentally. However, several clusters are now known, whose sheaths consist of other molecules, $0^+2(0_2)_n$, $N0^+$ $N0_2$ (Ref. 64), $NH^+4(NH_3)_3$ (Ref. 65) and others are classed as such clusters. In like manner, not only the proton and OH^- , but also practically all the known ions $(NO^+, O^-2, O^-, N^+2, O^+2)$ etc can be hydrated. We have not set ourselves the task of making any kind of complete survey of information on cluster ions, but if we have

succeeded in creating the impression that in this rapidly developing field there are still considerable gaps in the knowledge acquired, in spite of the fresh and extremely interesting results obtained, then our aim will have been reached. Thus, although it is impossible at present to state with confidence that there is a metastable cluster plasma carrying a considerable charge of internal energy, such an assumption at best does not conflict with current knowledge.

4.3 Composition, energy and density of plasma comprising hydrated H⁺ and OH⁻ions

At present we still do not know which cluster ions constitute the matter of which ball lightning consists. It is most likely that these are molecular and atomic ions of these elements which enter into the composition of atmospheric air $(0^+2, N^+2, H^+, H_20^+, OH^-, O^-2, O^- \text{ etc})$. However, if the lightning channel passes through metal objects, this could also involve metal To some extent the cluster sheaths of these ions probably consist of molecules of water, which is always present in the atmosphere and on the surface of the ground in considerable quantities, especially when it is raining, although it is possible that other molecules as well are encountered, for instance O2, N2, CO2 etc. Among this great variety of ions a relatively detailed study has so far been made of H3O+ and OH- ions only, the hydration sheaths of which are very similar. It is not only their bonding energies which are known (see Table 4.1), but also the equilibrium constants, as well as the hydration reaction rate constants. For this reason alone we shall examine below ball lightning consisting of such ions. The question arises as to whether it is worth looking for a lost purse only where the lantern shines, because it is lighter there? Whilst agreeing with such a reproach, we shall nevertheless continue our calculations, although we have to point out that they involve not the development of a true model of ball lightning, but only a demonstration of those possibilities which the cluster hypothesis include. We are far from

stating that ball lightning largely consists of hydrated H₃O⁺ and OH⁻ ions, but we are fully prepared to show on the strength of this example that, under the conditions in which ball lightning exists, the hydration sheaths of ions do in fact contain a large number of molecules (in contrast to the conditions in the ionosphere, where the degree of hydration is usually small). Moreover, the density and internal energy of the matter consisting of such ions correspond to those which can be expected in the case of ball lightning. Of course, it does not follow from this that what is said above must refer exclusively to H₃O⁺ and OH⁻ ion hydrates.

The equilibrium constants for a reaction of type

$$H_3O^+(H_2O)_{4-1}-H_2O \rightleftharpoons H_3O^+(H_2O)_4$$
 (4.7)

are determined as

$$K_{s-1} = n_s / (n_{s-1} n_0),$$
 (4.8)

where n_s is the quantity of $H_30^+(H_20)_s$ ions in 1 cm³; n_o is the quantity of water molecules, cm⁻³. In similar manner we shall determine the equilibrium constant for the hydration of the OH⁻ ion:

$$OH^{-}(H_{2}O)_{s-1} + H_{2}O \rightleftharpoons OH^{-}(H_{2}O)_{s}; \qquad (4.9)$$

$$K'_{s-1} = n'_{s}/(n'_{s-1}n_{0}), \qquad (4.10)$$

where n'_s is the density of the $OH^-(H_2O)_s$ ions. The constants K_s and K'_s and their relationship to the temperature in the 300-900°K range were obtained in the works listed as Refs. 56 and 57. Figs. 4.4 and 4.5 show the values of the equilibrium constants $K_s^{(p)}$ and $K'_s^{(p)}$, which are determined not by the density of the number of ions, but by the partial pressures. They are associated with K_s and K'_s by the simple relations

$$K_s = TK_s^{(p)}; K'_s = TK'_s^{(p)},$$
 (4.11)

where T is the absolute temperature in energy units (ergs). Ref. 56 describes how also the relationship of $K_S^{(p)}$ to the temperature was obtained in the form

$$\lg K_s^{(p)} = A_s / T - B_s. \tag{4.12}$$

The coefficients ${\rm A_S}$ and ${\rm B_S}$ for 1 $\,\leqslant\,$ s $\,\leqslant\,$ 6 were determined at the same time .

We shall use these data for calculating the composition of the mixture consisting of $\mathrm{H_3O^+(H_2O)_S}$, $\mathrm{OH^-(H_2O)_S}$ ions and water vapour at atmospheric pressure. Using as a basis the results obtained for ball lightning we shall assume that the temperature of the mixture is $500^\circ\mathrm{K} \leqslant T \leqslant 700^\circ\mathrm{K}$. The constant $\mathrm{K_6}$ was, apparently, determined insufficiently reliably, whilst the $\mathrm{K'_S}$ values were determined for $\mathrm{s} \leqslant 4$ only. We shall consider that ions with hydration sheaths containing more than six water molecules hardly form (this does, in fact, occur when T > $600^\circ\mathrm{K}$), whilst the missing constant $\mathrm{K'_S}$ is obtained by extrapolation:

$$K_5/K_4 = K_5/K_4.$$
 (4.13)

The relation (4.13) is probably close to the truth due to the similarity of the ${\rm H_3O^+}$ and ${\rm OH^-}$ hydrates with an identical number of molecules in the sheath. Table 4.2 shows the ${\rm K_S}$ and ${\rm K'_S}$ values used by us. Let us note that the equilibrium constants for the reactions examined were obtained by various authors; the results obtained by them agree with each other. The ${\rm K_O}$ and ${\rm K'_O}$ values are not given, because the unhydrated ion content under the conditions examined is insignificant and need not be calculated.

In order to calculate the composition it is necessary to set a further degree of ionization or quantity of free water molecules in 1 cm^3 (n_0). We shall use n to denote the number of pairs of positive and negative ions in a unit of volume n:

$$n = \sum_{s=1}^{6} n_s = \sum_{s=1}^{6} n'_s. \tag{4.14}$$

The total number of particles in the system is determined by the temperature and pressure.

$$2n + n_0 = p/T.$$
 (4.15)

Two further cases will be examined:

1) $2n/n_0 = 4$ and 2) $2n/n_0 = 1$. The solution to the chemical equilbrium equations (4.8), (4.10) can be conveniently represented in the form

$$n_6 = n/D$$
, $n_i = n_{i+1}/(K_i n_0)$, $i = 5, 4, ..., 1, (4.16)$

where

$$D = 1 + \sum_{i=1}^{5} \frac{1}{n^{i} \cdot \prod_{i=0}^{i} K_{i-i}}, \tag{4.17}$$

and, in similar manner, n'_{S} can be expressed by K'_{S} . Tables 4.3 and 4.4 give the results obtained from the calculations.

It will be seen from these tables that when $2n/n_0 = 1$ (identical content of ions and free water molecules) ions with hydration sheaths comprising 4-6 water molecules predominate in the mixture in the entire 500-700°C temperature range. In the case of small concentrations of free molecules $(2n/n_0 = 4)$ these ions predominate at 500-600°K only, whilst at 700°K the content of ions with s = 6 becomes small and the main components in the mixture are clusters with s = 3-5. Ions with an unfilled first sheath (s < 3) are encountered in all the cases examined, solely in the form of an impurity. However, unlike the predominant ion components (s \geqslant 3), the density of such ions increases rapidly as the temperature rises. Thus, the concentration of ${
m H_3O^+(H_2O)_2}$ ions increases when there is an increase in temperature from 500 to 600°K by approx. four orders of magnitude, and by a further two or three orders of magnitude during the transition from 600 to 700°K, whilst the concentration of the ${\rm H_30^+(H_20)_4}$ ion increases at best by an order of magnitude and less when the temperature increases by 100°K, and the concentration of the H₃0+(H₂0)₆ ion decreases monotonically as the temperature rises. The cause of this is readily understood since, according to (4.16)

$$n_2 = (n/D) \left[K_5 K_4 K_3 K_2 n_0^4 \right]^{-1} \sim n \exp\left(-E_s/T\right). \quad (4.18)$$

Because n and D \approx 1 + (K₅n_o)⁻¹+(K₅K₄n²_o)⁻¹ depends only slightly on the temperature, the relationship n₂(T) is largely determined by the hydration constants in the denominator (4.18). The latter decrease exponentially with the temperature, the indices of the exponential curve for K₃ and K₂ being particularly great. The use of formula (4.12) and values of coefficients A_s obtained in Ref. 56 yields E_s \approx 2.5 eV.

We shall calculate the energy contained in 1 cm³ of the mixture being examined. During the recombination of H⁺ and OH⁻ ions an energy of 11.8 eV is released (ionization potential of the hydrogen atom is equal to 13.5, whilst the energy for binding the electron with the hydroxyl group is 1.7 eV). The bonding of the H and OH atoms involving the formation of water molecules yields a further 5 eV. Thus, the energy released in the final analysis after recombination of these ions is approx. 17 eV. However, 7.2 eV are expended on the disintegration of the H₃O⁺ ion into a proton and water molecule. Consequently, approx. 9.6 eV must be released during the recombination of H₃O⁺ and OH⁻.

By using the data in Table 4.1 it is easy to calculate that the following energies in eV are expended on the disintegration of the hydration sheaths of ions:

Number of water	H ₃ O ⁺ (H ₂ O) _s	OH-(H2O)s
molecules in the		
sheath (s)		
. 3	3.28	2.47
4	3.94	3.09
5	4.5	3.70
6	5.01	4.2

Furthermore, to be specific we shall examine the case T=600°K, $2n/n_0$ =4. During the recombination of 0.48×10^{19} pairs of H_30^+ and OH^- ions contained in 1 cm³ an energy of 7.6 J/cm³ is released. It follows from Table 4.3 that an energy of 6.4 J/cm³ is expended on the disintegration of the hydration sheaths of these ions; in this case 5.0×10^{19} water molecules form. The total quantity of water molecules, together with two molecules per pair of ions (these molecules form as a result of the recombination of H_30^+ and OH^-) and $O.24 \times 10^{19}$ free water molecules, amounts to 0.2×10^{19} cm⁻³. During the condensation of each of these molecules in the surrounding air approx. 0.45 eV is released, thus yielding a further 4.5 J/cm^3 . Thus, when 1 cm³ of cluster

matter is transformed into water, 5.7 J/cm^3 are released. 47 KJ are contained in a 25 cm diameter sphere.

The density of the matter being examined can be easily determined by multiplying the total number of water molecules contained in a unit of volume (6.2×10^{19}) by the mass of one molecule. This yields $1.8 \times 10^{-3} \text{g/cm}^3$. Thus, we obtain the energy density corresponding approximately to that which can be expected in ball lightning and exceeding the air density under normal conditions. A similar calculation for $T = 600^{\circ}\text{K}$, $2 \text{n/n}_0 = 1$ yields an energy density of 3.7 J/cm^3 and a density of the matter of $1.34 \times 10^{-3} \text{g/cm}^3$, i.e. that approximately equal to the air density.

A higher energy density can be obtained if we examine instead of the oxonium ion the hydrates of other ions contained in atmospheric air, for instance 0⁺, 0⁺2, or N⁺, N⁺2, N0⁺. The fact is that a very considerable energy level - more than 7 eV - is expended on the disintegration of the H₃0⁺ ion. In the case of other ions, the hydration of the first water molecule does not, as a rule, result in such high binding energies. This yields additionally from 7 to 10 J/cm³. As a result the energy density of the matter constituting lightning can reach 10-15 J/cm³, whilst the total energy of ball lightning of average size reaches approximately 100-150 kJ. In the case of lightning of large dimensions (50 cm in diameter) the energy reserve can amount to several hundred kilojoules.

The frequency of triple collisions between two oppositely charged clusters and an arbitrary third particle is equal to $\delta n_s n'_t \delta \bar{\nu}$, where $n_s n'_t$ are the densities of the positively and negatively charged clusters with s and ℓ water molecules in the hydration sheaths; δ is the collision section of two clusters; $\bar{\nu}$ is the mean velocity; δ is the ratio of the number of triple and binary collisions; it is equal to the probability of

finding the arbitrary third particle around two colliding cluster ions. On this basis the order of magnitude of δ must be equal to the ratio of the volume of colliding particles to the specific volume per particle, i.e.

 $\delta \simeq n_{\Sigma} (4/3/\pi D^3)$, where D is the cluster diameter, and $n_{\Sigma} = 2n + n_0$ is the total number of particles in 1 cm³.

In the foregoing we assessed the cluster diameter D with a filled first sheath having a value of 6 x 10^{-8} cm. In the case of clusters with a small number of molecules in the hydration sheath, which will now be of interest to us, the value of D is 1.5 - 2 times less. However, with the intention of assessing the upper limit of the number of triple collisions, we shall adopt $D \approx 6 \times 10^{-8}$ cm with $T = 600^{\circ}$ K, $D^{\Sigma} = 1.2 \times 10^{19}$ cm³, $\delta \approx 10^{-2}$. By also assuming $\delta = \pi D^2 \simeq 10^{-14}$ cm⁻² and $\tilde{\nu} = 2.7 \times 10^4$ cm/sec ($T = 600^{\circ}$ K, and the relative molecular mass is 70), we find that the number of triple collisions examined is equal to

$$2,7 \cdot 10^{-12} \, n_b n'_l. \tag{4.19}$$

If we assume that recombination takes place at each triple collision, the recombination time of all the ions through the path in question (s, l) is determined by expression

$$0.4 \cdot 10^{12} \, n / (n_s n'_l) \,. \tag{4.20}$$

Let us assume that recombination can take place only in the case of a collision between clusters with not fully filled sheaths (s, $l \le 2$). Since n_1 , $n'_1 \le n_2$, n'_2 it is sufficient to examine channel s = l = 2. By using the values of n_1 , n'_2 from Tables 4.3 and 4.4 we find that, when $T = 600^{\circ}K$, the recombination time is 21 secs when $2n/n_0 = 4$ and $2x10^4$ sec when $2n/n_0 = 1$. If, for clusters of unfilled sheaths, we take a value of diameter D which is 1.5 times smaller, the figures shown increase approximately by an order of magnitude. Thus, the recombination time via this route (through collisions between the light clusters) greatly exceeds the life span of ball lightning. This means that, at not very high temperatures (of the order of $600^{\circ}K$), another,

more effective recombination route must exist. One of the possible mechanisms is examined below.

In conclusion let us dwell on the rate at which the hydration sheaths of ions are formed. The coefficients of the ion hydration rate by the first, second and third water molecule were measured in Ref. 66, and at T = 400° K they were equal (in cm⁶ sec ⁻¹) $k_1 = 3.4 \times 10^{-27}$, $k_2 = 2.3 \times 10^{-27}$, $k_3 = 2.4 \times 10^{-27}$. All three reactions were of third order; since the experiments were conducted in a nitrogen atmosphere, the N₂ molecule was the third body (not involved in the reaction). A number of different results were obtained in Ref. 67 (at T= -340° K): $k_1 = 6 \times 10^{-28}$, $k_2 = 6 \times 10^{-28}$, $k_3 = 2 \times 10^{-28}$. The decrease in the reaction rate was probably due to the fact that Ar was the third body in the case in question. In some other works (see for example Ref. 64) results were also obtained, according to which the hydration rate constants were within limits of $1-4 \times 10^{-27}$ cm⁶ sec⁻¹ at T = 400° K. Hence the time (in seconds) taken for a cluster sheath to form is

$$\tau_0 = 1/(kn_0n_v) \approx 10^{-11}$$

with k=2x10⁻²⁷cm⁶ x sec⁻¹, n=0.5 x 10¹⁹ cm⁻², $n_{\chi} = 10^{19}$ cm⁻³. Because the hydration rate depends only slightly on the temperature, \mathcal{T}_0 has, at higher temperatures (600-1000°K) as well, approximately the same value. Consequently, the time taken for hydration sheaths to form is of the same order of magnitude as the recombination time of unhydrated ions. The hydration process can compete successfully with recombination, particularly under conditions where there is a considerable quantity of neutral water molecules, whilst the ion concentration is small.

The reverse reaction (dehydration) rate at room temperatures is considerably less. This second order reaction, with $k=10^{-12}$ - 10^{-14} cm³ x sec⁻¹ leads, when n $\approx 10^{19}$ cm³, to $\mathcal{T} = 10^{-5} \cdot 10^{-7}$ sec. The dehydration rate increases rapidly when there is a rise in temperature. It is evident that

during the life span of ball lightning the equilibrium state of the hydration sheaths of ions manages to establish itself in any case.

4.4 Thermal stability of cluster plasma

In this section we shall be examining the processes which can result in ball lightning exploding, and also in fluctuations in its temperature (and its radiation intensity) (Ref. 68). It has been shown in the previous section that, at fairly low temperatures (500-600°K), recombination through the collision of ions with unfilled hydration sheaths takes place very slowly (due to the low concentration of such ions). However, it appears that under these conditions another recombination route, in which all the ions are involved, is more likely. A collision between these two oppositely charged clusters can lead to the formation of a neutral cluster containing both a positive and negative ion, which are separated from each other by hydration sheaths. Such a particle can be regarded as a microscopic water droplet, in which two ions with charges of opposite signs have been placed. Because of the high dielectric permeability of water, the interacton of ions will be very considerably weakened (almost by two orders of magnitude) by hydration sheaths. Nevertheless the probability of recombination in such a cluster increases considerably in comparison with the gas phase due to prolonged direct contact between the ions themselves. A certain activation energy E' is required to pull the charge out of the cluster sheath, so that the mean life span of a neutral cluster \mathcal{T}' with regard to the recombination of ions in it is subject to relation.

$$\tau' \sim \exp(E'/T)$$
. (4.21)

The neutral clusters consisting of ions with a large number of molecules in the hydration sheath are very loose formations, whose bond energy with regard to disintegration into two two cluster ions is, apparently, not great. Therefore, when the temperature increase, the concentration of the

neutral clusters n' must decrease - $n/n' \sim \exp{(-E_0/T)}$, where E_0 is the order of magnitude of the binding energy determining the temperature relationship of the corresponding equilibrium constant. The recombination rate (i.e. the number of recombinations in a unit of volume in a unit of time) by this route is given by expression

$$n'/\tau' = \gamma \exp \left[-(E' - E_0)/T\right],$$
 (4.22)

where coefficient γ depends on the ion density n.

Thus, cluster plasma is a metastable and gradually disintegrating substance. Unfortunately, the magnitudes of E' and E are not known at present. Apparently they are approx. 0/5-1 eV. However, the magnitude n'/\mathcal{T}' can be assessed if it is assumed that the disintegration time of cluster plasma by this path coincides with the maximum life span of ball lightning (without allowance for cases involving an explosion and disintegration due to instability) \mathcal{T}_{max} , i.e that

$$\tau_{max} \simeq n\tau'/n'$$
. (4.23)

In the case of lightning of average size $\tau_{max}=25\text{-}50$ sec. When $n=0.5 \times 10^{19}$ we find that $n'/\ell' \approx 10^{17}$ cm⁻³ · sec ⁻¹.

Moreover, the recombination rate due to direct collisions involving clusters with light hydration sheaths in accordance with (4.19) and (4.18) is equal to νn , where ν is the recombination frequency referred to the number of ions

$$v \sim n \exp[-(E_{\bullet} + E'_{\bullet})/T].$$
 (4.24)

In addition, for negative ions n'2,it is possible to write an expression similar to (4.18) with exponent E' $_{\rm S}/{\rm T}$. The magnitude of E $_{\rm S} \approx$ E' $_{\rm S}$ is approx. 2.5 eV, i.e. E $_{\rm S}$ + E' $_{\rm S}$ 5 eV \gg E' - E $_{\rm O} \simeq$ 0.1 eV. Thus, we actually have two recombination paths, one of which (4.22) depends only slightly on the temperature, whilst the other is very temperature-dependent. The overall recomination rate is equal to

$$n'/\tau' + \nu n.$$
 (4.25)

If, during the recombination of a pair of cluster ions, energy $E_{\dot{1}}$ is released, the energy balance in the volume V can be written in the form

$$E_iV(n'/\tau'+vn) = hS(T-T_{\infty}), \qquad (4.26)$$

where S= surface area, h= heat transfer coefficient, T, T_{∞} - temperature of the plasma and surrounding cold air respectively. Assuming that volme V has the form of a sphere of radius R, we find that

$$E_i(n'/\tau' + \nu n) = (3h/R)(T - T_{\infty}).$$
 (4.27)

Let temperature T have increased by magnitude ΔT . Then the heat release, which is determined by the right-hand of (4.27), increases by magnitude $E_i n \Delta v = E_i [(E_s + E'_s)/T^2] n v \Delta T. \qquad (4.28)$

When obtaining (4.28) use was made of equation (4.24) and it was assumed that the dependence of n'/τ' on the temperature can be ignored in comparison with the strong relationship of $\nu(T)$. At the same time the heat transfer increases by a value of $(3/R)h\Delta T$. The state is stable if the interest in heat transfer exceeds the rise in heat release:

$$(3/R)h\Delta T > E_i[(E_s + E'_s)/T^2]n\nabla \Delta T. \qquad (4.29)$$

By using (4.27) it is possible to write the last inequality in the form

$$\frac{vn}{n'/\tau' + vn} \frac{E_s + E'_s}{T} < \frac{1}{1 - T_{\infty}/T}$$
 (4.30)

Since the maximum life span is

$$\tau_{max} = \frac{n}{n'/\tau' + n\nu}, \tag{4.31}$$

then, when $T \approx 600$ °K, $T_{\infty} = 300$ °K, the stability condition (4.30) can be written in the following form:

$$v\tau_{max} \frac{E_s + E'_s}{T} < \frac{1}{1 - T_{\infty}/T} \approx 2.$$
 (4.32)

When condition (4.32) is not fulfilled, the rise in the heat release in cluster plasma is not compensated by heat transfer, and this leads to a rise in temperature and a further increase in the recombination rate and, consequently, in the heat release. The metastable equlibrium state is disturbed, and a chain reaction commences which leads to a sharp increase in temperature and the release of a large quantity of heat, i.e. to an explosion. Since, according to (4.24), ν rises very rapidly when there is an increase in T, an explosion can occur even when there is a comparatively small increase in temperature - by 100-200°K. This is possibly the reason for the explosively hazardous nature of ball lightning.

When $T_{\rm max}=25\text{-}50$ sec, $E_{\rm S}+E_{\rm S}'=5$ eV and $T\simeq0.06$ eV we find that the stability condition (4.32) is fulfulled if $1/\nu\lesssim1\text{-}2$ x 10^3 sec. Thus, in the case of a stable state the recombination time due to direct collisions involving clusters with light hydration sheaths must exceed by several times the maximum life span of ball lightning. Under these conditions recombination will take place almost solely as a result of a neutral cluster forming, i.e.

$$n'/\tau' \gg n\nu. \tag{4.33}$$

The recombination rate (4.25) is determined in a stable state by the first term, and the values of the life span of the metastable state \mathcal{T}_{max} , calculated from formulae (4.23) and (4.31), coincide.

We shall now show that the heat release from ball lightning even in a stable state can undergo considerable fluctuations and be accompanied by fluctuations in the radiation intensity. By taking account of (4.33) we shall write the non-steady equation for the heat balance in the form

$$dW/dt = E_i V n'/\tau' - hS(T - T_{\infty}), \qquad (4.34)$$

where W is the thermal energy contained in the volume V filled with clusters: $W = (2cnT + n_0c_0T)V. \tag{4.35}$

Here n = the number of pairs of ion clusters in 1 cm 3 ; c = their heat capacity; n_0 , c_0 = the number of free water molecules in a unit of volume and their heat capacity repsectively. For the sake of simplicity we shall examine only one type of positive and negative cluster ions and assume that their heat capacities are identical. If the temperature is expressed in energy units, c is a dimensionless number (equal to the ratio of the ordinary heat capacity of a molecule to the Boltzmann constant). In the case of water (at constant pressure), c_0 = 4, and in the case of a cluster ion $4 \le c \le 8$, depending on whether the vibrations of the hydration sheath molecules in the temperature range under examination are excited or not, the number of which is conventionally adopted as being equal to 4. Let us assume that 2 nc $\gg n_0 c_0$, i.e. that the thermal energy contained in the water molecules can be ignored in

comparison with the ion energy.

In time intervals which are brief in comparison with the life span of the metastable state it is possible, by ignoring recombination, to consider that the total number of pairs of ions in the plasma is preserved, i.e. nV = const. By taking this into account we shall remove the product of nV from under the sign of the derivative and, by using formula (4.22), we shall write equation (4.34) in the form

$$d\Theta/dt' = \Theta^{2} \exp(-\eta\Theta) \{ F(\Theta) - \mu \}, \qquad (4.36)$$
where $\Theta = T_{\infty}/T$; $\eta = (E' - E_{0})/T_{\infty}$; $\mu = (E_{i}/T_{\infty}) (R\gamma/3h)$;
$$F(\Theta) = [(1 - \Theta)/\Theta] \exp(-\eta\Theta); \qquad (4.37)$$

$$t' = t/t_{0}; \ t_{0} = 2nRc/(3h). \qquad (4.38)$$

As was mentioned above, the turbulent coefficient of convective heat transfer is equal to 10-20 W (m² x °K) or (1-2) x 10^4 erg/(cm² x °K). If the temperature is measured in energy units, this value has to be divided by the Boltzmann constant equal to 1.38×10^{-16} erg/°K. As a result we shall obtain $h = (0.7-1.4) \ 10^{20} \ cm^{-2}$. When $n = 0.5 \times 10^{19} \ cm^{-3}$, $R = 10 \ cm$, $c \approx 4-8$ we find that the characteristic time scale, in which thermal equlibrium is established with the surrounding air, is $t_0 \approx 2$ sec. Since this value is considerably less than the life span of the metastable state ($\tau_{max} = 25-50$ sec) it can be regarded as justified that the recombination time intervals can be ignored (i.e. $nV \simeq const$).

The right-hand of (4.36) becomes zero when

$$F(\Theta) = \mu. \tag{4.39}$$

The form of function (F(0) depends on the parameter η . When $\eta \leqslant 4$, F(0) diminishes monotonically for $0 \leqslant \theta \leqslant 1$ and, consequently, in the entire temperature range $T_{\infty} \leqslant T \leqslant \infty$ there is only one solution for equation (4.39) and, accordingly, one steady state (at the given μ value), the temperature of which is determined by the root of (4.39). When $\eta > 4$ the relationship of F(θ)

becomes non-monotonic, the position of the extrema being determined by expressions

$$\theta_{1,1} = (1/2) (1 \pm \sqrt{1 - 4/\eta}).$$
 (4.40)

The root θ_1 , which is lower in magnitude, corresponds to the minimum of function $F(\theta)$, and θ_2 corresponds to the maximum. Fig. 4.6 shows the general form of function $F(\theta)$ when $\eta=4.05$. When $F(\theta_1)<\mu< F(\theta_2)$ the system has three steady states which correspond to the roots of equation (4.39). However, only those roots are stable which relate to the diminishing branches of $F(\theta)$, whilst the root lying between θ_1 and θ_2 is unstable. In fact, as will be easily seen from (4.36), any departure from the equilibrium point in this range leads to those values of $d\theta/dt'$, at which these departures increase with time. Thus, a forbidden temperature range arises, which lies between $T_2 = T_{\infty}/\theta_2$ and $T_1 = T_{\infty}/\theta_1$. Accordingly, there are two stable regime ranges: a low temperature one when $T < T_2$ and a high temperature one when $T > T_1$.

Let the cluster plasma be in a high temperature regime range and let the coefficient of the heat exchange h with the ambient air rise slightly, thus resulting in a reduction in μ . When μ is made less than $F(\theta_1)$, the plasma jumps into the low temperature regime range (from point b to point d in fig. 4.6). According to the assessments obtained above, the period of this transition must be of the order of $t_0 \approx 2$ secs. A reduction in the temperature of the cluster plasma and cooling of the air surrounding it can lead to a reduction in the heat transfer coefficient and to an increase in μ . If μ exceeds the value of $F(\theta)_2$, the matter once more passes into the high temperature regime range (from c to a in fig. 4.6). Such a transition is accompanied by an increase in temperature (by more than 200° for $\eta = 4.05$) and an increase in heat-exchange. This transition must also lead to a considerable increase in the luminous emittance from the lightning. When the temperature of the lightning increases, the ambient air heats up, the heat transfer coefficient

increases, and the entire cycle is repeated. It is interesting to note that changes in the heat transfer coefficient, resulting in such great changes in temperature are insignificant in themselves; as will be seen from fig. 4.6, they amount to less than 0.5%. Thus it is possible to explain (Ref. 68) the periodic fluctuations in the radiation intensity of ball lightning observed on a photograph (Ref. 24). The observed period of oscillations is of the order of $1 \sec$, a value which coincides with the magnitude t_0 .

When $\eta \geqslant 5$ the high temperature regime range T > T_{∞}/θ_2 accounts for temperatures exceeding 1000°K. Under these conditions the number of clusters with light sheaths increases sharply and the stability condition is disturbed. Accordingly, the upper part of the curve in fig. 4.6 (higher than point a) is also represented by a dotted line. When $\eta = 4$, the difference E'-E₀ is equal to approx. 0.1 eV. Let us note in conclusion that the purpose of this calculation is to illustrate the possibility in principle of explaining the considerable fluctuations in the heat release and temperature of metastable cluster plasma, which is in thermal equlibrium with the ambient air. We cannot claim precise knowledge of the boundaries of various temperature regimes or even a full qualitative analysis of the phenomenon. In fact, a series of important factors influencing the thermal balance, for instance heat release due to a change in the cluster sheaths during a shift in the thermodynamic equilibrium, were not taken into account. The binding energies and the equlibrium constants of neutral clusters are likewise not known.

4.5 Stability, size and life span

We saw in the preceding sections that a plasma consisting of cluster ions must, in the same manner as ball lightning, be a very unstable or metastable state of matter which gradually disintegrates due to recombination.

Insignificant changes (~0.3-0.4%) in the heat transfer coefficient can lead to a considerable (by more than 200°) temperature variation, whilst comparatively small temperature variations (by 200-300°) can lead to an explosion. In addition to the thermal instabilities, the disintegration of ball lightning can also be caused by the build-up of vibrations on its surface. As a result, cluster ions are dispersed in the ambient atmosphere and the lightning vanishes without an explosion. This can occur due to its moving, although, as was shown in Chapter 2, surface tension leads to stabilization of the tangential velocity gradient or step on its boundary.

Let us examine another important instability which develops due to the difference in the density of cluster plasma and the ambient air. It is referred to as the Rayleigh-Taylor instability.

It is known that the state in which a dense fluid is on top of a light one is unstable. The small perturbations affecting a planar boundary in such a system start to increase aperiodically and, as a result, the layer of heavier fluid disintegrates into separate "pieces" which penetrate downwards into the light fluid where they sink. The same phenomenon is observed in fluids or gases in the field of gravity when the temperature of the medium diminishes with height. As a result of thermal expansion, the denser layers are above the less dense ones, and this also leads to unstable mechanical equilibrium, which is disturbed by any small perturbations exciting the convective flows.

It is only by pure chance that the matter constituting the lightning, the temperature and relative molecular mass of which differ from the temperature and molecular mass of the ambient air, can have a density equal to that of air. Although a change in density due to a rise in temperature very largely balances

the molecular weight of cluster ions, precise compensation is, of course, highly unlikely. However, in this case, the question is not solved as for a planar layer, where the boundary is stable, if the lighter medium is on top of a heavier one, and unstable if the position is reversed. In the case of a spherical body, whatever its density with regard to the density of the ambient medium, on one half of the surface of the sphere the heavy medium will be on top of the light one, whilst on the other half the position will be the reverse. The question regarding the stability of a spherical boundary was examined in Ref. 69, the main results contained in which will be given here.

We shall introduce a spherical system of co ordinates $r\theta \rho$. Let the matter constituting the ball lightning be inside a sphere with radius $r=R_0$. The occurrence of a wave on the surface of the sphere leads to a small displacement in the boundary points by a value of $\xi=R-R_0$. We shall use p, ρ, ψ respectively to designate the pressure, density and the velocity potential. Since, in an incompressible liquid $\rho \partial \psi/\partial t + p + gz \rho = const$, the pressure difference on the boundary is equal to

$$p_1 - p_2 = -\rho_1 \partial \psi_1 / \partial t + \rho_2 \partial \psi_2 / \partial t - (\rho_1 - \rho_2) gz \qquad (4.41)$$

(g = free fall acceleration). Here and henceforward subscript "l" refers to the matter constituting the lightning, and "2" refers to the ambient air.

In accordance with the Laplacian law for surface tension, the left-hand of expression (4.41) is proportional to the sum of the reverse radii of curvature, and it can be shown (Ref. 27, p.292) that, when $\xi \ll R_o$, it is expressed in the form

$$\rho_1 - \rho_2 = 2\xi \sigma / R^2_0 - \sigma \hat{M} \xi / R^2_0, \tag{4.42}$$

where the operator M is determined as

$$\widehat{M} \equiv \frac{1}{\sin \theta} \frac{\partial}{\partial \theta} \left(\sin \theta \frac{\partial}{\partial \theta} \right) + \frac{1}{\sin^2 \theta} \frac{\partial^2}{\partial \varphi^2}, \quad (4.43)$$

whilst σ is the surface tension coefficient. The velocity potentials inside $(\psi_1(r,\theta,\varphi))$ and outside $(\psi_2(r,\theta,\varphi))$ the sphere must satisfy the Laplace equation

$$\Delta \psi = 0, \qquad (4.44)$$

and on the boundary (R $_{
m o}$, heta, arphi) the equality of normal derivatives is fulfilled:

$$\partial \psi_2 / \partial r = \partial \psi_1 / \partial r.$$
 (4.45)

By equating (4.42) and 4.41) it is possible to obtain a second boundary condition

$$-\rho_1 \frac{\partial \psi_1}{\partial t} + \rho_3 \frac{\partial \psi_2}{\partial t} - (\rho_1 - \rho_2) gz = \frac{\sigma}{R^2_0} (\widehat{M} + 2) \xi.$$

$$(4.46)$$

By taking into account that $z=(R_0+\xi)\cos\theta$, $(\partial\xi/\partial t)_{\theta,\varphi}=v_r=(\partial\psi/\partial r)_{\theta\varphi}$, we shall differentiate (4.46) with respect to t in the case of constants R_0 , θ , φ . By assuming ψ -exp(-i ω t), we obtain

$$(\rho_1 \psi_1 - \rho_2 \psi_2) \omega^2 - (\rho_1 - \rho_2) g \cos \theta \frac{\partial \psi}{\partial r} + \frac{\sigma}{R^2 \sigma} (\hat{M} + 2) \frac{\partial \psi}{\partial r} = 0. \tag{4.47}$$

The restricted solution (when r=0) to the Laplace equation within the sphere $r=R_0$ has the following form

$$\psi_{i} = \sum_{l=1}^{\infty} \sum_{m=-l}^{l} A_{i}^{(m)} Y_{i}^{(m)} (0, \varphi) r^{l}, \qquad (4.48)$$

where $Y^{(m)}_{l}(\theta, \varphi)$ are spherical functions. The term with l=0 is discarded because the velocity potential is determined with an accuracy to an arbitrary constant, the appropriate choice of which can result in this term becoming zero. Outside the sphere the restricted solution (when $r \rightarrow \infty$) to equation (4.44) can be written as

$$\psi_{2} = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} B_{l}^{(m)} Y_{l}^{(m)} (\emptyset, \varphi) r^{-l-1}. \tag{4.49}$$

The equality (4.45) determines the association of the factorization coefficients $A_1^{(m)}$ and $B_1^{(m)}$:

$$B_{\circ} = 0; \quad B_{l}^{(m)} = -\frac{l}{l+1} R_{0}^{2l+1} A_{l}^{(m)}.$$
 (4.50)

By taking this into account and substituting the expression obtained into (4.47), we find

$$\sum_{l=1}^{\infty} \sum_{m=-l}^{l} C_{l}^{(m)} Y_{l}^{(m)} \left\{ \left(1 + \frac{l}{l+1} \frac{\rho_{2}}{\rho_{1}} \right) \Omega^{2} - l (l-1) (l+2) \right\} = 2\eta \sum_{l=1}^{\infty} \sum_{m=-l}^{l} C_{l}^{(m)} l \cos \theta Y_{l}^{(m)}, (4.51)$$

where the following designations have been introduced:

$$C_{l}^{(m)} = A_{l}^{(m)} R_{0}^{l};
\eta = (\rho_{1} - \rho_{2}) g R_{0}^{2} / 2\sigma;
\Omega^{2} = \omega^{2} \rho_{1} R_{0}^{3} / \sigma.$$
(4.52)

By multiplying (4.51) by $Y_n^{(s)*}$ and carrying out integration over the angles, we arrive at the following system of equations

$$C_{l}^{(m)}(\Omega^{2}-E_{l})=2\eta(\mu_{l}^{(m)}C_{l-1}^{(m)}+\lambda_{l}^{(m)}C_{l-1}^{(m)}),$$
 (4.53)

where

$$E_{l} = \frac{l (l-1) (l+2)}{1 + [l/(l+1)] (\rho_{2}/\rho_{1})}; \qquad (4.54)$$

$$\mu_{l}^{(m)} = \frac{l-1}{1 + [l/(l+1)] (\rho_{2}/\rho_{1})} \sqrt{\frac{l^{2} - m^{2}}{4l^{2} - 1}};$$

$$\lambda_{l}^{(m)} = \frac{l+1}{1 + [l/(l+1)] (\rho_{2}/\rho_{1})} \sqrt{\frac{(l+1)^{2} - m^{2}}{4 (l+1)^{2} - 1}}.$$

Equation (4.53) can be used to determine coefficients $\binom{l}{l}$ when l=2,3,4 etc. (l=1 corresponds to the reciprocal movement of the sphere as a whole, and not any surface wave mode). However, it is more important to find the frequency spectrum of these waves, i.e. the value of Ω for each mode.

When $\eta \ll 1$ the right-hand of (4.53) is small and this equation can be solved by the perturbation method (Ref. 70, p.159). The unperturbed spectrum is determined by the equality $\Omega^2 = E_l$, which corresponds to the normal spectrum of surface vibrations on a sphere in the absence of the force of gravity (Ref. 27, p.293). Corrections to these frequencies occur in the second order of the theory of perturbations and are determined by expressions:

$$\Omega^2 = E_1 + \Delta_1^{(m)} \,, \tag{4.56}$$

where

$$\Delta_{l}^{(m)} = -4\eta^{2} \left(N_{l+1}^{(m)} - N_{l}^{(m)}\right); \qquad (4.57)$$

$$N_{l}^{(m)} = \frac{l^{2} - m^{2}}{4l^{2} - 1} \times \frac{l}{l} \times \frac{l}{l(l+2)\left\{1 + \frac{l(l-1)/l}{l(\rho_{2}/\rho_{1})} - \frac{(l+1)(l-2)\left\{1 + \frac{l}{l(l+1)}\right\}}{l(l+1)\left[\frac{(\rho_{2}/\rho_{1})}{l(\rho_{2}/\rho_{1})}\right\}} \qquad (4.58)$$

Thus, the difference in densities $[\eta \sim (\ \rho_2 - \ \rho_1)]$ leads - irrespective of its sign - to a reduction in the natural frequencies of the capillary waves and to removal of the degeneration in terms of m (vibrations with varying values of m have a different frequency). Corrections to a reduction in the natural frequency $\ell=2$ will be of interest to us. If the density of the ball lightning and of the ambient air do not differ greatly one from the other, then, by assuming that $\rho_2/\rho_1=1$ in the expression for $N_2^{(m)}$ (although not for η), we obtain

$$\Delta_2^{(0)} = \frac{2}{315} \eta^a$$
, $\Delta_2^{(1)} = -\frac{2}{105} \eta^a$, $\Delta_2^{(2)} = -\frac{2}{21} \eta^a$. (4.59)

The maximum reduction in the frequency is experienced by a vibration with m = 2. When this change is made so appreciable that

$$E_1 + \Delta_2^{(2)} = 0,$$
 (4.60)

the natural frequency of the corresponding mode will become zero, after which (when η is further increased) its square will be made negative. The wave amplitude will start to increase aperiodically and the stability of the boundary will be disturbed. It follows from (4.59) and (4.60) and the expression for E₂ (4.54) that the instability region corresponds to

$$\eta > \eta_0 \approx 7. \tag{4.61}$$

If the air around the boundary of the lightning has become heated and has acquired a temperature close to that of the matter constituting the lightning, then, because of the high relative molecular mass of the latter (1) > 0 and in (4.54), (4.58) can be assumed to be (0) < 0 and (0) < 0. This leads to somewhat different values of (0) < 0 although the stability criterion in terms of (0) almost coincides with (4.61) in this case as well. It follows from (4.61) and a determination of (4.52) that ball lightning maintains its stability if

$$\sqrt[V]{g|\rho_1 - \rho_2|/2\sigma}R < \sqrt{\eta_2} \approx 2.5. \tag{4.62}$$

It should be noted that the formulae obtained above for Ω^2 and $\Delta_l^{(m)}$, are, strictly speaking, true only when $\eta < 1$. Condition (4.60) requires that the limits of this range be greatly exceeded and, therefore, the numerical value of the stability boundary η_0 can be different. However, as will be seen from (4.62), the stability condition depends only slightly on η_0 .

According to the results given in Chapter 2, the surface tension coefficient 6 must lie within limits of 1 < 6 < 10 erg x cm². Let us assume for the estimates that 6 = 2 erg x cm⁻². Then, when $\eta_0 = 7$, we shall obtain from formula (4.62) the upper limit of the permissible value of the modulus of difference [ϱ_1 - ϱ_2]. For comparison purposes it is convenient to relate this value to the density of cold air $\varrho_0 = 1.3 \times 10^{-3} \mathrm{g \ x \ cm^{-3}}$:

$$|\rho_1 - \rho_2|/\rho_0 < 21.5/R^2,$$
 (4.63)

where R is expressed in cm. If the air around the lightning does not become heated, $\rho_2 = \rho_0$.

Formulae (4.62), (4.63) enable us to understand why ball lightning of large diameter (~1 m and greater) is not encountered. In fact, in accordance with (4.63), when R = 50 cm, we find that the density of the matter constituting the lightning must differ from the density of the ambient air by less than 1%, i.e. special initial conditions, which are very difficult to fulfill, are required for the stability of the ambient air. Moreover, even if this is achieved and the initial value of ho_1 lies in the required narrow range, it can be stated with confidence that such ball lightning disintegrates rapidly. In reality, the density of its matter varies in the course of time because the recombination of cluster ions leads to the release of light molecules of water from the ion sheaths and to a gradual reduction in the value of $\,
ho_1.\,$ In the case under examination, recombination of a very small proportion (~1%) of the clusters brings the ball lightning outside the limits of the stability range. Even small fluctuations in the density of the ambient air $\, e_2 \,$ (for example, due to its being heated with a flow of heat) can lead to the same result. Therefore, even when a fairly large number of cluster ions are present they may not form a connected body whose diameter would exceed 1 m.

Condition (4.63) imposes practically no restrictions on ball lightning of small dimensions (with R of the order of a few centimetres). However, the life span of ball lightning must diminish in proportion to the decrease in its radius. In fact, the energy reserve decreases proportional to R^3 , whereas the energy flux diminishes only as R^2 . Therefore, if lightning of medium size ($R \approx 10\text{-}12 \text{ cm}$) becomes de-excited in approx. 20-25 secs, then in the case of a diameter of approx. 1 cm it should become de-excited within a time of the order of 1 second. Such fire balls are practically inaccessible as regards observations. In the case of the dimensions most frequently encountered ($R \approx 10 \text{ cm}$) condition (4.63) represents an appreciable, although not rigid

restriction. In this case it amounts to a requirement of $|\rho_1 - \rho_2|/|\rho_0| \approx 0.2$. A variation in σ within limits of from 1 to 10 erg x cm⁻² hardly changes these conclusions.

In conclusion let us return to the question regarding how ball lightning vanishes. If its thermal equilibrium becomes unstable (see (4.32)), it explodes. If the stability condition is disturbed (4.62), a build-up of surface waves commences, which terminates either in the lightning disintegrating into a number of fire balls with a smaller radius (and, accordingly, a reduction in life span) or the matter constituting it becoming completely mixed with the surrounding atmosphere. In either case ball lightning may vanish long before its energy reserve is exhausted. However, there are also data available from a considerable number of observations (approx. 30%), where ball lightning becomes quietly extinguished. Apparently, this occurs when lightning, which has escaped destruction through various forms of instability, has spent its energy. An interesting fact is that it normally does not change during the greater part of its life span. This can be explained by the existence of effective mechanisms which stabilize the temperature of ball lightning.

In particular, the release of heat during the formation of hydration sheaths can ensure one of the mechanisms involved in automatic temperature control. In fact, when the temperature decreases, the hydration ion sheaths increase due to the combination of free water molecules. This is accompanied by the release of a considerable quantity of heat, which impedes any further reduction in temperature. On the other hand, when the temperature increases, the heat is absorbed by the disintegrating cluster sheaths. In principle, the possibility of the recombination of hydrated ions being made unfavourable in terms of energy is not precluded when the hydration sheaths are sufficiently large. Moreover, heat release and radiation do, of course, cease, the temperature drops, and the remaining ions are dispersed in the ambient air.

4.6 More about the occurrence of ball lightning

There is no doubt that the origin of ball lightning is closely linked with a discharge of linear lightning. First of all it is necessary to discuss two questions:

- 1. Where does the energy stored in ball lightning come from?
- Where does the matter constituting ball lightning come from?

As far as the first question is concerned, there is practically no doubt that energy is fed to the lightning via a linear lightning channel, after which (in any case according to the cluster hypothesis) it is stored in the form of energy resulting from the ionization of cluster ions. By assuming that the difference in potentials between a cloud and the earth can reach 10^8V ., and the charge carried by a discharge of lightning, 20-30 coulombs (Ref. 1), we find that the energy released in a discharge of linear lightning is 2-3 x 10^9 J. With a mean channel length of 3-5 km (Ref. 1) the energy per unit of length is approx. 5×10^5 J/m, i.e. approx. equal to the upper limit of the energy contained in the ball lightning. During discharge this energy is distributed along the channel and can initiate the occurrence of ball lightning. In some cases it can be transmitted along conductors for a considerable distance from the point struck by linear lightning.

It is more difficult to solve the problem regarding the matter constituting ball lightning. The source materials are without doubt ionized particles of air, which are then hydrated by water molecules or other molecules having a high dipole moment. As experience gained from studying the chemistry of the D layer of the ionosphere shows, the ion composition can further change greatly due to a series of ion-molecular reactions taking place in the system. The quantity of water necessary for forming the hydration sheaths of ions is relatively small. Thus, in the example, examined above, 6.2 x 10^{19} water molecules are required for the formation of 1 cm³ of plasma from ion hydrates $\rm H_30^+$ and $\rm OH^-$ with allowance also for the free $\rm H_20$ molecules in equilibrium with

the ion sheaths. In this case, approx. 7.5 g of water are expended on ball lightning with a diameter of 20 cm, and less than 1 g in cases involving a diameter of 10 cm.

It is not at all difficult to find this water close to the ground. can be on the surface of the ground, in the form of dew on the leaves of plants or on the surface of other objects. During the time lightning is being discharged (~0.1-0.2 sec) it vapourizes and can fill a considerable volume. In the air (particularly in clouds) the water is distributed in the form of droplets and vapour. Since the matter constituting ball lightning possesses surface tension it will have a tendency to collect at one point in a manner similar to an extended elastic film. It can, therefore, be thought that the ions constituting ball lightning form and clothe themselves in hydration sheaths in a fairly large volume exceeding by several times the volume of the ball lightning, followed by their contraction and combination into a single body only afterwards. Eye-witnesses also speak of this (see Chapter 2). It should be remembered that one of them in particular mentions how, after linear lightning had struck a ploughed field, a series of "will-o'-the-wisps" ran across the surface of the field before gathering into a single ball which then detached itself from the ground and floated in the air.

We have now come to the most complex question as to where and how ball lightning is formed. At least two weighty arguments speak in favour of its not being able to arise in the discharge channel of linear lightning. Secondly, its size testifies against this. According to current data, the width of the current-conducting channel of linear lightning is of the order of 1 cm, whereas the mean diameter of ball lightning is approx. 20-25 cm. An important fact is that the probability density of ball lightning with a diameter of less than 10-15 cm occurring rapidly decreases as the size becomes smaller. If it were to arise directly out of a current-conducting channel, we could expect a maximum probability density in the diameter range of the order of several centimetres.

The second argument resides in the fact that the formation of ball lightning occupies a space of time amounting to a few seconds. Although ball lightning also occurs following a discharge of linear lightning, accounts by eye-witnesses indicate that a certain time is required for it to "heat up" or increase in diameter to a steady diameter or form into an independent spherical body. This time ($\approx 1\text{-}2$ secs) exceeds by approximately an order of magnitude the total life span of a linear lightning channel (0.1-0.2 secs) and is greater by two orders of magnitude than the time the channel takes to disintegrate (≈ 10 msec).

The most likely place for ball lightning to occur is, in our opinion, in the discharge corona of linear lightning. Just like any conductor at a high potential, a linear lightning channel is surrounded by a corona discharge occupying a wide region (of the order of 1 m in diameter), in which a large number of ions are formed during the discharge. The temperature of this region is far below that of the lightning channel and hardly exceeds 10^3 °K - particularly in its peripheral sections. Under such conditions the ions can easily be covered by hydration sheaths after they have been transformed into ion hydrates and other forms of cluster ions. We can see that both the size and temperature conditions existing in the corona are considerably more suitable for the formation of ball lightning that conditions which are characteristic of a current-conducting discharge channel.

It was already mentioned above that the volume of ball lightning forming does not necessarily coincide with that volume in which the matter constituting it originally arose. For the want of a better criterion we shall assume that the latter volume must be such that the required quantity of water vapour is contained in it. In such a case this volume must be of the order of 0.5-1 m³. (The mass of saturated water vapour in 1 m³ at a temperature of 18°C is 15.4 g).

The main question now is: how does the necessary quantity of ions form in the volume of the corona? Because of the low temperature, a large number of ions can occur here solely through various non-equilibrium mechanisms - particularly as a result of radiation and corona discharge on the current-conducting linear lightning channel. Let us note that the lightning channel itself does not contain the necessary quantity of ions. At a radius of 0.5 cm and a temperature of 10^{4} °C there are approx. 10^{20} ions per metre of channel. Moreover, 2 x 10^{22} pairs of ions (n $\simeq 0.5$ x 10^{19} cm⁻³) are necessary for the formation of ball lightning. Therefore, even if we ignore recombination during cooling, it would be necessary to gather all the ions from a 200 m long section of channel for one medium size fire ball.

It is also not difficult to calculate that the energy contained in the matter constituting the channel is insignificant in itself: this energy is equal to the ionization energy of 10^{20} ions/m, i.e. it amounts to approx. 200 J/m. Thus, almost all the discharge energy which, as we have seen, amounts to hundreds of kilojoules per metre of length, leaves the channel mainly in the form of radiation, although a considerable part of it is held back in the corona. About 30-50 kJ, amounting to less than 10% of the total radiated energy (per 1 m of length) are required for the formation of 2×10^{22} pairs of ions. Ionization takes place mainly under the effects of hard ultraviolet radiation occurring during the recombination of ions in the channel. The remaining radiant energy heats the air in the corona. It is easy to calculate that even the complete absorption of 500 kJ in a cylindrical volume of air with a radius of 0.5 m and a height of 1 m heats the air in it to a temperature not exceeding 1000°K. Thus, the radiation from the channel can ensure the formation of the required quantity of ions at comparatively low temperatures. The mean ion density in the corona must be approx. 10^{16} cm⁻³ for the formation of the necessary quantity of ions in 1 m^3 .

Another possible ion formation mechanism is corona discharge. This appears to be the main ion source for fire balls arising out of metal objects. As was mentioned above, the charge carried in one linear lightning discharge is equal to several dozen coulombs. If, for one reason or another, the channel resistance on any section increases sharply, an appreciable charge can be ejected into the surrounding space during corona discharge. It is more than likely that this occurs due to the emission of electrons. If the electrons being emitted have sufficient energy, they can give rise to an avalanche process, in which each electron produces several dozen pairs of ions (when the temperature of the medium is low the electrons occurring during ionization quickly form negative ions). The ejection of approx. 1-2 thousand electrons accelerated to an energy of the order of 1 keV can give rise to approx. 10^{21} pairs of ions, a quantity sufficient for the formation of ball lightning with a diameter of up to 10 cm. If this happens on a section of channel measuring approx. 1 m in length, then at a radius of 0.5 cm and a discharge time of 0.2 sec the corona current density must be approx. 0.02 α x cm⁻². Such high current densities (exceeding by several orders of magnitude those observed in laboratories) require a conductor to carry both a high current and high charge, i.e. the conductor has to be at a high potential. This can explain the numerous failures encountered in attempts to reproduce ball lightning artificially. Under laboratory conditions use is made either of high currents or high potential differences, but not both.

If the viewpoint expressed is close to the truth, ball lightning has, in fact, a direct bearing on corona discharge, although it is not a variety of it, but instead a direct result of such a discharge. Lightning discharge corona is a complex ion factory, in which, under very special conditions (comparatively low temperatures, high potential differences and ion densities) due to a series of ion-molecular reactions, many different types of complex ions are produced, including ions which are "stable" with regard to recombination.

After the lightning discharge has ceased, the hydrated ions formed in the corona and recombining fairly slowly will strive to congregate together because this reduces the energy in the system. The latter phenomenon occurs first and foremost as a result of a reduction in surface energy. As has already been noted, a similar tendency towards the formation of luminous spheres manifests itself in a gas discharge even at relatively low ion densities $(n \approx 10^{13} {\rm cm}^{-3})$. Moreover, this will occur at high values of n when some sort of role can be played (in addition to surface energy) also by departures from ideality, as a result of which a reduction in the system volume leads to a reduction in the internal energy.

For contraction of the ions in the corona it is probably necessary for their density to exceed a certain level. It is also possible to expect the hydrated ions retained in the corona to be distributed in a very non-uniform manner (largely around water droplets which have evaporated, for example). At first they form a body with a very complex and developed surface, parts of which gather together only gradually. The first few seconds necessary for forming ball lightning are also expended on this process. If the density of the matter obtained does not differ very greatly from the density of the ambient air and if its temperature is low enough to prevent the danger of an explosion, an autonomous spherical body arises, which consists of metastable and gradually disintegrating ion matter, i.e. ball lightning.

From a cluster hypothesis point of view, ball lightning is, because of its low temperature, a unique ion-chemical reactor in terms of its characteristics. Evidently the most interesting practical application of cluster plasma resides precisely in this fact, although the possibility of a considerable amount of energy accumulating in a comparatively small volume involving a completely negligible mass likewise cannot be dismissed. The creation and investigation of cluster plasma is also interesting, irrespective of what the nature of ball lightning is. As far as the latter is concerned,

this means that until ball lightning is produced in a laboratory experiment its true nature cannot be regarded as being definitively established.

It appears to us, however, that the viewpoint expressed in this chapter requires a minimum of independent hypotheses in order to explain the various properties of ball lightning. One assumption about the retardation of recombination by large cluster sheaths makes all the remaining features of ball lightning logically explicable and comprehensible. As far as the initial hypothesis itself is concerned, we see that, firstly, it does not, at a first glance, contain anything improbable or anything contradicting the basic laws of physics, and secondly, it refers to a field of science which has been studied quite inadequately so far. Naturally, this cannot be an argument in favour of the hypothesis in question being true, but it does make it more attractive for investigations and an experimental check.

Conclusions

Well then, what is ball lightning? The reader has already been warned to the effect that, because there is no direct evidence obtained by experiments, all the opinions on this subject belong to the realm of conjecture and are of a provisional nature. Nevertheless we cannot get away from this question by off-loading all the responsibility for its solution onto the shoulders of future generations. Two types of answer are possible from the outset.

First answer. Ball lightning is an autonomous body consisting of some sort of unstable matter, upon whose disintegration energy is released.

Second answer. Ball lightning is a certain process, for example a particular form of gas discharge or wave-guide process which combines it with the ambient air, from which it continually derives its energy.

The facts set out in this book speak in favour of the first viewpoint, rather than the second. The following points testify to the autonomy of ball lightning:

- 1. The nature of its movement (it moves as an independent, separate body not revealing any trace of channels connecting it with the surrounding medium).
- 2. The existence of an interface between the ball lightning and the surrounding medium which, apparently, has surface tension, indicates that the matter constituting the lightning forms a separate phase in the air.
- There is a correlation between the life span and size of a fire ball.

The fact that the energy of ball lightning is accumulated in the form of matter and not in the form of an electromagnetic field will be recognized from its mass. The density of ball lightning is roughly equal to the density of air, whereas the radiation mass at any reasonable energy valus (W) must be negligibly small (W/c^2). Moreover, plasmoids, i.e. formations comprising an electromagnetic field and matter, are unstable and must give up their energy to the surrounding medium rapidly. Moreover, in order for the dissipative processes within the lightning to be small, very high temperatures are necessary hundreds of thousands or millions of degrees, something lightning does not have.

Furthermore, we have to answer the question regarding the particles of matter constituting the lightning, i.e. are they charged or neutral? At a first glance logic infers that these are neutral particles because, at the temperaures found with ball lightning, the gaseous plasma media known to us recombine. However, it is necessary to draw the reader's attention to the following:

1. Ordinary gases consisting of neutral molecules do not form a separate phase in other gases and, in particular in air, as happens with the matter constituting ball lightning.

All three properties mentioned above can be found solely in plasma media, i.e. in gases consisting of charged particles.

However, there is absolutely no question of any detectable quantity of electrons being found in the composition of ball lightning, because in the ion field they would produce such a strong bremsstrahlung that the energy of ball lightning would be exhausted within minute fractions of a second.

As a result we come to the conclusion that the matter constituting ball lightning consists of heavy positive and negative ions which, for some reason or other, in contrast to ordinary ions known to us, do not recombine.

The cluster hypothesis of ball lightning is based on this very fact.

TABLES

Table 4.1.

AII. eV		n-1; n						
	0; 1	1; 2	2; 3	3; 4	4; 5	5; 6	6; 7	
For H ₁ O+(H ₂ O) _n For OH-(H ₂ O) _n	1,56	0,97	0,74	0,67 0,62	0,57 0,61	0,51 —	0,45	

Table 4.2

	Temperature, K			
K _s	500	600	700	
2 8 6 7 1 1 2 7 1 4 7 1 6 1 7 1 6 1 6 1 7 1 6 1 6 1 7 1 6 1 7 1 6 1 7 1 6 1 7 1 6 1 7 1 6 1 7 1 6 1 7 1 6 1 7 1 6 1 7 1 6 1 7 1 6 1 7 1 6 1 7 1 6 1 7 1 6 1 7 1 6 1 7 1 6 1 7 1 6 1 7 1 6 1 7 1 6 1 7 1 7	2,04·10 ⁻¹³ 1,73·10 ⁻¹⁴ 3,15·10 ⁻¹⁷ 1,14·10 ⁻¹⁷ 4,56·10 ⁻¹⁸ 0,644·10 ⁻¹⁸ 1,20·10 ⁻¹⁸ 3,15·10 ⁻¹⁷ 0,629·10 ⁻¹⁷ 0,26·10 ⁻¹⁷	6,33·10-16 1,28·10-16 2,94·10-18 1,55·10-18 0,785·10-18 5,73·10-18 1,22·10-16 3,01·10-18 0,721·10-18 0,365·10-18	5,43·10 ⁻¹⁶ 2,05·10 ⁻¹⁷ 5,52·10 ⁻¹⁸ 3,82·10 ⁻¹⁸ 2,29·10 ⁻¹⁸ 2,37·10 ⁻¹³ 0,556·10 ⁻¹⁸ 1,33·10 ⁻¹⁸ 0,917·10 ⁻¹⁸	

Table 4.3

 $2 n/n_0=4$

omposition -	Temperature, K				
	500	600	700		
n,	0,29.101	0,24-1010	0,21.1019		
n	0,58.1019	0,48.101	0,43.101		
n_{\bullet}	0.54.1019	0,29.101	0,56-1018		
$n_{\mathfrak{s}}$	$0.41 \cdot 10^{14}$	0,15.101	0,11-1010		
n_{4}	1,2.1014	0.40.1018	0,14.1019		
n_{\bullet}	1,3.1014	0,56.1017	0,12.1019		
n,	2,7.1010	0,18.1014	2,7.1016		
n_1	0,45.10	0,12.1011	2,3.1014		
n'	0,51.101	0,16.1019	0,12-101		
n'	0.68.1011	0,20.10	0,62·10 ¹⁸ 0,19·10 ¹⁹ 0,16·10 ¹⁹ 0,31·10 ¹⁷		
n'	$0.37 \cdot 10^{17}$	0,11.101*			
n'.	0,41.10	1,5.1017			
n'_{2}	1,2.1011	0.51.101			
n'_1	0.62.10	0.37.1011	1,40.101		

Table 4.4

 $2 n/n_0 = 1$

Composition	Temperature, K				
	500	600	700		
n_{o}	0,72.1019	0,60-101	0,54-1010		
n	3,6.1014	3,0.1014	2,7.101		
n_{\bullet}	3,5.1014	2,5.1014	1,1.10**		
n_{\star}	0.11.1014	0.52.1014	0,93.1018		
n,	$0,13 \cdot 10^{14}$	0,55.1017	0.45.101		
n_1	0,56.1013	3,1-1016	0,15.101		
n ₂	$0.45 \cdot 10^{\bullet}$	4,0.1012	1,4.10		
n_1	$0.30 \cdot 10^{3}$	1.0.10	0.48.104		
n^{i}	3.4.1013	1.9.1014	0.42 104		
n'	0,18.101	0.88-1014	0,85.101		
n'_{\bullet}	0.40-1014	0,20.1014	1.0.10"		
n'	1.8.1014	1,1.1014	0.35.104		
n'	2.0.10	1.5.1014	0.28 10		
R'1	4,3.10	4,4.10*	5,1.1011		

Figure Captions

- Fig. 4.1 Schematic view of hydrated ions. Below are two hydrated ions which have combined into one neutral complex.
- Fig. 4.2 Various possible structures of hydrated hydrogen atom ions.
 - a water molecule
 - b,c,e chain structure of ${\rm H_50}_2^+$, ${\rm H_70}_3^+$ and ${\rm H_90}_4^+$ ions
 - d oxonium ion (H_30^+)
 - o hydrogen atoms
 - 0 oxygen atoms

(The atom charges indicated (in electon charge units) were calculated numerically (Ref. 63)).

- Fig. 4.3 Various possible structures of hydrated hydrogen atom ions a,b proton-centered structures of $H_70_3^+$, $H_90_4^+$
 - c oxonium structure of $H_90_4^+$
 - d ring structure of ${\rm H}_50^+_2$ (same symbols as shown in Fig. 4.2)
- Fig. 4.4 Reaction equilibrium constants of the hydration of the $\rm H_30^+$ ion (Ref. 56): straight lines 1-6 correspond to values of $\rm K_0^{1(P)}$ $\rm K_4^{1(P)}$
- Fig. 4.5 Reaction equilibrium constants of the hydration of the OH^- ion (Ref. 57): straight lines 1-5 correspond to values of $K_0^{1(P)}$ $K_4^{1(P)}$
- Fig. 4.6 Relationship of function $F(\Theta)$ (4.37) to $\Theta = T_{\infty}/T$ explaining the mechanism involved in the fluctuations in the luminescence and heat release of ball lightning.

FIGURES

$$Fig. 4.1$$

$$-0.26$$

$$+0.13$$

$$a$$

$$+0.28$$

$$+0.28$$

$$+0.28$$

$$+0.28$$

$$+0.28$$

$$+0.28$$

$$+0.28$$

$$+0.28$$

$$+0.28$$

$$+0.28$$

$$+0.37$$

$$+0.37$$

$$+0.37$$

$$+0.37$$

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$$+0.34$$

$$+0.34$$

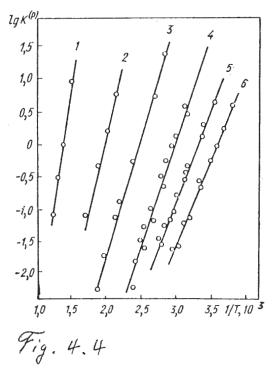
$$+0.34$$

$$+0.34$$

$$+0.38$$

е

Fig. 4.3



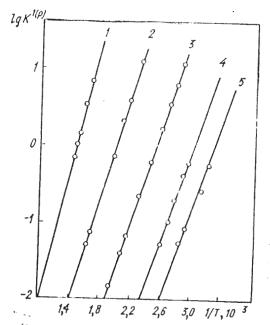


Fig. 4.5

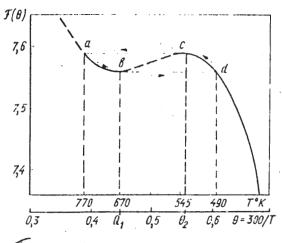


Fig. 4.6

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