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Problem of Ball Lightning

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PROBLEM OF BALL LIGHTNING

by

B.M. Smirnov

Specific Authority

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U. S. BOARD ON GEOGRAPHIC NAMES TRANSLITERATION SYSTEM

Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere.
When written as ё in Russian, transliterate as yё or ё.

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English	Russian	English	Russian	English
sin	sin	sh	sinh	arc sh	sinh^{-1}
cos	cos	ch	cosh	arc ch	cosh^{-1}
tg	tan	th	tanh	arc th	tanh^{-1}
ctg	cot	cth	coth	arc cth	coth^{-1}
sec	sec	sch	sech	arc sch	sech^{-1}
cosec	csc	csch	csch	arc csch	csch^{-1}

Russian	English
rot	curl
lg	log

GRAPHICS DISCLAIMER

PROBLEM OF BALL LIGHTNING.

B. M. Smirnov.

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Is carried out analysis of results of observations of ball lightning, on basis of which is comprised its physical shape. Is represented the information, which relates to the processes, which occur in excited air, and connected with different aspects of nature of this phenomenon: the methods of storing internal energy, character of the processes of the heat release, structure and form of ball lightning, electrical phenomena in ball lightning and its glow. In the popular form other phenomena of nature, allied to ball lightning or capable of causing its onset, are analyzed. The analogs of ball lightning are examined. The comparison of the obtained information with the results of observations makes it possible to understand nature of ball lightning and to construct its phenomenological model.

Russian Translations (jhd)

For great circle of scientific workers, engineers and studying VUZ [BУЗ - Institute of Higher Education], which are interested in contemporary state of problem of ball lightning and other atmospheric phenomena.

Pages 3-4.

No Typing.

Page 5.

PREFACE.

Ball Lightning - surprising phenomenon, which attracts attention of many people as interesting riddle of nature. The scientists of all times develop special interest to this phenomenon. In the study of ball lightning large scientific potential is inserted. The achievements of last time in the investigation of this phenomenon are reflected, in particular, in J. Barry's books "Ball and beaded lightning" (1980) and I. P. Stakhanova "About physical nature of ball lightning" (1985). In these books at the high scientific level of working of the observed parameters of ball lightning is carried out, as a result of which we have the reliable information, which relates to properties and manifestations of ball lightning.

Together with set of factographic material is also series of experiments, whose results can be examined as simulation of separate processes, which are component parts of phenomenon in question. Furthermore, there is an abundance of theoretical models of this physical phenomenon and a large flow of propositions with the new explanation of nature of ball lightning, although in the majority of the cases the new hypotheses are versions or combination examined earlier. It should be noted that a whole series of interesting investigations by nature of ball lightning appeared in the last decade. To their number should be related, for example, the aerosol model of ball lightning with the filamentary structure of aerosols. During the construction of this model its authors (I. V. Podmoshenskiy with associates) took as the base the analysis of the experiments carried out by them.

However, in spite of serious efforts on way of experiment of ball lightning are required essential advance in this region. Now, when we have a representation about nature of this phenomenon, it is possible to understand, why the resolution of the problem of ball lightning so tightened itself. Such position is connected with the complexity of phenomenon itself, which includes the set of the separate elements, which relate to the different directions of physics and chemistry, moreover without the resolution of each of the separate problems it is not possible to construct the model of ball lightning.

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To these problems - the fundamental sides of phenomenon - should be related the following:

1) the method of storing the internal energy;

2) the character of heat release;

3) the structure of active material and the form of ball lightning;

4) electrical phenomena in ball lightning;

5) the emission of ball lightning.

At present from positions of contemporary science we can answer each of these questions individually. This makes it possible to obtain the physical picture of nature of ball lightning and to outline the direction of further investigation of this phenomenon, connected with the laboratory experiments with the specific systems. Such investigations will make it possible to understand some laws, which relate to the structures and the processes in the real world, surrounding us, and therefore they are of independent scientific interest.

This book reflects contemporary state of problem of ball lightning. In connection with this in Chapter 2-6 are analyzed the separate sides of this phenomenon taking into account of contemporary scientific information and observational data. The last chapter of the book (Chapter 8) sums up the result to the carried out analysis, in it fundamental conclusions are represented, the analogs of ball lightning are examined, is given phenomenological model of the phenomenon in question, which includes the results of the carried out analysis.

Together with material indicated, intended for specialists, in book are Chapters, designed for wider circle of readers. It is here involved in chapter 1, where the analysis of observational data on ball lightning is given and the shape of ball lightning with the average parameters is created on its base. At the popular level is presented Chapter 7, where the analogous phenomena of nature are examined. View on these phenomena from the wide positions is interesting in the plan of understanding the complexity of ball lightning as the phenomena of nature, and also from the point of view of general difficulties and approach during the study of the physical phenomena of nature. Furthermore, part from these phenomena of nature can cause the appearance of ball lightning, which also justifies their examination in this book. Some materials of popular character are contained also in special chapters. The author hopes that the combination of special and popular materials in the book will make it possible to transmit the contemporary state of the problem of wider audience, after preserving in this case strictness and validity of presentation.

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INTRODUCTION.

Ball lightning - surprising phenomenon of nature. During several centuries men have attempted to understand however this. Riddle is explained by the fact that ball lightning appears rarely and unexpectedly, and also fact that in the majority of the cases it does not leave after itself traces. Ball lightning still for long will be riddle, also, after we will learn to simulate it under laboratory conditions - too strong much mysterious was accumulated in the centuries of her observations.

Before determining, what observed phenomenon we will call ball lightning, let us turn to one of examples of description of ball lightning, F. Arago [1] undertaken from book. To this book we will repeatedly revert, since, although it was published in the middle of the past century, assembled in it the description of ball lightning, until now, did not lose her value and supplements well contemporary observations.

Occurred case is described by Mrs. Esper in letter to F. Arago, where following speaks:

I live on second landing, whence is opened view of place of Bozhon. It was June, 1849, on the 16th on Friday, 6 hours 30 minutes in the evening evening, at the same time when cholera most raged in

Paris.

Weather was suffocating and sky seemed at that minute calm, but from all sides there was evidently sparkling sheet lightning.

Passing before my window, which is very low, I was astonished by form of large red sphere, completely similar to moon, painted and increased by action of vapors. This sphere tripped slowly and perpendicularly from the sky to one of the trees of the place of Bozhon.

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The first thought was, that this is the balloon of Grimm, but the color of sphere and the time of day soon convinced me of the error, and thus far my mind searched for solutions of this phenomenon, I saw, that light twas revealed from below the sphere, which hung at the height from 5 to 7 meters above the tree, it seemed, it would burn easily paper, with small sparks and flashes, then, when opening was doubled or tripled more than of hand, sudden terrible blast broke entire shell, and from the middle of this infernal machine flew out dozens of rays of serpentine lightning, which dispersed along different sides and one of which hammered into house No 4, and opened in the wall hole, as if from cannon fire. This hole exists even now. Finally, the remainder of electrical material began to burn white, bright and bright flame and to be reversed as fireworks wheel.

This phenomenon continued about one minute. Spectacle was so wonderful that to me and did not come to mind the thought against the danger or the fear. I could only exclaim: "Ah, how wonderful".

However, blast was so strong, that it overturned three people on street and produced, as you easily will verify, impression on entire block. My cook was almost suffocated by the ray of lightning, which flew before his window. Doorkeeper did drop from the hands dish, himself without knowing, from fear, or from the shock of the ray of lightning, which descended on the main stairway on the lower area, on which it then stood. One more ray of lightning fell into the boarding house of Mrs. Luazo on the street of Nevi de Bern, where it wounded one of the teachers. The inhabitants of house No 4 from fear were thrown into the court, but not one of them was injured.

Paris was shaken by terrible noise of this terrible thunder impact, but perhaps I was the only one who saw randomly entire resulting phenomenon. I for a high price would not sell the event, which has befallen me, to be witnessing so exquisite and wonderful a spectacle".

Being distracted from emotional aspect of observation of ball lightning and on the basis of described case and many other observations, assembled in different surveys and books, dedicated to ball lightning, let us define ball lightning as glowing formation in air, observed for several seconds and longer.

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This formation most frequently has spherical form, not attached to walls and does not change noticeably its sizes for the time of its existence.

This determination of ball lightning makes it possible to separate ball lightning from other atmospheric phenomena. This proved to be very essential, since it made possible during several centuries to accumulate information from the observational parameters of ball lightning, so that at present we have clear representation about the quantitative parameters of ball lightning. But this creates reliable bed for the analysis of nature of this phenomenon.

Chapter 1.

OBSERVATIONS OF BALL LIGHTNING.

S1.1. Reality of phenomenon and the authenticity of its descriptions.

In present chapter we will try on basis of observational data to compose shape of typical ball lightning, which subsequently can be utilized for analysis of its nature. Our problem is simplified because at the present time is already carried out the extensive work according to the analysis of data of the observed phenomenon. Even in the middle of the past century Arago [1] described about thirty cases of observing ball lightning (some of them we give below). Subsequently repeatedly occurred the examination of the cases of observing ball lightning, whose number increased. For example, in the book of Brand [2] are taken into consideration 215 observations of ball lightning, and in the works of Humphrey's [3, 4] - about 280 observations.

Further we will utilize contemporary data on ball lightning, to number of which let us relate data of Mac Nellie [5] (USA) - 513 events; of Reilly [6] (USA) - 112 events; Cherman [7] (England) - 76 events; Stakhanov [8, 9] (USSR) - are more than 1000 events, Grigoryev, Dmitriev [10] (USSR) - 327 events [1]).

FOOTNOTE [1]). Should be especially noted I. P. Stakhanov's contribution, who is not limited to the description of the large number of assembled and processed cases. The analysis of the reports of the eyewitnesses of ball lightning, which guided its observations into the journal "Nauka i zhin'" [Science and life], became the subject of the publication of this journal in 1976 and comprised the material of the first edition of the book of Stakhanov [8]. After the analysis of the obtained reports of eyewitnesses of ball lightning was sent new questionnaire, responses to which made it possible to obtain more detailed information about this phenomenon of [9], that is absent in the systems of other data (for example, information about the luminous density of ball lightning). ENDFOOTNOTE.

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These data differ somewhat in terms of the methods of processing of observations and are utilized the reports of eyewitnesses from different regions, i.e., all these data mutually supplement each other. Should be considered also the information, which is contained in other contemporary publications, dedicated to ball lightning. In the book of Singer [11] is represented the variety of the theoretical models of this phenomenon. Into the book of Barry [12] entered the descriptions of the laboratory investigations of phenomena, which simulate the separate properties of ball lightning, the photographs of ball lightnings were assembled and studied, and the large bibliography, which includes about two thousand works, is also given. Many curious facts are contained also in popular books on ball lightning [13, 14]. All together this is large scientific value and gives the possibility us to create the reliable shape of ball lightning, and to also understand the contradictions, which appear during the attempt to describe physical nature of this phenomenon.

Conducted investigations make it possible unambiguously to answer question, is there generally ball lightning as physical phenomenon. In its time was advanced the hypothesis about the fact that ball lightning is optical illusion. This hypothesis exists at present (see for example, [15]). The essence of this hypothesis lies in the fact that the strong flash of forked lightning as a result of photochemical processes can leave trace on the retina of the eye of the observer, who is retained on it in the form of spot for 2-10 s; this spot is received as ball lightning. This confirmation is rejected by all authors of surveys and monographs, dedicated to ball lightning, which preliminarily processed the large number of observations. This for two reasons is done. First, each o. the numerous observations, utilized as reason in favor of the existence of ball lightning, ir the process of its observation includes many parts, which could not arise in the brain of observer as the aftereffect of the flash of ball lightning. In the second place, is a series of reliable photographs of ball lightning, and this objectively proves its existence. Thus, on the basis of the totality of data according to the observation of ball lightning and their analysis it is possible with the complete confidence to assert that ball lightning - this real phenomenon.

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Following question, which should be examined, relates to degree of authenticity of communicated facts about observations of ball lightning. There is a whole series of the examples, when it is possible to compare the description of the observed fact by eyewitness with the publication of this case in the press. The very significant case of this type is given in book [14]. In the newspaper "Komsomol'skaya pravda" for 5 July 1965 was published the note "Igneous guest", in which is described the behavior of ball lightning with the diameter of approximately 30 cm, which was being observed not a long time before this in Armenia. In the article, in particular, it is said:

"After circling the room, the fireball penetrated through the open door to the kitchen, and then flew out the window. Ball lightning was hammered in the court against the ground and exploded. Explosive force was so great, that fifty meters away a clay house collapsed. Fortunately, no one suffered".

Demand in administration of Main Administration of the Hydrometeorological Service of Armenian SSR was sent apropos of behavior of this ball lightning. In the response it was said that ball lightning actually was observed. Is described the character of the motion of ball lightning in the apartment, which had no relation to the text of "Komsomol'skaya pravda". At the end of the response is said: however,

"As far as the clay house described in the newspaper is concerned, this wreck is no relation to ball lightning".

Unfortunately, this matter did not end. The report of the correspondent of "Komsomol'skaya pravda" became the basis of the estimate of energy of ball lightning [16], which comprised order 10^9 kcal (energy of ton of explosive). This estimate was calculated in many publications on the basis of power engineering of ball lightning, including in books [11, 12]. Since observations, on which it is possible to estimate energy of ball lightning (see [9, 12]), not very much, this publication is unpleasant disinformation.

Another, less critical case of such type is given in introduction to books of Stakhanov [8, 9]. The discussion deals with ball lightning, which flew in on 5 August, 1977, into the Arkhangel'sk cathedral of the Moscow Kremlin.

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Let us give newspaper report by the name "Lightning ... guest of museum":

"To the morning opening of museum in Arkhangelsk the cathedral of the Moscow Kremlin remained one-and-a-half hours, when the strongest thunderstorm broke out. Unexpectedly above the belfry of Ivan the Great appeared bright yellow incandescent sphere and it began to move to the Arkhangel'sk cathedral. Door was opened, the supervisor of museum Nadezhda Stepanovna Antonova was prepared for the workday. Her attention was drawn by unusual hissing. After being enveloped, she saw, as half-meter sphere slowly swam into the opening of door, it was directed through entire cathedral to the abundantly decorated with gilded thread iconostasis and stopped at the tsarist gates. Flash, impact, and in air smelled ozone. Fortunately, air guest did not bring damage".

I. P. Stakhanov gives more detailed description of behavior of ball lightning, which is comprised on basis of observations of three eyewitnesses, but not one as in newspaper. In this case, according to their evidence, the diameter of sphere composed 5, but not 50 cm, and noone discussed the odor.

These examples are evidence the fact that to newspaper reports one should relate with large precaution. Can be attributed reports about ball lightning to the output of sensation which can cause the haste of publication and the distortion of the transmitted information.

To much with more difficulty explain authenticity of descriptions of individual observers of ball lightning, since frequently these descriptions do not compare. The authenticity of data of the eyewitnesses of ball lightning is analyzed almost in all books on ball lightning. From the test of this analysis it is possible to indicate for two reasons, which decrease the authenticity of the given facts. First, the onset of ball lightning occurs in an unexpected manner, when man for this is not ready. Being located in the excited state, it can subsequently be mistaken in the description of the observed phenomenon itself to verify into this. In the second place, attempting to comprehend that seen and to put this into the specific diagram, observer somewhat distorts colors in the reproducible picture, and this can be reflected in the authenticity of its separate parts.

We analyze from these points of view episode, described in introduction to this book. From the description it is evident that the observed ball lightning by woman was situated in the excited state, as a result of which her description accepted bright emotional coloration.

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Further, that fact in the episode in question, that the sphere was colored and increased by the action of vapors, and also all results of acting the blast of ball lightning, which were discovered by eyewitness undoubtedly after the observation of ball lightning, can be subjected to doubt. This is the confirmation of the second thesis.

Thus, separate description of ball lightning has limited authenticity, which is caused by fact that eyewitness was not ready to its correct perception. Therefore to each single report about the observation of ball lightning one should relate with precaution.

At the same time there are objective errors during reproduction of observed facts, which are caused by inadequacy of human possibilities during estimate of parameters of seen picture. The possibilities of man in this respect can be established from the statistical processing of the mass observations of other phenomena. A successful example of this type is given in the survey of Cherman [7]:

Drake gave the interesting investigations of the reliability of description by the witnesses of unusual events. These events - two bright meteors, which appeared at the night sky of Western Virginia in the interval of approximately one month. Since the time of appearance in both cases was about 10 in the evening, objects were observed by many people. In each case the common physical characteristics of events were well known: strong flash illuminated entire sky as in the daytime, loud sonic noise during several minutes followed it. Astronomers from the national radio-astronomical laboratory took interview from so many witnesses, was how much possibly (78 and 35 for both events). It should be noted that the accuracy of reports rapidly decreased in the course of time during several days. Time was evaluated amazingly good: the glowing sphere in 4 seconds crossed sky, and the majority of estimates were located between 3 and 5 seconds. The communicated time interval when sonic noise (from 1 to 5 minutes) came two were correct with an accuracy to factor. On the other hand, the represented color of objects covered entire spectrum. The estimates of the trajectory of the glowing sphere were also imprecise.

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Curious fact for observations of both events was the fact that the noticeable part of witnesses (12%) of both meteorites communicated that the sound was audible at the same time, when was observed object - hissing sound, similar to sound of roasting of brisket. In this case this sound would be physically impossible and could have only physiological nature. This bears out the fact that the sonic perceptions of ball lightning "must undergo doubts".

From this example it is possible to draw conclusion that authenticity of separate report falls with an increase in time interval from observation of phenomenon to its description. Furthermore, the authenticity of the geometric and time parameters of phenomenon is much higher than optical and sonic. Summing up the result to the carried out analysis, let us note that the authenticity of each separate description of the observed properties of ball lightning is limited. Therefore conclusions about the parameters of this phenomenon can be drawn on the basis of statistical processing of the totality of the large number of observations.

S1.2. Geometry, lifetime and the character of motion.

Let us now move on to description of shape of ball lightning. In this case we will be based with pillar on the previously assembled material of observations [1, 2, 5-14, 17, 18]. Let us first note that, in spite of name, ball lightning on always has spherical form [1]).

FOOTNOTE [1]). Frequently ball lightning has cylindrical form. Thus, of 327 descriptions of the cases of observing ball lightning, assembled by Grigoryev and Dmitriev [10], this form was observed in nine cases, when the form of snake, cord, sausage, harness/bunch, tape, stick was noted. The thickness of this formation is 1-4 cm, and the length of 30-60 cm. Usually is discussed the fibrous structure of glow. In two of these nine cases the glowing mass in the final analysis was rolled up into a ball. ENDFOOTNOTE.

The spherical form of ball lightning is observed in 83% of cases according to the statistics of Brand [2] and in 87% of cases (98 cases of 112 observations) according to the statistics of Reilly [6].

Significant dimension of ball lightning comprises order 10 cm. Fig. 1.1 gives the distribution of observed ball lightnings on diameter d) in accordance with the data of the different authors. In this case the mean diameter of ball lightning is equal to 30 cm according to data of Mac Nellie [5], 32 cm according to data of Reilly [6], 26 cm according to Cherman [7] and 22 cm according to Stakhanov [8].

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Statistical processing of the given mean diameters gives value $\bar{d} = (28 \pm 4)$ cm, so that subsequently we will consider that the mean diameter of ball lightning is equal to 28 cm.

Taking into account too rough a method of determining lifetime of ball lightning in each description (it is determined by sensation, but not hours, and is communicated after certain time), we will not analyze distribution of ball lightnings on lifetime in each of data sets. Let us compare to each of time allocations τ, for which separates half of ball lightnings. Value τ is equal to 4 s according to Mac Nellie [5], 5 s according to data of Reilly [6] and Cherman [7] and 14 s according to the data of Stakhanov [8]. The geometric mean on these values with an accuracy to factor 1.75 is 6 s. If we consider that the distribution function by the lifetime of ball lightning is determined by simple exponential law, then we will obtain that the mean life of ball lightning comprises

$$9^{+6}_{-4}\,\mathrm{s}.$$

Character of motion of ball lightning is of interest.

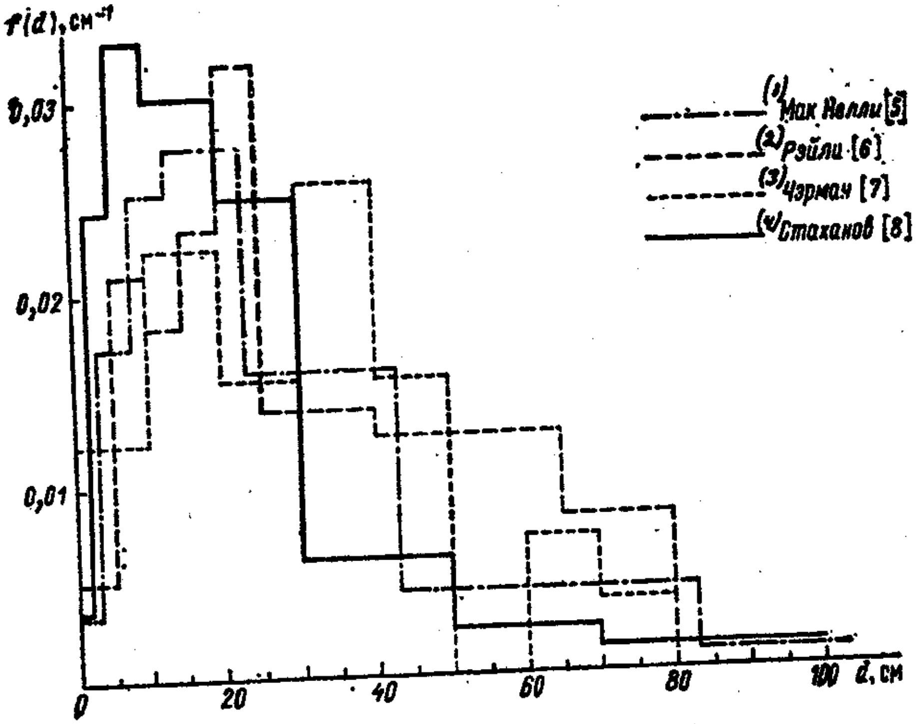

Fig. 1.1. Distribution of ball lightnings along diameter.

Key: (1). Mac Nellie. (2). Reilly (3). Cherman. (4). Stakhanov.

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In the majority of the cases ball lightning is moved smoothly and horizontally. Ball lightning moved horizontally in accordance with the data of Reilly [6] in 58 case of 110 of those observed (or 52%), in 20 cases (19%) vertically and in 20 (19%) it had complicated trajectory. According to Stakhanov when was observed motion (91% of all events), in 684 descriptions (6o-), it moved horizontally, in 183 (18%) - down and in 47 cases (5%) - upward. The speed of its movement is concentrated predominantly in the interval of $0.1-10\ m\cdot s^{-1}$. Since the value of speed is determined by the division of the passed distance into the period of observation, and each of these values already itself contains error, the accuracy of the determination of the speed of movement, apparently, is estimated by factor of 2. Therefore let us give only the average speed of movement. This value is 5.1 $m \cdot s^{-1}$ according to data of Reilly [6] and 2.8 $m \cdot s^{-1}$ according to data of Stakhanov [8]. It is possible to consider on the basis of these values in the rough approximation that the average speed of the movement of ball lightning is 4 $m \cdot s^{-1}$.

Ball lightning is observed both in open air and indoors. Thus, after processing 71 cases of observing ball lightning, Cherman [7] notes that of them 15 cases relate to the determination of ball lightning indoors, 45 - outdoors and in 11 cases ball lightning penetrated or entered into the location. Ball lightning can be discovered at the different heights. Are several cases [8, 9, 12], when were observed within aircraft, are not so rare the collisions of ball lightning with aircraft [19]. As an example let us give excerpts from the note, published in the newspaper "Pravda" for 8 November 1981 and dedicated to the collision of military aircraft with ball lightning, who occurred at the height of 1300 m. This is how describes the correspondent of impression pilot Korotkov during the collision of aircraft with ball lightning:

"I with peripheral vision saw some object. I raised my eyes: directly the fireball hung before me through the glass of the cockpit canopy. Aircraft as if it hit it, and at some instant flew in series/row. And it seemed that the enormous, to five meters in diameter, circle continued to increase. In the memory remained this part: sphere was bright red, and center - with size of a soccer ball - is darker. Then sphere disappeared. And blast here in the tail section was heard, smelled fumea".

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As a result of collision aircraft strongly suffered ("was upset upper part of keel, crack in skin"). Further correspondent writes:

"I saw on the airfield the aircraft of Korotkov. It stood still separately from other machines, in the hangar. In the nose section on the metal - traces, as if from the spot welding. In these places the fireball touched.

"Such markers are characteristic for ball lightning" - deputy commander of regiment for engineer service explained and he showed notebook, where were collected materials about similar phenomena".

Its ability to penetrate location through narrow openings and slots is surprising special feature of ball lightning. A whole series of such examples is assembled in the book of Stakhanov [9]. Ball lightning well "feels" open doors, windows, it can penetrate through them, if it is required, along the broken trajectories, can itself "find" such openings. Let us demonstrate this based on the example of report from the book of Arago [1], which is interesting also in other respects. The discussion deals with the case, which occurred in France on 2 June, 1843,:

"After the sufficiently strong blow of thunder, but not directly after it, tailor, sitting in her table and finishing dinner saw that the pasted over by paper frame, which closed fireplace, fell, as overturned by moderate wind gust, and the fireball, with size of the head of child, easily left the fireplace and began slowly to move along the room at the small height from the brick floor. The form of this fireball was according to tailor, similar on the average value of the kitten, that was rolled up by ball and that moves without the aid of blades. The fireball seemed faster bright and light, than burning and incandescent, and worker felt from it no heat. Sphere approached his legs as the young kitten, that desires to play and to be ground against the legs as usual of these animals, but tailor moved aside legs and by several evasive motions of precaution, ideal, according to him, is very easy, avoiding the touch of meteor.

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It seems, the latter remained several seconds at the legs of the sitting worker, who attentively examined it, being sloped forward and down. After wandering to the different sides, without leaving the middle of room, the fireball raised vertically to the height of the head of the worker, who for the avoidance of the touch of meteor to face and, in also the time, for the sequence after it eyes, raised itself, spreading to the back of the chair, on which it sat. After reaching the altitude of approximately one meter from the floor, the fireball was extended and indirectly directed to the opening, pierced in the fireplace at the height of approximately one meter above the upper shelf.

This opening was made for passage of tube of oven, which in winter served for heating room. But, according to the expression of craftsman, lightning could not it see, because it was glued by paper. The fireball was directed directly toward this opening, unglued paper from it, without injuring it, and was raised into the tube. Then, on the story of tailor, after being raised along the tube, sphere achieved the top of tube, which is located, at least, 20 meters above the surface of the court, where it brought with the terrible crack, after destroying the part of the top of tube and after tossing up fragments to the court; the roofs of several small construction were probits, but god had pity from any accident.

Room of tailor was located in third landing and did not reach to half of height of house. In the upper levels thunder didn't penetrate, but the motions of light sphere were constantly slow, also, without sudden gusts. Its flash was not glaring and generally sphere did not propagate sensitive heat. Apparently, it did not attempt to follow throughout the bodies those conducting or to be inferior to air currents".

Usually ball lightning moves in air, but are frequent cases, when it rolls along ground or floor. Here is the example, undertaken also from the book of Arago [1]:

"Doctor Steinman in the letter to me communicates the observation of the cloud of lightning, made in Al'ton in 1826.

Here are his words:

"It seems, in 1826 thunder clap broke out above house of one of my friends and comrades in Al'ton, where I had medical practice.

This house was found at height from 30 to 40 meters above level of Elba. My friend, a doctor von der Smissen, walked in his drawing room, when thunder clap was heard; at the same instant igneous mass appeared on the floor of room and took the form of oval sphere with size of egg near the wall along the panel, covered on the assigned custom with varnish. Ball rolled to the door with the speed of the run of mouse; there, after producing new blast, it jumped over the rails of the staircase, which leads into the ground floor, and disappeared - exactly as it was, having caused no harm".".

S1.3. Onset and decay.

Appearance of globular lightning is usually connected with thunderstorm activity. Statistics shows that 73% of 513 cases according to data of Mac Nellie [5], 62% of 112 cases according to Reilly [6] and 70% of 1006 according to Stakhanov [8] relate to the thunderstorm weather. According to the data of Barry [17] in 90% of assembled by it cases globular lightning was observed during thunderstorm. In this case in many works it was communicated that ball lightning appeared immediately after the impact of forked lightning.

I. P. Stakhanov specially carried out analysis of description of observations of ball lightning from point of view of their onset. They selected 67 cases, when the onset of ball lightning was fixed. From them in 31 cases of ball lightning arose in immediate proximity of the channel of forked lightning, in 29 cases it appeared from the metallic objects and the devices - sockets, radio receivers, antennas, telephone sets, etc., in 7 cases it was fired in air "from nothing".

Is interesting question about probability of observing ball lightning; as statistics shows, this probability is not so small. Thus, the request of Reilly [6], carried out by 4400 colleagues of the organization of NASA [HACA - National Aeronautics and Space Administration], showed that of them 180 people observed ball lightning. Stakhanov [8], being based on obtained by it data, considers that the average probability to see ball lightning for the man in the course of its life comprises order 10^{-3}.

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Barry [12, 20] estimates the probability of the appearance of ball lightning by the value, which lies within limits (10^{-9}-10^{-8}) $km^{-2} \cdot min^{-1}$, i.e., on the average on terrestial globe each hour must exist 100-1000 ball lightnings. This numeral is time average and space. It is clear that the probability of the occurence of ball lightning depends both on the conditions of specific locality and on the season. Since the thunderstorm weather strongly raises the probability of the appearance of ball lightning, ball lightnings are more frequently summer. This is demonstrated by Fig. 1.2, where are cited the data of Stakhanov [8] for distributing the observations of ball lightning on the months. A similar result follows from the data of Reilly [6], according to which for the summer months (June, July and August) are 81% of observations (on Stakhanov - 83%).

Let us note that frequency of occurence of flash of usual lightning for entire Earth comprises order 100 s^{-1} [128].

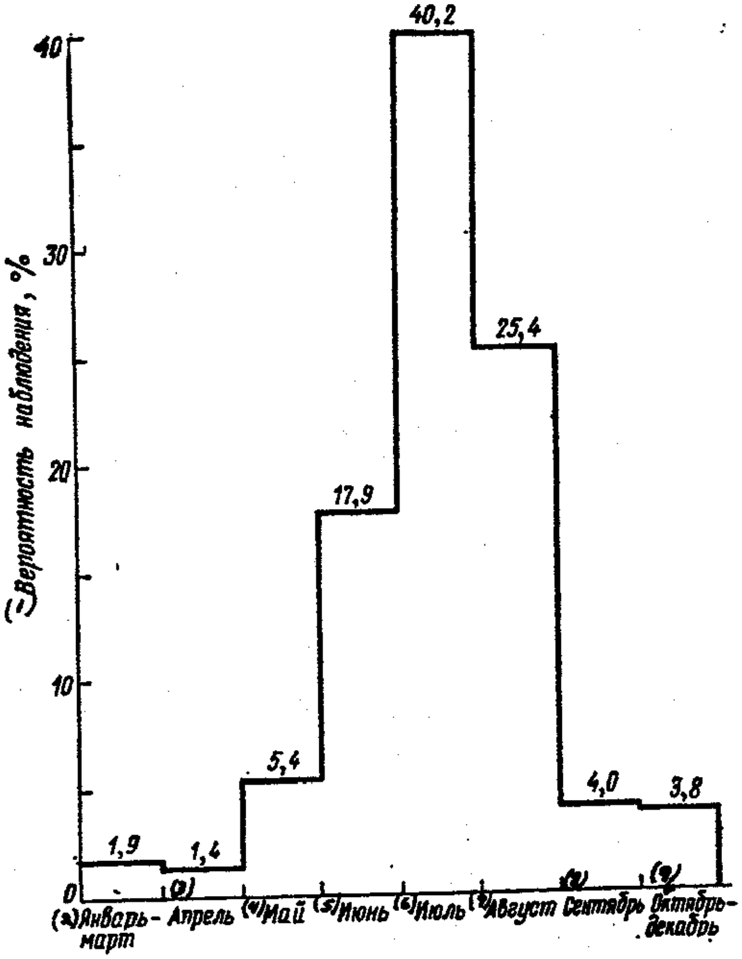

Fig. 1.2. Distribution of probability of observations of ball lightning on months according to data of Stakhanov [8]. Numerals indicate the probability of observing the phenomenon in the appropriate month.

Key: (1). Probability of observation, %. (2). Jan. March. (3). April. (4). May. (5). June. (6). July. (7). August. (8). September. (9). Oct. December.

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Thus, to one ball lightning is 1000-10000 usual lightning.

Let us examine character of decay of ball lightning. Observations show that its existence can end by blast or it can quietly go out. In this case according to data of Mac Nellie [5] were observed 309 cases of the sudden decay and 112 cases of the slow decay of ball lightning in those observations, when its end was recorded. According to the data of Reilly [6] in 54 cases was observed calm extinction, in 24 cases the blast of ball lightning, and according to data of Cherman [7] in 25 cases occurred calm extinction, in 26 cases the blast of ball lightning. According to the analysis of Stakhanov [8] in 610 cases of the observations of ball lightning, when the end of the life of ball lightning began on the eyes of eyewitnesses, in 335 cases occurred the blast, in 78 cases decay on the part and in 197 cases was observed calm extinction.

As is evident, somewhat different terminology and data processing interfere with comparing given results. Being based on them, it is possible to only draw the conclusion that most frequently the existence of ball lightning concludes with blast, somewhat less - probability that ball lightning slowly will go out. However, are frequent the cases, when ball lightning separates on the part. Let us give two examples, undertaken from the book of Arago [1]:

"Brief time after the advent of Philipp the V in Madrid, thunder fell on the palace. The persons, assembled at that time in the royal choir, saw, as two fireballs invaded. One of these spheres was subdivided into several smaller, which before they disappeared, made several springs, similar to elastic balls from rubber".

"In 1809 thunder passed through tube in David Sutton's house at Newcastle-on-Tyne. After blast many persons saw on the floor of the room, in which they were located, motionless fireball. This sphere joggled then to the middle of room and was divided into several individual parts, which everyone thought were similar to the stars of the rocket".

Usually blast of ball lightning occurs without large destruction.

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Of 335 reports about the blast of ball lightning among the data of Stakhanov [8] only in 34 cases was communicated about the damages. Most frequently this of splitting of trees or wooden columns (in 19 cases). Sometimes ball lightning breaks down lightning is relatively small; therefore for the people, which fall into the zone of the blast of ball lightning, this, as a rule, it is not terminated tragically. Let us give one additional example of the book of Arago [1], who contains the description of head of the French Ministry of Internal Affairs at Zhamenyu:

"During June 1852 in first half of the twelfth hour of evening I went along the street of Montoloni, when suddenly thunder with the force, rarely noted in Paris, burst out. First I little gave to this attention and continued my path, but suddenly among the street flashed the enormous lightning, which almost instantly followed the impact, similar to artillery volley. It seemed me that an enormously strong deserted bomb with the crack was broken on the street. This moving sphere seemed to me the moon, which fell from the sky, and this similarity stretched not only to the sizes, but also the color of meteor. This impact did not retard my gait, because I recalled that as soon as you see it moved lightning, then already something more to fear. I only moved my hat, which the wind or the jolt, produced by electrical blast, it fell back, and it went further without any connections to the area of barrels. When after passing area I wanted to step to the pavement, then saw moving somewhat an inclined new fireball, similar to the first, but had on the upper part kind of the red flame, which can be compared with the fuse and detonator of bomb, only into somewhat larger sizes. This sphere, which did not precede the lightning (at least, to me thus it seemed), fell with terrible speed and brought with it such a crack, that I never heard similar. I received on the right side such a jerk, that I was thrown to the wall. Undoubtedly crack seemed me so strong because I was situated in the position to hear it completely, on the whole more remarkable seemed to me the spherical form of lightning. My recollections in this respect are extremely precise.

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However, the case itself did not have very serious consequences and everything was restricted to the fact that my stomach could not digest food for two weeks".

Blast of ball lightning is not always inoffensive and sometimes leads to human victims. Among more than thousand descriptions of the observations of ball lightning, assembled by I. P. Stakhanov, it is communicated about five cases of death, although not always the result of the direct action of ball lightning. In the book of Arago [1] is a following example of this kind:

"Subsequently, when we will search for the explanations of the globular form, taken in certain cases by lightning, for us probably it is necessary to request, is sometimes this form at sea? In order previously to answer this question, I will say that on 13 July, 1798, the ship of East-Indian Co. "Good Hope", being located at 35°40' south latitude and 42° eastern longitude was affected by ball lightning, which produced extremely strong blast, that killed outright one sailor and which heavily wounded another."

The most tragic consequences during the blast of ball lightning occurred in the case, described in "Literaturnaya gazeta" on 21 December, 1983,:

"Twenty three women and one man worked in sunny valley. Mountains surrounded valley. Suddenly in the sky cloud appeared. Cloud was bulky, as if illuminated from within. Blinding rain gushed out. People were sent to the mulberry tree - shelter. Ball Lightning was already here".

Note is dedicated to courage and dignity of people, which arrived to aid victims. However, in this note it is not said, that was ball lightning, which exploded and scattered people, which hid under the tree. Majority of them lost consciousness. Aid was operational but three people died, without coming into consciousness.

S1.4. Emission.

Its glow is most important property of ball lightning. Qualitative representation about its brightness can be obtained from Table 1.1, where answers to questionnaire [6] are represented. It follows from the table that ball lightning is the source of light of average intensity.

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Specifically, the limited brightness of ball lightning is the reason for the fact that it relatively rarely is observed at large distances. For example, according to data of Stakhanov [8] half of the observed ball lightnings were located at a distance from the observer of less than 5 m.

It should be noted that glow of ball lightning is not always uniform. The nucleus of ball lightning, which is characterized by luminous intensity, while sometimes - by color, sometimes is isolated. In certain cases ball lightning is surrounded by halo. Frequently the glow is accompanied by discharge of sparks.

Valuable information in luminous intensity of ball lightning is assembled by Stakhanov [9]. Table 1.2 gives undertaken from its book data of 697 eyewitnesses, who compare the luminous intensity of ball lightning with the brightness of electric lamp.

Table 1.1. Luminous intensity of ball lightning according to data of Reilly [6].

(1) Характеристики интенсивности свечения	(2) Число положительных ответов
(3) Яркая, как разряд линейной молнии	12
(4) Достаточно яркая, чтобы осветить окружающие предметы	23
(5) Достаточно яркая, чтобы быть ясно видимой при дневном свете	66
(6) Еле видна при дневном свете	9

Key: (1). Characteristics of luminous intensity. (2). Number of positive responses. (3). Bright as discharge of forked lightning. (4). Sufficiently bright so as to illuminate surrounding objects. (5). Sufficiently bright so as to be clear to that seen with daylight. (6). It is hardly visible with daylight.

Table 1.2. Comparison of the intensity of the emission of ball lightning with the intensity of the emission of electric lamp.

(1) Мощность эквивалентной электрической лампы, Вт	(2) Число случаев	(3) Доля от полного числа случаев, %	
		(4) число сообщений очевидцев	(5) формула (1.1) при $\mathcal{P}_0=100$ Вт
0÷10	55	9,2	9,5
10÷20	83	13,9	8,5
20÷50	109	18,3	21,1
50÷100	140	25,5	23,9
100÷200	150	25,1	23,3
200÷500	39	6,5	13,0
(6) свыше 500	21	3,5	0,7

Key: (1). Power of equivalent electric lamp, W. (2). Number of cases. (3). Portion of total number of cases, %. (4). Number of reports of eyewitnesses. (5). Formula (1.1) with ... W. (6). More than.

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Let us process these data, considering that probability that the intensity of the glow of ball lightning, which coincides with the brightness of the electric lamp with a power of $\mathcal{P}$, is equal to

$$W(\mathcal{P}) = \frac{1}{\mathcal{P}_0} \exp\left(-\frac{\mathcal{P}}{\mathcal{P}_0}\right), \quad (1.1)$$

where $\mathcal{P}_0$ - average power of equivalent electric lamp. It follows, in particular from formula (1.1), that the relative number of ball lightnings with the intensity of the glow, which is found in the brightness range of the emission of electric lamp with power $\mathcal{P}_1$ and $\mathcal{P}_2$ $(\mathcal{P}_1 > \mathcal{P}_2)$, is equal

$$W(\mathcal{P}_1, \mathcal{P}_2) = \exp\left(-\frac{\mathcal{P}_2}{\mathcal{P}_0}\right) - \exp\left(-\frac{\mathcal{P}_1}{\mathcal{P}_0}\right).$$

Processing data of table 1.2 on basis of formula (1.1), for power of electric lamp, whose brightness coincides with average/mean intensity of the glow of ball lightning, we will obtain

$$\mathcal{P}_0 = 10^{2.0 \pm 0.2} \text{ Вт}^{(1)}.$$

Key: (1). W.

Let us note that the error indicated considers only the statistical straggling of data and is not included their authenticity; a real error in the given value is more. In spite of this, this information is very valuable.

Passing to illumination engineering units, for luminous flux, emitted by ball lightning of average intensity, we will obtain

$$\mathscr{P}_0 = 1400^{+800\,(1)}_{-600}\ \text{лм},$$

Key: (1). lm.

moreover is here considered only an error in the statistical averaging. Hence we find that ball lightning emits emission with the power of 2 W, if it occurs in the region of the spectrum (wavelength in the area 0.55 μm - green color) most advantageous for the eye. After multiplying this value for the lifetime of average ball lightning , we find that the emitted by average ball lightning energy is approximately 20 J, if emission is created in the region of the spectrum optimum for the eye. In other cases it is above.

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Color of its glow is another important radiation characteristic of ball lightning. Table 1.3 gives the color characteristics of observed ball lightnings.

It should be noted that during working of observations certain uncertainty sometimes appears, where should be related one or the other specific observation, if color or hue of ball lightning - intermediate. In this case in the coverage indicated there is no single diagram of the representation of these cases. Adhering to the simplified circuit of Stakhanov, we shared the cases of the intermediate colors, represented in other diagrams, into the case of simple colors. In the last column table 1.3 the relative probability of observing this color of ball lightning with the use of all data is given, and are here in the brackets indicated the values of this probability, obtained on the basis of data of Stakhanov [8]. It is evident that, with exception of the case of multicolored ball lightning, is a good agreement between different data. The disagreement of probabilities for the mixed color of ball lightning is caused by the fact that the methods of processing the observed data in these cases were different.

Table 1.3. Color characteristics of ball lightning.

(1) Наблюдаемый цвет	(2) Число наблюдений				(3) Сумма наблюдений	(4) Вероятность, %
	(5) Мак Нелли [5]	(6) Рэйли [6]	(7) Чэрман [7]	(8) Стаханов [8]		
Белый (9)	44	27	15	244	330	23(26)
Красный (10)	48	7	5	180	240	16(19)
Оранжевый (11)	50	46	12	113	221	15(12)
Желтый (12)	40	37	20	246	343	23(26)
Зеленый (13)	3	10	2	12	27	2(1)
Голубой, (14) фиолетовый	42	25	5	111	183	13(12)
Смесь цветов (15)	84	—	9	30	123	8(3)
(16) Общее число случаев	311	152	68	936	1467	

Key: (1). Observed color. (2). Number of observations. (3). Sum of observations. (4). Probability, %. (5). Mac Nellie [5]. (6). Reilly [6]. (7). Cherman [7]. (8). Stakhanov [8]. (9). White. (10). Red. (11). Orange. (12). Yellow. (13). Green. (14). Azure, violet. (15). Mixture of colors. (16). Total number of cases.

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Analysis of data, given in Table 1.3, testifies about presence of wide radiation spectrum of ball lightning. If this glow is created by the electronically excited molecules, which are formed in the presence of the chemical reactions, radiation spectrum testifies about the large set of such possible molecules. If the glow of ball lightning is connected with the emission of the surface of dust or aerosol particles, then the wide range of temperatures of these particles follows from the radiation spectrum. The higher probability of the colors, which correspond to the long-wave part of optical spectrum (red, orange, yellow), in comparison with the color of the short-wave part of the spectrum (blue, violet) is completely understood - the excitations, which lead to the birth of long-wave photons, more simply are created with the different methods of excitation. Thus, the fundamental conclusion, which can be made from the analysis of data of table - the glow of ball lightning it is not possible to explain by the only specific diagram, which uses the specific set of chemical compounds.

Let us pause now at some other special features of observed glow of ball lightning; one of them - irregularity of glow. Luminous intensity can change in the process of observation. Ball Lightning can flare up to the short period.

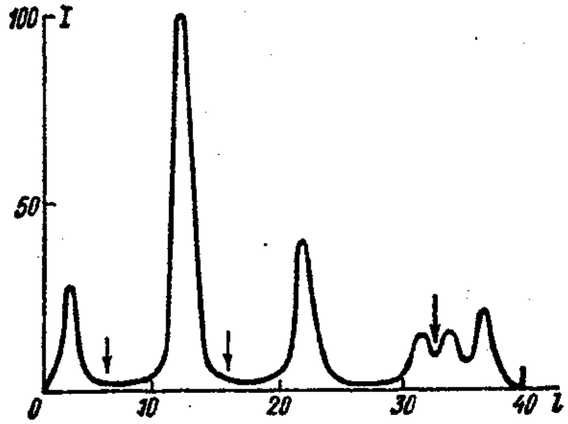

Fig. 1.3. Longitudinal photometric measurement of trace of ball lightning [21]. The dependence of relative luminous intensity I on the distance *l*, passed by ball lightning along the trace (*l* is expressed in the relative units, by arrows are indicated the points, at which the transverse photometric measurement of trace was conducted, see Fig. 1.4.

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Most significant in this respect it is Fig. 1.3, where dependence on the time (distance along the trace) for the intensity of the emission of ball lightning [21] is represented with the aid of the photometry of the trace of ball lightning. Photograph is conducted by V. M. Deryugin during the thunderstorm on the weather station of Karabad in the Guryev region on 9 June, 1958, at 2130. As is evident, the dependence of the intensity of emission on the time carries the oscillating character, moreover basic part of the emission is emitted in the short period in comparison with the lifetime of ball lightning.

As far as character of glow of ball lightning is concerned, in majority of cases it is not communicated about change in color of ball lightning for time of its observation. At the same time there are cases, when the color of ball lightning in the course of time changed. Therefore in this respect there is no complete stability. In a number of cases (with a sufficient statistics) was observed the nucleus - brighter interior of ball lightning, which was sometimes characterized by not only brightness, but also color hue. The presence of this nucleus in ball lightning testifies about the possibility of the heterogeneous structure of ball lightning.

It is usually customary to assume that emission of ball lightning occurs of all its parts, i.e., optical density of active material of ball lightning is small. The most convincing proof of this confirmation can be obtained with the aid of the photometric measurement of the photograph of the trace of ball lightning. We analyze data of this photometric measurement. A quantity of light, which falls on this section of photograph, is proportional to the power of light (incident at the given instant in the selected section of photograph), summed in the time. Let ball lightning - spherically symmetric system, which has radius R_0 and which moves evenly. Let us calculate a relative quantity of light, which falls into this point of photograph in the direction perpendicular to the motion. Let us make this in two limiting cases. In the first ball lightning emits about the surface (optically thick system), the second - from entire space (optically thin system). In the second limiting case we will count the density of the radiating particles in ball lightning of constant on a radius.

If ball lightning emits only with surface, intensity of emission, planned into this point of photograph, constant value until some point of ball lightning is projected to this point of photograph.

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Then the total quantity of light, which fell into this point of photographic film, is proportional to the time, during which into this point of film is projected the emission from ball lightning. Let into this point the emission, which corresponds to impact parameter ρ be projected (i.e. to minimum distance from the center for the totality of the points of ball lightning, projected into this point of photograph). Then the relative blackening at this point of film, proportional to the time of exposure $2\sqrt{R_0^2-\rho^2}/v$ (where v - speed of motion), is equal $(1-\rho^2/R_0^2)^{1/2}$.

Here the blackening, which corresponds to the center of trace, is undertaken one.

If emission occurs from space, then at each moment of time intensity of light is proportional to chord length, projected to this point of film. In this case a total quantity of light J is proportional

$$J \sim \int_{0}^{\sqrt{R_0^2-\rho^2}} \sqrt{R_0^2-\rho^2-x^2}\, dx.$$

Hence it is apparent that if we for one accept the blackening, which corresponds to the center of trace, then relative blackening at the point, which corresponds to impact parameter ρ, will be $1 - \rho^2/R_0^2$. The comparison of the transverse photometric measurement of trace with these dependences makes it possible to reveal the character of the emission of ball lightning .

Fig. 1.4 different data of photometric measurement of trace of ball lightning, gives to one of models examined. Let us explain, for example, the first model, which assumes that the radiating region optically thick, i.e., emission goes from the surface of ball lightning (Fig. a). In work [21] in three sections of the photograph of the trace of ball lightning (see Fig. 1.3) are restored the relative values of radiant energy $I(\rho)$, which correspond to impact parameter ρ.

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According to the analysis carried out above value $1(\rho)/I(0)$ in this model must be equal to $\sqrt{1-\rho^2/R_0^2}$, the value

$\frac{I(\rho)}{I(0)}\left(1-\frac{\rho^2}{R_0^2}\right)^{-1/2}$ must be equal to one. These values are given in Fig. 1.4a, and 1.4b are given the values of the relation

$\frac{I(\rho)}{I(0)}\left(1-\frac{\rho^2}{R_0^2}\right)^{-1}$, which must be equal to one in the case, when emission is created by entire space of ball lightning.

Conclusion about which of two models better describes real situation, can be made, after explaining, for which of two models corresponding relation nearer to one.

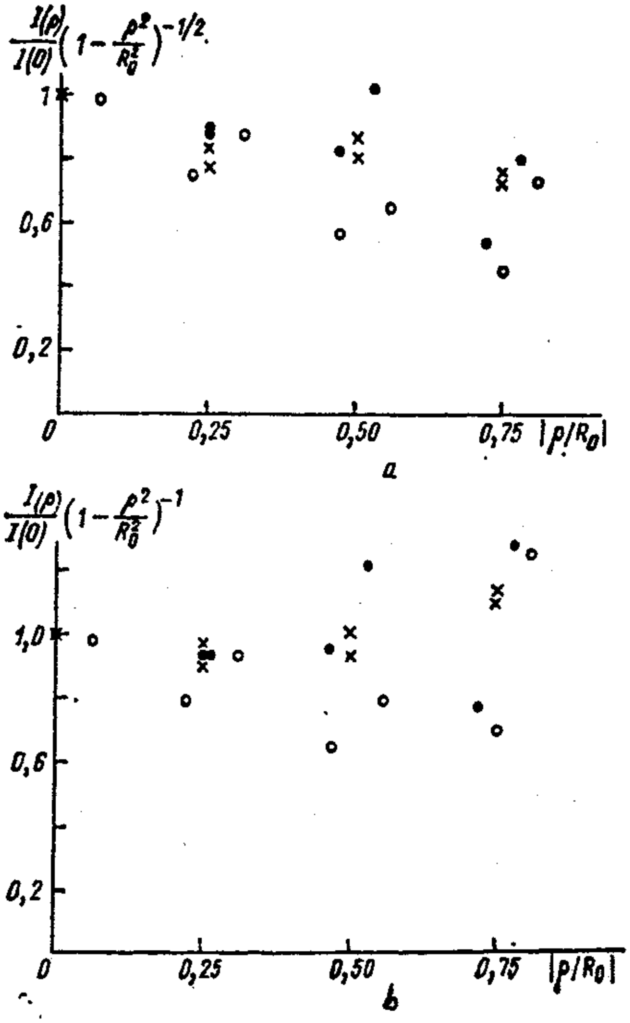

Fig. 1.4. Transverse photometric measurement of trace of ball lightning [21]. Relative luminous intensity I in the direction ρ, perpendicular to motion, is given to the appropriate model: glow goes from surface of (a); glow goes from the space of ball lightning (b). In the ideal case, if this model works, the value of the given relation must coincide precisely with one.

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Let us note that the disagreement between these models is not so great so that it would be select "to the eye", as the authors of work [21] entered. Actually, statistical processing of data of Fig. 1.4a gives the average result: 0.81±0.16; the averaging of data of Fig. 1.4b leads to the result: 0.56±0;.17. As is evident (although we must give the preference of the second model in accordance with the conclusions [8, 21]), the large scatter of results does not make it possible to arrive at the conclusion that the first model is invalid. Moreover, if we exclude data, which correspond to value and contributing the greatest error, then the statistical averaging of data of Fig. 1.14a will give result 0.87±0.13, and the averaging of data of Fig: 1.4b - the result: 0.93±0.13. As is evident, these average/mean values and their statistical errors do not make it possible to make a selection between the models [1]) in question.

FOOTNOTE [1]. It would be possible to draw this conclusion, if the difference between one and average value exceeded the doubled statistical error. ENDFOOTNOTE.

One should add to this that supplementary errors in data processing are caused by both the determination of the boundary of trace and by change in the intensity of its glow in the course of time.

Thus, from analysis of data on transverse photometric measurement of photograph of trace of ball lightning [21] it is possible to draw conclusion that volumetric emission of ball lightning is more probable than emission from its surface. However, the scatter of data does not make it possible to unambiguously make a selection between these cases even for the experiment examined.

S1.5. Other properties.

Let us pause at other properties of ball lightning, which are developed in process of its existence. During the analysis of the thermal effect of ball lightning on the observer let us return to the case, described in S1.2. Let us note that although ball lightning sufficiently closely approached the tailor, it did not feel heat. This result is noted in many instances of observing ball lightning.

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According to data of Reilly [6] sensation of heat during the observation of ball lightning they assert only four eyewitnesses, whereas 100 people gave negative response. According to the data of Stakhanov [8, 9] 25 people of 294, who observed ball lightning from the distance less than 1 m, write about the sensation of heat; about this communicate 8 people of 131, who observed ball lightning from the distance from 1 to 2 m; 20 of 379 people, near distance from whom to ball lightning was in the limits of 2-5 m; even 9 of 676 people, who observed it from the distance more than 5 m.

In small number of cases it is noted, that action of ball lightning in calm state, to people located by series can lead to burns and injuries. One of such cases, occured 8 August of 1975 in England, is described in article [22]. A participant in this incident was located in the kitchen during the thunderstorm, when she detected near herself ball lightning with diameter equal to approximately 10 cm, which was surrounded by halo and had a color from the vividly azure to the violet. When ball lightning approached, woman felt from it heat and odor of burning. Furthermore, ball lightning sent a crack. Woman herself communicates:

"It seemed the sphere hung near me lower than belt; then I automatically brushed it off, and it immediately disappeared. The left hand, by which I brushed off, reddened and swelled". Appeared hole in the dress and the underwear, where the contact of ball lightning occurred. Legs reddened and numbed.

Ball lightning can leave odor, which testifies about chemical composition of substance, being present in it after itself. This can be the odor of sulfur, oxides of nitrogen, ozone. Let us give two examples of this type from the book of Arago [1]:

"On 7 October, 1711, large fireball fell after the thunderstorm among the inhabitants of Sempford-Courtney (in Devonshire), who stood on the the church parapets. However, in the same instant four similar spheres, but only with size of a dog, brought in church itself and filled it with light and sulfuric fume. One of the apexes/vertexes of tower was stripped by the same impact".

"During the same day (1772), when during thunderstorm they saw above Steeple-Estom oscillating fireball, about which we above mentioned, priests Winehouse and Pitcairn, that were being found at that time in church house, suddenly saw at height of their size and within one foot of distance from their faces fireball with size with dog.

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This sphere was surrounded by black fume. With the disruption it produced the sound, similar to volley from the artillery instruments. Strongly smelled of sulfur vapors was propagated following the fact throughout entire house. Pitcairn was dangerously injured. His body, clothing, shoes, watch, presented all signs of usual lightning stroke. The light flame of different colors filled room and was found in the very strong oscillatory motion".

There is only case, when it was possible to determine chemical composition of trace of ball lightning [23, 24]. The author of this experiment M. T. Dmitriev - specialist in the field of the chemistry of the atmosphere, found in the summer of 1965 on river Onega in the expedition. They prepared test tubes for the sampling of air. By itse will at this time appeared ball lightning. It moved past the scientist, leaving after itself trace in the form of bluish mist. M. T. Dmitriev utilized his equipment for the analysis of the trace of ball lightning. The chemical analysis of air showed increased content in it of only two components - ozone and nitrogen dioxides. Their maximum content was 1.3 $g \cdot m^{-3}$ for ozone and 1.6 $g \cdot m^{-3}$ for dihydroxy - nitrogen. This is 50-100 times more than in the normal air.

Calm phase of existence of ball lightning is sometimes accompanied by weak sound - hissing, whistle. In a number of cases it is noticed that it affects radio communication. In the example given above M. T. Dmitriev detected the approach of ball lightning from the sharp amplification of crackling on the radio receiver, that also forced him to leave tent. From the assembled by him 45 cases of the observations of ball lightning [18] in six cases was noted the effect of ball lightning on the radio communication.

Ball lightning, apparently, bears electric charge. This is developed by the fact that it frequently is attracted to metallic objects, sometimes concluding thus its existence. Frequently it moves in the direction of wires or metallic objects. According to Mac Nellie [5] this phenomenon is observed in 20% of cases, based on materials of Reilly [6] - 16%.

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Evidence in favor of the presence of electric charge in ball lightning is the fact that the injuries, obtained with the contact with ball lightning, are similar to those, which are obtained by men, hit by voltage. A series of the cases, when the electrical properties of ball lightning were developed, was assembled in the books of Stakhanov [8, 9].

51.6. Power engineering.

Question is essential, what energy ball lightning contains. Unfortunately, ball lightning rarely leaves after itself traces, on which it is possible tc estimate the energy stored in it. Nevertheless are several cases, which make it possible to make (Table 1.4) this. Let us comment the facts, reflected in this table.

Table 1.4. Energy parameters of ball lightning in different cases [1].

№	(a) Характер выхода энергии	(b) E, кДж	(c) ε, Дж·см$^{-3}$
(1.)	Нагревание воды в бочке	$(1-3)\cdot10^3$	2000÷6000
(2.)	Расщепление бревна	150	85
(3.)	Ожог женщины	0,4	1
(4.)	Образование озона и двуокиси азота в следе шаровой молнии	0,5	0,4
(5.)	Расщепление асфальта	—	100
(6.)	Подпаленная трава	1700	900
(7.)	Нагревание провода	150	18
(8.)	Сгиб железной трубы в петлю	80÷100	10÷12
(9.)	Прожигание дыры в металлической трубе	150÷200	—
(10.)	Испарение металла на шомполе ружья	2	—
(11.)	Расщепление бревна	90÷120	10÷15
(12.)	Проплавление дыры в стекле	10÷20	—
(13.)	Оплавление садового крана	5	—
(14.)	Испарение металла на антенне самолета	20÷120	9÷60
(15.)	Оплавление металлического багра	0,7	—
(16.)	Разрушение кирпичной трубы	10÷20	5÷10

Key: (a). Character of energy production. (b). kJ. (c). ϵ, J·cm^{-3}. (1). Heating water in barrel. (2). Splitting of log. (3). Burn of woman. (4). Formation of ozone and nitrogen dioxide in trace of ball lightning. (5). Splitting of asphalt. (6). Singed grass. (7). Heating wire. (8). Bend of iron tube into loop. (9). Burning through of hole in metal tube. (10). Evaporation of metal on ramrod of gun. (11). Splitting of log. (12). Smelting hole in glass. (13). Fusing of garden tap. (14). Evaporation of metal on antenna of aircraft. (15). Fusing of metallic hook. (16). Destruction of brick tube.

FOOTNOTE [1]. Cases of 1-6 are undertaken from the book of Barry [12], case of 7-16 - from the book of Stakhanov [9]. ENDFOOTNOTE.

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Case 1 - sufficiently known case [25], when ball lightning fell into barrel with water, and 20 min after this water in barrel proved to be hot. Very description of this episode can cause doubt. Stakhanov [8, 9] disputes the given estimate because it exceeds reasonable value, and therefore also, what at its disposal is similar case with another result - ball lightning fell into the bucket with the water, water partially was splashed out, but was not heated.

Case of 2 contains estimate of energy, which is necessary in order to split log, wooden column, wooden pile. Cases 2 and 11 are completely equivalent, but estimates themselves are obtained differently (the first is borrowed from the book of Barry [12], the second belongs to Stakhanov [9]). The disagreement between the represented numerals testifies about the arbitrariness, which this estimate allows.

Case 3 is working of episode described above, when ball lightning burned woman and scorched her clothing. In the case 4 the energy, necessary for the formation of ozone and nitrogen dioxide in the quantity, measured by M. T. Dmitriev, is designed. This case was also previously described. Let us note that cases 3, 4, 10, 13 and 15 give the decreased value of energy, since on the processes in question, apparently, is spent a small portion of energy of ball lightning.

In remaining cases energy was designed by expenditures, necessary for realization of observed effect. In greater detail let us pause at case of 6, where the estimate is carried out erroneously. In this case during the thunderstorm ball lightning was not observed, but after one of lightning strokes near the house arose the glow, which was continuing 2-3 s. The bent singed trace was discovered after this, on the grass near the house. Utilizing a heater adjusted by power, the authors works [26] explained, in what parameters it will create on the grass the same trace as discovered earlier. It turned out that the approaching conditions correspond to height above the ground of 10 cm, power of heater 30 W and time of heating 300 s. In order to obtain trace on entire long, equal to 10 m, it is possible to move this source for 100·300 s=8 h. After multiplying this time to the power, we will obtain the numeral given in the table: 900 kJ.

It is not difficult to see series of contradictions in this approach.

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The obtained time of the creation of trace in no way will be coordinated with the time of the observation of glow or the lifetime of ball lightning. Already this one it is sufficient in order to recognize the inaccuracy of approach. Furthermore, it does not from anywhere follow that grass is burn due to the thermal effect of ball lightning (but not chemical or electrical). Further, the assumption about the stability of source in the case, when effect strongly depends on its power, also can lead to appreciable error. The errors of this approach indicated convince us in the inaccuracy of obtaining estimate. Therefore subsequently this estimate we into the account accept will not.

Rejecting in the case 6, let us conduct statistical averaging for geometric mean value of values, represented in Table 1.4. For the average value of energy of ball lightning we will obtain value $10^{1.3\pm1.1}$ kJ, while for the average value of energy density $10^{1.2\pm1.1}$ $J\cdot cm^{-3}$. Error in this distribution exceeds an order of magnitude itself.

Let us process data of Table 1.4, discussing as follows. Let us assume that the disagreement of the energy parameters, which relate to the different occurred cases, they are determined not by errors in each estimate, but fact that possible energies can be located in the wide interval of values. Let us process from this point of view of data table. We will consider that energy of ball lightning E is located in interval $E_{max} > E > E_{min}$, moreover probability that value E falls into energy range dE, is proportional dE/E. Hence follows - probability that energy of observed ball lightning exceeds value E, it is equal to

$$P = A - B\lg E, \quad (1.2)$$

moreover parameters A and B are connected with parameters $E_{\min}$, $E_{\max}$ with the relationships/ratios

$$B=\left(\lg\frac{E_{\max}}{E_{\min}}\right)^{-1},\quad A=B\lg E_{\max}.$$

For processing of data of Table 1.4 on basis of formula (1.2) it will arrange 14 cases in descending order of energy examined above. Then, if to the k case corresponds energy E', then probability P(E) of the fact that energy of ball lightning exceeds E', is equal to $(2k+1)/30$.

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The corresponding results are represented in Fig. 1.5, whose working gives $E_{\min}=0{,}2$ kJ, $E_{\max}=1{,}5\cdot10^3$ kJ. The probable value of energy (probability greater and the smaller values of energy is equal to 0.5) is 20 kJ. In this case lgE is restored with an accuracy to 0.24 (factor 1.8).

Similar working for energy density ϵ gives value $\varepsilon_{\min}=0{,}24$ J·cm^{-3}, $\varepsilon_{\max}=1$ kj·cm^{-3}, probable value of energy density 15 J·cm^{-3} (accuracy - factor 3). As is evident, the intervals of the possible values of energy and energy density of ball lightning compose almost four orders of magnitudes. If we forego the cases, where the estimated energy characteristics are understated, then this interval will prove to be already. The nearness of the average and most probable energy parameters is natural.

After subdividing value of energy of average/mean ball lightning for its space, we will obtain energy density, equal to $10^{0,2\pm0,4}$ $J\cdot cm^{-3}$. This value by an order is lower than found of the analysis of the estimated energy densities carried out earlier. This disagreement, apparently, testifies also about the accuracy, with which it is possible to determine the value of the energy density of ball lightning, since it is deliberately less than the accuracy of the determination of energy itself.

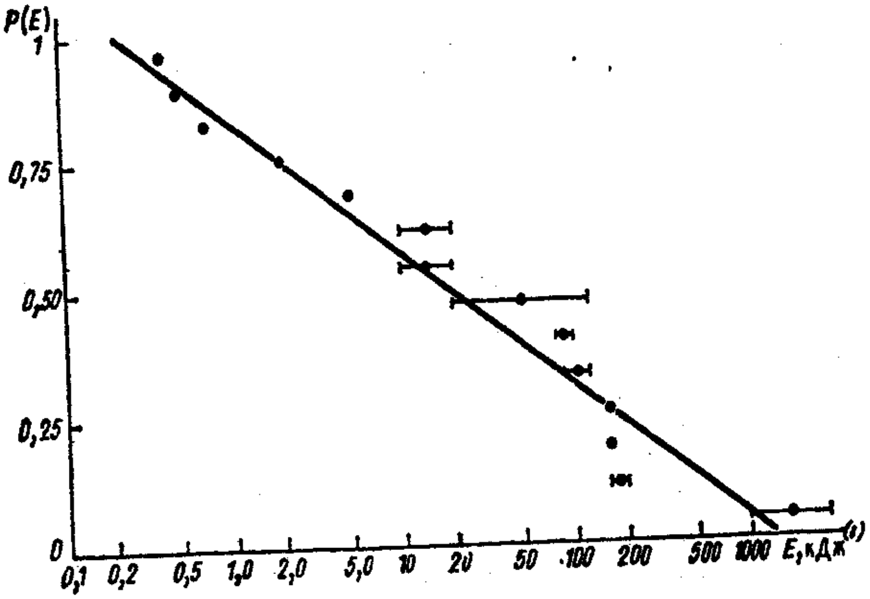

Fig. 1.5. Distribution of ball lightnings on energy reserve.

Key: (1). kJ.

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Taking into account this, let us represent further energy density as average between the values indicated, and error will characterize the degree of their disagreement. Then we obtain value $10^{0.7\pm0.5}$ J·cm^{-3}.

On basis of obtained data let us estimate average power of ball lightnings. According to the previously given estimate of Barry (see §1.3) the frequency of the appearance of ball lightning on the entire Earth is (0.01-0.1) s^{-1}. It follows from formula (1.2) that on the average ball lightning bears the energy

$\int E\,dP = 200$ kJ. For the power of energy release, included in ball lightnings, this gives (2-20) kW. Stationary this value with the power of usual lightning, taking into account that average/mean potential cloud - the Earth is 30 MV [129, 130], and average current to the earth under the action of lightning is equal to 1600 A [131, 132]. Hence we find the average power of energy release in lightning - order $5 \cdot 10^{10}$ W. If we consider that ball lightning is the secondary phenomenon of usual lightning, hence it follows that on ball lightnings it is expended the order of 10^{-7} parts of the energy of usual lightning.

§1.7. Parameters of average ball lightning.

Totality of observational data and their processing make it possible to create shape of ball lightning with averaged parameters. The parameters of average/mean ball lightning are given in Table 1.5. To these data it is possible to add the following. Ball lightning (glowing formation in air) usually has spherical form. It is observed also in locations, and in open air, and can move both in the horizontal and in the vertical directions. Ball lightning can have internal structure, can be surrounded halo. The sparks frequently escape from it. The motion of ball lightning is usually accompanied by sonic effects - hissing, whistle and crack.

Ball lightning develops electrical properties and is radiation source in radio-frequency wave band. The effect of ball lightning on man is analogous with the defeat of man by electric current. Usually ball lightning does not possess the properties of intense radiation source.

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In the majority of the observed cases its thermal effect on the surrounding bodies is not developed. To this it is necessary to add transiency and the irregularity of this phenomenon.

We will subsequently utilize represented shape of average ball lightning, based on observational data, during analysis of hypothetical models of ball lightning for purpose to understand its nature.

Table 1.5. Mean statistical parameters of ball lightning.

(1) Параметр	(2) Его значение
(3) Вероятность сферической формы	89±1%
(4) Диаметр	28±4 см
(5) Время жизни	$10^{0,95\pm0,25}$ с (6)
(7) Скорость перемещения	4±1 (8) м·с$^{-1}$
(9) Энергия шаровой молнии	$10^{1,3\pm0,2}$ кДж (10)
(11) Плотность энергии шаровой молнии	$10^{0,7\pm0,5}$ (12) Дж·см$^{-3}$
Цвет (13)	(14) Белый (24±2%), желтый (24±2%), красный (18±2%), оранжевый (14±±2%), голубой и фиолетовый (12±±1%) и другие*)
(15) Световой поток	1400^{+800}_{-600} лм (16)
(17) Световая отдача	$10^{-0,2\pm0,65}$ (18) лм·Вт$^{-1}$
(19) Корреляция с электрическими явлениями	(20) 70±10% шаровых молний наблюдается в грозовую погоду
Сезонность (21)	(22) Свыше 80% шаровых молний наблюдается в летние месяцы (июнь — август)
(23) Распад	(24) В 50±20% случаев конец существования шаровой молнии связан со взрывом, в остальных случаях — с медленным погасанием или распадом ее на части
(25) Вероятность появления	$10^{-8,5\pm0,5}$ (26) км$^{-2}$·мин$^{-1}$

Key: (1). Parameter. (2). Its value. (3). Probability of spherical form. (4). Diameter. (5). Lifetime. (6). s. (7). Speed of movement. (8). m·s^{-1}. (9). Energy of ball lightning. (10). kJ. (11). Energy density of ball lightning. (12). J·cm^{-3}. (13). Color. (14). White ... yellow ... red ... orange ... azure and violet ... and others). (15). Luminous flux. (16). lm. (17). Luminous efficiency. (18). lm·W^{-1}. (19). Correlation with electrical phenomena. (20). ... ball lightnings it is observed in thunderstorm weather. (21). Seasonality. (22). More than 80% ball lightnings are observed in summer months (June - August). (23). Decay. (24). In ... cases end of existence of ball lightning is connected with blast, in remaining cases - with slow extinction or its decay on part. (25). Probability of appearance. (26). $km^{-2} \cdot min^{-1}$.

FOOTNOTE [1]. In the brackets are given the values of the relative probability of observing ball lightning of the color indicated. ENDFOOTNOTE.

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Chapter 2.

METHOD OF STORING THE ENERGY IN BALL LIGHTNING.

S2.1. Hypotheses about the sources of energy of ball lightning.

From facts of observation of ball lightning it is possible to create general idea about this phenomenon. The desire to explain its nature is natural. Since the observation of ball lightning has rich history, there is a large number of hypotheses about nature of this phenomenon. On the basis of hypotheses are constructed the theoretical models, target of which is the description of ball lightning as physical phenomenon. At their base is included the information about the processes, which occur in excited air.

With respect to hypothetical models it is necessary to note following. First, the number of hypotheses themselves is sufficiently great. Some of them are forgotten in the course of time, and then appear again, in new works with new hues. Therefore for explaining nature of ball lightning there is no sense to search for the physical principles, placed in its nature. The possibilities of this explanation with one or the other degree of elaboration are taken into consideration in the existing hypotheses. In the second place, it is necessary to consider that ball lightning - complicated phenomenon, which combines contradictory, is at first glance, property.

Attempts to describe only separate sides of phenomenon frequently are made in the same time with the aid of existing models. It is possible to arise to the point of view, which constitutes the base of the corresponding model, and to critically estimate other sides of phenomenon, utilizing for this purpose contemporary scientific information about the processes and the phenomena in excited air.

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If this leads us to the fundamental contradictions between the utilized theoretical model and the observed facts, then hence it will be possible to make a conclusion about the groundlessness of the analyzed model of ball lightning. Thus, the complexity of the phenomenon of ball lightning proves to be in this case useful, since it makes it possible to taper the set of hypotheses, which explain same this phenomenon.

Below we will carry out critical analysis of existing hypotheses, connected with power engineering of ball lightning. Each of these hypotheses must, in the first place, explain, whence energy in ball lightning is taken. We will adhere to that point of view, that ball lightning is supported due to the internal energy. In accordance with this let us divide the existing hypotheses according to the proposed energy sources. Then possible hypotheses we can relate to one of the following five categories:

1) plasma,
2) gas with the excited particles,
3) electrical,
4) chemical,
5) exotic.

It is explained each of represented categories. It is simplest to begin with the latter, which we conditionally called "exotic". In it we included such assumptions, under which the energy of ball lightning is connected with antimatter, X-radiation, thermonuclear energy, etc., i.e. all assumptions, to which it cannot be related seriously not only due to idea itself, but also due to the character of its representation. Nevertheless such hypotheses are taken into consideration and undergo the criticism (for example, see [7, 11, 27]), which frees us from the need for spending time on them.

Plasma hypothesis is completely natural, since ball lightning, apparently, is connected with electrical phenomena, and in channel of usual lightning plasma is formed. Internal energy of this formation reserves itself in the charged particles - electrons and the ions. It is isolated during the recombination of the charged particles. Depending on the type of the charged particles in the plasma - electrons, the ions, cluster ions or aerosol particles - there can be the different versions of the plasma model of ball lightning.

Second method of storing energy in excited gas can be connected with creation of large number of excited atoms or molecules.

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For this purpose is possible the use of two types of the excited particles - metastable atoms or the molecules and oscillation-excited molecules. Both types of particles possess long lifetime relative to the time of the emission of photon, so that this channel of their decay under the atmospheric conditions is unessential. In both cases the probability of the quenching of the excited particle during the thermal collision with the gas atoms or the molecule is very small. Therefore this hypothesis deserves attention, its authenticity can be explained during the use of specific scientific information on the processes of collision with the participation of excited atoms and molecules.

To electrical hypotheses let us relate such, in which it is customary to assume that internal energy of ball lightning is connected with electric fields, created by system of charged particles. In this case we initially have a system of the charged particles (ions or aerosol particles), assembled into the predetermined element of space. The energy, spent on that in order to place the there charged particles, after overcoming the forces of Coulomb interaction between them, is utilized further as internal energy of system.

And finally apparently, most ancient hypothesis of ball lightning is connected with chemically of storing energy. F. Arago almost 150 years ago in book [1] wrote:

"These fireballs seem the accumulation of the material, strongly saturated with thunderstorm substance .... Lightning, passing through the atmosphere, connects places two compound gases and is formed nitric acid. Therefore it is not possible to consider it impossible that the same action produce the sometimes instantaneous semi-joining of all possible substances, which can exist in the known volume of air".

§2.2. Analysis of the plasma models of ball lightning.

Analyzing existing models of ball lightning, we will proceed from contemporary information about processes, which take place in hypothetical systems, and compare parameters of systems with observed parameters of ball lightning in question designed on basis of this. From the observed properties of ball lightning we will use the following.

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First, we will consider that energy into ball lightning is not supplied from without, but occurs the internal energy source. In the second place, we will consider that the temperature of ball lightning is small (for the certainty we will consider that it is limited by the value of 2000-3000 K, so that atmospheric air is weakly dissociated).

Carrying out analysis of processes, which take place in hypothetical ball lightning, we will consider that, according to observed data (see § 1.6), average density of internal energy of ball lightning is 5 $J \cdot cm^{-3}$ and, in any case, it exceeds 0.2 $J \cdot cm^{-3}$. Accordingly, the average value of the product of the density of internal energy of ball lightning ϵ and time of its life τ is approximately 40 $J \cdot s \cdot cm^{-3}$ and in any event must not comprise less than 1 $J \cdot s \cdot cm^{-3}$. We subsequently utilize this fact.

Energy stored in plasma is connected with ionization of atoms and molecules. In the rough approximation it is possible to consider that specific energy of plasma is equal to

$$\varepsilon = N_i J, \quad (2.1)$$

where J - ionization potential of atoms or molecules, N_i - density of the charged particles.

For conducting analysis of models it is necessary to define concretely plasma models, after connecting charges with specific type of charged particles. During the elaboration of the composition of plasma according to this principle let us examine, further, the separately following models of ball lightning, where active material is:

1) the plasma, which consists of the electrons and the positive ions;

2) plasma from the positive and negative ions;

3) the plasma, which contains cluster ions;

4) the aerosol plasma, where the positive and negative charges are connected with the aerosol particles.

We will enter as follows during analysis of parameters of hypothetical ball lightning. The recombination velocity of the charged particles is characterized by recombination coefficient α; taking into account only the recombination of the charged particles the equation of balance for the density of charged particles N_i takes the form

$$dN_i/dt = -\alpha N_i^2.$$

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In this case we count the plasma of quasi-neutral, i.e., the densities of positively and negatively charged particles coincide. Hence it follows that the characteristic time of recombination, i.e., the characteristic time τ, during which in the plasma can be retained the energy, in order of magnitude composes

$$\tau \sim 1/(\alpha N_i).$$

Taking into account expression (2.1) for the energy density, stored up per unit of volume of ball lightning, we will obtain the following relationship/ratio:

$$\varepsilon\tau \sim J/\alpha \sim 2 \cdot 10^{-18}/\alpha \quad (2.2)$$

(here dimensionality $\varepsilon\tau$ is expressed in J·s·cm^{-3}, recombination coefficient α - in cm^3·s^{-1}). While conducting of estimate we took ionization potential for the molecule of nitrogen (15 eV).

Table. 2.1 gives some characteristic values of parameters of recombination for typical processes, which take place in systems in question. We analyze each of the types of plasma separately taking into account the parameters of processes. In the plasma, which contains electrons at a not very high temperature, when molecular ions, are the fundamental type of ions, by the preferred channel of decay the dissociative recombination of electrons and molecular ions (in Table 2.1 are given recombination coefficients for the ions, which are formed in the air plasma) serves. From an increase in the temperature the recombination coefficient somewhat falls, but this is not reflected in an order of magnitude of the parameter $\varepsilon\tau$.

In plasma, which consists of negative 1) and positive ions, at atmospheric pressure of gas recombination of ions occurs during triple collisions with molecules of gas.

FOOTNOTE 1. It should be noted that in air at the atmospheric pressure and room temperature process $e+2O_2\rightarrow O_2^-+O_2$ for the thermal electrons is passed for time on the order of 0.2 μs. Therefore under standard conditions in weakly ionized air negative charge is connected with the negative ions. ENDFOOTNOTE.

The effective coefficient of ion recombination is expressed as the rate constants $\mathcal{K}$ of triple collisions according to the formula

$$\alpha = \mathscr{K}(N_2)[N_2] + \mathscr{K}(O_2)[O_2],$$

where $\mathscr{K}(N_2)$, the rate constant of the triple collision of ions with the molecules of nitrogen, expressed in units $cm^6 \cdot s^{-1}$.

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Table 2.1. Parameters of characteristic processes in the air plasma.

(1) Гипотетическая модель	(2) Процесс рекомбинации в возбужденном воздухе	(3) Константа скорости 1)		(4) $\eta\tau$, Дж·с·см$^{-3}$
(5) Плазма из электронов и ионов	$e + N_2^+ \rightarrow 2N$	$2 \cdot 10^{-7}$	[28]	$1 \cdot 10^{-11}$
	$e + O_2^+ \rightarrow 2O$	$2 \cdot 10^{-7}$		$1 \cdot 10^{-11}$
	$e + NO^+ \rightarrow N + O$	$4 \cdot 10^{-7}$		$6 \cdot 10^{-12}$
	$e + N_4^+ \rightarrow 2N_2$	$1{,}6 \cdot 10^{-6}$		$2 \cdot 10^{-12}$
(6) Плазма из отрицательных и положительных ионов	$O_2^- + O_2^+ + O_2 \rightarrow 3O_2$	$1{,}6 \cdot 10^{-25}$	[29]	$7 \cdot 10^{-12}$
	$NO^+ + NO_2^- + O_2 \rightarrow NO + NO_2 + O_2$	$3{,}4 \cdot 10^{-26}$		$1 \cdot 10^{-11}$
	$NO^+ + NO_2^- + N_2 \rightarrow NO + NO_2 + N_2$	$1{,}0 \cdot 10^{-25}$		$1 \cdot 10^{-12}$
(7) Плазма из кластерных ионов	$e + H_3O^+ \cdot H_2O \rightarrow$ (8) рекомбинация	$2{,}4 \cdot 10^{-6}$	[28, 30]	$1 \cdot 10^{-12}$
	$e + H_3O^+ \cdot (H_2O)_2 \rightarrow$ »	$(5 \div 10) \cdot 10^{-6}$		$(2 \div 5) \cdot 10^{-12}$
	$Cl^- + H_3O^+ \cdot (H_2O)_3 \rightarrow$ »	$4{,}8 \cdot 10^{-6}$	[30]	$5 \cdot 10^{-11}$
	$NO_3^- + H_3O^+ \cdot (H_2O)_3 \rightarrow$ »	$5{,}5 \cdot 10^{-6}$		$4 \cdot 10^{-11}$
	$NO_3^- \cdot HNO_3 + H_3O^+ \cdot (H_2O)_3 \rightarrow$ »	$5{,}7 \cdot 10^{-6}$		$4 \cdot 10^{-11}$

Key: (1). Hypothetical model. (2). Process of recombination in excited air. (3). Rate constant. (4). $\eta\tau$, j·s·cm^{-3}. (5). Plasma from electrons and ions. (6). Plasma from negative and positive ions. (7). Plasma from cluster ions. (8). recombination.

FOOTNOTE [1]. Rate constant for the paired processes is measured in cm^3·s^{-1}, and for the triple processes - in cm^6·s^{-1}; are to the right of values the surveys/coverage and the monographs, where information in this circle of processes, is assembled indicated. ENDFOOTNOTE.

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Table. 2.1 gives rate constants for some specific triple processes. For the plasma of air at the atmospheric pressure the effective recombination coefficient of positive and negative ions is $2\cdot10^{-6}$ $cm^3\cdot s^{-1}$, i.e., for this plasma parameter $\varepsilon\tau$ on the order of 10^{-12} $J\cdot s\cdot cm^{-3}$.

In the case of plasma, which consists of positive and negative ions, table 2.1 gives only rate constants for paired collisions. At the atmospheric pressure the recombination will occur in essence during the triple collisions with the effective recombination coefficient, in order of magnitude equal to 10^{-6} $cm^3\cdot s^{-1}$. The more rapid recombination of cluster ions will lead to the decrease of the parameter $\eta\tau$ in comparison with its value, given in table 2.1, although this will not affect the general conclusion - plasma models cannot explain the observed parameters of ball lightning.

Let us pause separately at recombination of aerosol plasma (not included in table 2.1). The recombination of the oppositely charged aerosols in air corresponds to Langevin's model. Particles converge due to the forces of Coulomb attraction, but this motion is braked by frictional forces in the gas. If we use Stokes's formula for the frictional force, then according to Langevin's formula effective recombination coefficient will be equal (see [31]).

$$\alpha = 1{,}5\langle q^2\rangle/(\eta r_0),$$

where q - charge of aerosol, r_0 - its mean radius, η - coefficient of the viscosity of air. Substituting this expression into formula (2.2) and utilizing numerical values of the entering parameters, we will obtain for the aerosol plasma

$$\varepsilon\tau \sim 10^{-7} r_0/\langle q^2\rangle. \quad (2.3)$$

Here value $\varepsilon\tau$ is expressed in $J \cdot s \cdot cm^{-3}$; r_0 - in μm; and the charge of aerosol q - in the unit charges of electron e.

Value of parameter $\varepsilon\tau$, which follows from observational data - on the order of 5 $J \cdot s \cdot cm^{-3}$. Each of the plasma models of ball lightning examined gives value less to there are many orders. Hence follows the groundlessness of the plasma models of ball lightning. Actually, the process of converting the energy of the charged particles into the heat during the recombination of charges in the plasma occurs too rapidly, so that noticeable energy cannot be preserved in the plasma sufficiently for long.

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§2.3. Long-lived excited atoms and molecule in air.

We analyze possibility of storing energy in excited particles, which are found in air at atmospheric pressure. There have several metastable states the atoms and molecules of nitrogen and oxygen, whose parameters are given in table 2.2 [32]. It should be noted that problem itself about the use of metastable atoms and molecules of oxygen and nitrogen repeatedly was posed in different applications. In particular, the major cycle of investigations [33] was carried out for the creation of the high concentration of the metastable atoms of oxygen $O(^1S)$. Further it was planned to utilize this system as the active medium of pulsed laser with the record value of the ratio of energy of laser emission to the space of active medium. Only the detailed study of this question showed the noncompetitiveness of this approach.

Another specific method of realization of this approach - iodine laser, whose pumping is conducted from metastable molecules of oxygen $O_2(^1\Delta_g)$ [34]. The metastable molecules of oxygen are formed in the presence of the chemical reaction of chlorine with hydrogen peroxide and are utilized as the carriers of energy. In the final analysis the energy of metastable molecules is converted into the energy of laser emission. The power of such lasers in the continuous mode reaches several kW [35].

Table 2.2. Parameters for the metastable atoms and the molecules of nitrogen and oxygen.

(1) Метастабильный атом или молекула	(2) Энергия возбуждения, эВ	(3) Излучательное время жизни, с
$O\,({}^1D)$	1,97	140
$O\,({}^1S)$	4,19	0,8
$N\,({}^2D)$	2,38	$6\cdot10^4$; $1{,}4\cdot10^5$
$N\,({}^2P)$	3,58	12
$O_2\,(a^1\Delta_g)$	0,98	$3\cdot10^3$
$O_2\,(b^1\Sigma_g^+)$	1,64	12
$N_2\,(A^3\Sigma_u^+)$	6,22	2

Key: (1). Metastable atom or molecule. (2). Excitation energy, eV. (3). Emitting lifetime, s.

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Table 2.3 presents processes of quenching of long-lived excited atoms and molecules in air. The rate constants of quenching for the metastable atoms and the molecules are undertaken from work [32], for those oscillation-excited - from work [36]. It is evident in all cases that the values of the lifetime of excited atoms and molecules are noticeably lower than the observed lifetimes of ball lightning . Therefore metastable atoms and molecules, and also oscillation-excited molecules cannot be used as the keeper of energy in ball lightning. Metastable molecule $O_2({}^1\Delta_g)$, possesses the greatest lifetime but also its lifetime is small in comparison with the lifetime of ball lightning. Let us note, however, that the probability of quenching during collision two metastable of molecules $O_2({}^1\Delta_g)$ is relatively small, so that sufficiently high energy can be concentrated in period on the order of 0.1 s in these molecules. In particular, in the sphere in question by a radius of 20 cm this energy can reach order 10 kJ.

Thus, carried out analysis shows that processes with participation of excited atoms and molecules for atmoshperic air pressure proceed sufficiently rapidly.

Table 2.3. Processes of the quenching of excited atoms and molecules of oxygen and nitrogen in air.

(1) Возбужденная частица	(2) Процессы разрушения в воздухе	(3) Константа скорости, $см^3 \cdot c^{-1}$	(4) Время жизни в нормальном воздухе, с
$O_2(^1\Delta_g)$	$2O_2(^1\Delta_g) \rightarrow O_2 + O_2(^1\Sigma_g^+)$	$2\cdot10^{-17}$	—
	$O_2(^1\Delta_g) + O_2 \rightarrow 2O_2$	$2\cdot10^{-18}$	0,1
$O_2(^1\Sigma_g^+)$	$O_2(^1\Sigma_g^+) + N_2 \rightarrow O_2 + N_2$	$2\cdot10^{-17}$	0,01
$N^2(A^3\Sigma_u^+)$	$N_2(A^3\Sigma_u^+) + O_2 \rightarrow N_2 + O_2$	$4\cdot10^{-12}$	$5\cdot10^{-8}$
$O(^1D)$	$O(^1D) + O_2 \rightarrow O + O_2$	$5\cdot10^{-11}$	4· [illegible]
$O(^1S)$	$O(^1S) + O_2 \rightarrow O + O_2$	$3\cdot10^{-13}$	$5\cdot10^{-7}$
(5) Колебательно-возбужденные молекулы азота (N_2^*) и кислорода (O_2^*)	$N_2^* + N_2 \rightarrow N_2 + N_2$	10^{-19}	0,02
	$N_2^* + CO_2 \rightarrow N_2 + CO_2$	$6\cdot10^{-15}$	
	$O_2^* + O_2 \rightarrow 2O_2$	10^{-17}	0,02

Key: (1). Excited particle. (2). Processes of destruction in air. (3). Rate constant cm^3 rds^{-1}. (4). Lifetime in normal air, s. (5). Oscillation- excited molecules of nitrogen ... and oxygen ....

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Therefore those models of ball lightning, in which as the energy source are utilized the excited particles, prove to be also invalid.

§2.4. Electrical method of storing the energy.

It follows from observational data that ball lightning possesses relatively high electric charge. The created by charge electric field contains energy and can cause the discharge in air, which is accompanied by glow. Let us estimate the energy possibilities of this system.

We will consider that net charge of active material is equal to q and concentrated in sphere with radius R_0. Then if charge evenly distributed by the space of sphere, electrical energy of sphere is equal to

$$E = \int \frac{\rho(r)\rho(r')\,dr\,dr'}{|r-r'|} = \frac{3}{5}\frac{q^2}{R_0}, \qquad (2.4a)$$

where ρ - the bulk density of charge. But if charge evenly distributed over the surface of sphere, then its electrical energy is equal to

$$E = q^2/R_0. \quad (2.4b)$$

In this case the value of electric intensity F maximally on the surface of sphere comprises $F = q/R_0^2$. When $F_{max} = 30$ kV·cm⁻¹ occurs the breakdown of air at the atmospheric pressure. If in air aerosols are found or if breakdown occurs near the surface, then breakdown electric intensity is below.

Energy density of charged sphere, whose charge is concentrated on surface, in accordance with given formulas comprises

$$\varepsilon = \frac{3E}{4\pi R_0^3} = \frac{3F^2}{4\pi}.$$

Replacing electric intensity on the surface of breakdown, we obtain $\epsilon < 2 \cdot 10^{-4}$ J·cm⁻³, and since, according to observational data, $\epsilon > 0.2$

$J\cdot cm^{-3}$, we come to the conclusion that it is not possible to explain the observed values of energy of ball lightning by electrical interactions.

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§2.5. Chemical method of storing the energy.

With chemical method of storing energy in ball lightning its energy is isolated in the presence of chemical reactions. The elementary event of chemical process is connected with sub-Barryer transition of atoms and readjustment of atomic system at the moment of the approach of particles. With thermal energy the probability of this transition can be very small, so that it is possible to find numerous examples with the long storage time of chemical energy.

Among chemical compounds, which are formed in air, ozone occupies special position. Effectively and in large quantities ozone can be formed with the atmospheric electrical phenomena much more easily than any other compound of oxygen and nitrogen. Therefore further the possibility of long storage of chemical energy we investigate based on the example of ozone. Let us examine the processes, connected with the resolution of the molecule of ozone in the standard air. They occur according to the diagram

$$O_3+N_2 \rightleftharpoons O+O_2+N_2, \qquad (2.5)$$

$$O_3+O_2 \rightleftharpoons O+2O_2, \qquad (2.6)$$

$$\frac{O+O_3 \rightarrow 2O_2}{2O_3 \rightarrow 3O_2}. \qquad (2.7)$$

The special feature of the process of decomposition of ozone lies in the fact that two molecules of ozone do not enter into the chemical reaction. Therefore the conversion of ozone into oxygen occurs through its dissociation, which leads to deceleration of process.

Let us write equation of balance for density of oxygen and ozone. For simplicity processes (2.5) and (2.6) let us reduce to one, after designating [M] - molecule density of air, k_5 - rate constant of the process of dissociating the molecule of ozone, $\mathscr{K}$ - the rate constant of reverse process. the rate constant of process (2.7) let us designate k_7.

Then we have .

$$\frac{d[O_3]}{dt} = -k_5[O_3][M] + \mathscr{K}[O][O_2][M] - k_7[O_3][O],$$
$$\frac{d[O]}{dt} = k_5[O_3][M] - \mathscr{K}[O][O_2][M] - k_7[O_3][O]. \quad (2.8)$$

We analyze obtained equations. Let us note that the equilibrium on the density of atomic oxygen is established for the time of order $(\mathscr{K}[O_2][M])^{-1}$.

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At the atmospheric pressure and in the temperature range in question this composes order 10^{-5} s, i.e., the time, small in comparison with the observed lifetimes of ball lightning. Therefore it is possible to consider for the scale of time (order of second) in question that is established the quasi-equilibrium of atomic oxygen, and to disregard the value of derivative of the density of atomic oxygen. Then, after obtaining expression for the density of atomic oxygen with the aid of the second of relationships/ratios (2.8) and after substituting this value into the first, we lead the equation of balance for ozone density to the form

$$\frac{d[O_3]}{dt} = -\frac{2k_5[O_3][M]\cdot k_7[O_3]}{\mathscr{X}[O_2][M]+k_7[O_3]}. \qquad (2.9)$$

Let us introduce value $[O_3]_0$:

$$[O_3]_0 = \frac{\mathscr{X}[O_2][M]}{k_7}, \qquad (2.10)$$

and let us examine two limiting cases.

First case - ozone density is small $([O_3] \ll [O_3]_0)$, in this case is established thermodynamic equilibrium between atomic oxygen and ozone:

$$O + O_2 \rightleftharpoons O_3.$$

Therefore the relationship/ratio between the density of atomic oxygen and the density of ozone is expressed as the equilibrium constant $K_{\text{равн}}(T)$, which corresponds to this temperature:

$$f(T) \equiv \frac{[O]}{[O_3]} = K_{\text{равн}}(T)[O_2] = \frac{k_5}{\mathscr{X}[O_2]}. \qquad (2.11)$$

Then the equation of balance for ozone density, which considers this totality of processes, takes the form

$$\frac{d[O_3]}{dt} = -k_7 f [O_3]^2. \quad (2.12)$$

thus value $k_7 f$ is the effective rate constant of the total process, which has the second order on ozone density.

Second case - ozone density is great ($[O_3] \gg [O_3]_0$) in this case limiting stage of process of converting ozone into oxygen is process of its dissociation.

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Then the equation of balance for ozone density takes the form

$$\frac{d[O_3]}{dt} = -\frac{[O_3]}{\tau},$$

where

$$\frac{1}{\tau} = 2k_5[M] = 2f(T)\{\mathcal{K}(O_2)[O_2] + \mathcal{K}(N_2)[N_2]\} = 2k_7 f(T)[O_3]_0. \quad (2.13)$$

Here $\mathcal{K}(O_2)$, $\mathcal{K}(N_2)$ - rate constant of the triple process of the association of atom and molecule of oxygen, where the third body is respectively the molecule either of oxygen or nitrogen. As is evident, in this limiting case we have process first-order on ozone density.

Table 2.4 depicts parameters of process of decomposition of ozone in air, which characterize behavior and rate of course of this process taking into account reactions (2.5)-(2.7). The parameters are related to real air composition and atmospheric pressure. The values of equilibrium constant are undertaken from work [37], rate constant of triple processes (2.5) and (2.6), and also constant k, - from works [38, 39].

Analysis of data of table 2.4 shows that at low temperatures time of resolution of ozone, added to air, noticeably exceeds observed lifetime of ball lightning. It is possible to expect that the chemical reactions of ozone with the admixtures/impurities, which are found in air, substantially reduce the time of the resolution of ozone. Nitrogen oxides, which are formed together with ozone with the electrical phenomena in air, here play special role, and as a result of chain reactions they lead to the resolution of ozone.

Table 2.4. Parameters of the process of decomposition of ozone in air.

T	$\mathcal{K}(O_2)$, 10^{-34} $см^6 \cdot с^{-1}$ (1)	$\mathcal{K}(N_2)$, 10^{-34} $см^6 \cdot с^{-1}$ (1)	k_7, 10^{-14} $см^3 \cdot с^{-1}$ (2)	$[O_3]_0$, $см^{-3}$	$f(T)$	$k_7 f$, $см^3 \cdot с^{-1}$ ②	τ, с (3)
250	8,6	9,7	0,23	$6,3 \cdot 10^{19}$	$2,5 \cdot 10^{-15}$	$5,7 \cdot 10^{-30}$	$1,4 \cdot 10^{9}$
300	5,7	5,1	1,0	$5,3 \cdot 10^{18}$	$1,2 \cdot 10^{-11}$	$1,2 \cdot 10^{-26}$	$7,9 \cdot 10^{6}$
350	4,1	3,1	2,9	$8,8 \cdot 10^{17}$	$5,0 \cdot 10^{-9}$	$1,4 \cdot 10^{-22}$	$4,1 \cdot 10^{3}$
400	3,3	2,2	6,4	$2,2 \cdot 10^{17}$	$4,6 \cdot 10^{-7}$	$3,0 \cdot 10^{-20}$	76
450	2,8	1.7	12	$7,3 \cdot 10^{16}$	$1,6 \cdot 10^{-5}$	$1,9 \cdot 10^{-19}$	3,6

Key: (1). $cm^6 \cdot s^{-1}$. (2). $cm^3 \cdot s^{-1}$. (3). s.

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The detailed analysis, carried out in work [40] for resolving ozone taking into account nitrogen oxides, shows that under the actual conditions the decay of ozone is actually determined by the chain reactions of ozone with nitrogen oxides. However, in this case there is a parametric domain, where the resolution of ozone occurs slowly.

Fig. 2.1 gives temperature dependence of period of half-life of ozone with its different concentrations c_{O_3} in air. The concentration of nitrogen oxides by an order lower than concentration of ozone, which answers the actual conditions for the formation of these compounds during the electrical discharge in atmospheric air. Let us note that the conversion of ozone into oxygen with concentration 1% leads to heating of air on 50 K.

Thus, this example convinces us, that chemical energy can be stored sufficiently for long. This is connected with the slowness of chemical processes. As a result of the carried out analysis we come to the conclusion that the only method of storing the energy in ball lightning - is chemical. The chemical method of storing the energy has one additional advantage over others, providing high specific energy densities. For example, contemporary capacitors make it possible to store the specific electrical energy, equal to approximately 60 $J \cdot l^{-1}$. Average/mean electric intensity in them is 1 $MV \cdot cm^{-1}$, which 30 times approximately exceeds breakdown electric intensity in air.

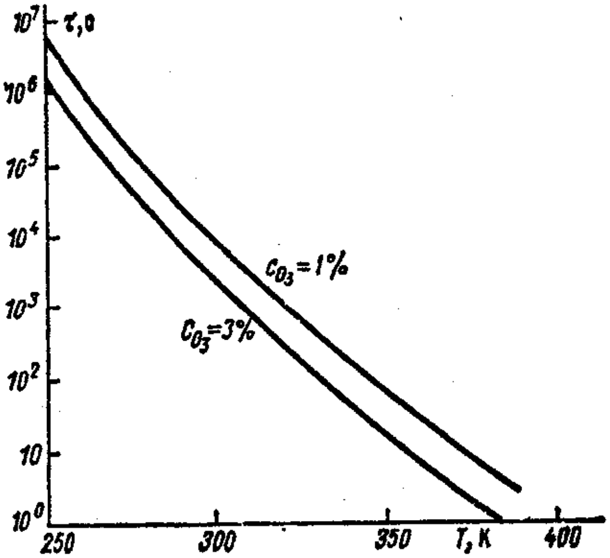

Fig. 2.1. Temperature dependence of time τ of semi-dicomposition of ozone in atmospheric air, which contains oxides of nitrogen [40].

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In order to accumulate energy of average ball lightning, it is necessary to engage by capacitors the space of 300 l, which 30 times almost exceeds the space of average ball lightning.

Let us make another estimate of electrical energy. Let us load the isolated electrical sphere so that its energy would coincide with the energy of average ball lightning, and electric intensity on its surface coincided with breakdown strength of field for atmospheric air (30 kV·cm^{-1}). Let us find this necessary for radius of sphere R=2.7 m, which 20 times exceeds a radius of average/mean ball lightning. The potential of this sphere would be 8 MV. Electrical energy of the charged sphere, whose radius coincides with a radius of average ball lightning, and electric intensity coincides with the breakdown of intensity for atmospheric air (30 $KV\cdot cm^{-1}$) and is 3 J, which is considerably less than the energy of average ball lightning (20 kJ). At the same time energy of average ball lightning is provided in all ten times by matches (weight less than 1 g). These estimates convince, that the electrical processes are unessential for power engineering of ball lightning.

High specific energy reserve of chemical energy in comparison with plasma is demonstrated by data of Table 2.5, where specific energy reserves for plasma and chemical systems are compared. As the plasma system is selected air at the atmospheric pressure, completely dissociated and half ionized, which corresponds to the temperature of 26000 K.

Table 2.5. Specific specific energy of air at the atmospheric pressure.

(1) Объект	(2) Тип энергии	(3) Удельная энергия, Дж·см$^{-3}$
(4) Полностью диссоциированный и наполовину ионизированный воздух (T = 26 000 K)	(5) Энергия диссоциации и ионизации молекул воздуха	0,66
(6) Воздух с примесью озона (концентрация озона 2%)	(7) Химическая энергия озона	0,13
(8) Воздух с угольной пылью с концентрацией более 0,08 г пыли на 1 г воздуха	(9) Химическая энергия при сгорании угля	3,6

Key: (1). Object. (2). Type of energy. (3). Specific energy, $J\cdot cm^{-3}$. (4). Completely dissociated and half ionized air:. (5). Dissociation energy and ionization of molecules of air. (6). Air with admixture/impurity of ozone (concentration of ozone 2%). (7). Chemical energy of ozone. (8). Air with coal dust with concentration is more than 0.08 g of dust by 1 g of air. (9). Chemical energy with combustion of carbon.

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Due to the high temperature per unit of volume of this system it is located two orders less particles than in the standard air. Therefore despite the fact that the value of the energy, which falls to one particle in the plasma system sufficiently high, chemical energy per unit volume can prove to be above.

Let us make one additional observation, which is conclusion from

Table 2.5. The greatest specific energy reserve answers the last case, which corresponds to the combustion of carbon to the carbon dioxide with the complete utilization of atmospheric oxygen. Obviously, due to the use of atmospheric oxygen it is not possible to obtain larger specific energy release. However, the account of data of Tables 1.4 and 1.5 gives the possibility to show that this specific energy release several times lower than observed for average ball lightning. Hence it is possible to draw the conclusion that the active material of ball lightning includes both the fuel and oxidizer.

As has already been emphasized above, among chemical compounds, which can become part of active material of ball lightning, ozone is preferred connection. It other more easily chemically active substances and in a larger quantity is formed with the electrical phenomena in the atmosphere and it simultaneously possesses the properties of both the fuel and the oxidizer, since in the gas phase it is decomposed/expanded according to the diagram

$$O_3 \rightleftharpoons O_2 + O, \quad O + O_3 \rightarrow 2O_2. \qquad (2.14)$$

Specific energy release during the resolution of ozone composes 3 $kj \cdot g^{-1}$, which by an order is less than with the complete combustion of carbon, but it is compared with the specific energy reserve of explosives.

Limiting stage in resolution of ozone (2.14) is first process - dissociation of its molecules. With an increase in the temperature the rate of this process and, consequently, also the rate of the resolution of ozone sharply grows.

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For example, the velocity of propagation of the thermal wave of the resolution of ozone, which is found in the buffer gas, is determined by the formula

$$u = \frac{1{,}37 T_m^{2{,}39}}{T_m - T_0} \exp\left(-\frac{5800}{T_m}\right), \quad (2.15)$$

where the rate of thermal wave is expressed in cm·s^{-1}, and initial T_0 and maximum T_m of the value of the temperature of gas in the wave are expressed in Kelvins. According to this formula, for example, an increase in the maximum temperature in the thermal wave from 490 to 1070 K increases wave velocity by three orders: from 1 mm·s^{-1} to 1 m·s^{-1}.

In accordance with observational data ball lightning - calm phenomenon, which just as sharply does not depend on parameters of process. Therefore it is possible to draw the conclusion that ozone is not the fundamental energy-containing substance of ball lightning. The more adequate for it role - this is the role of detonator, i.e., it is possible to expect that the participation of ozone creates conditions for the course of fundamental energy processes in ball lightning.

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CHAPTER 3.

THERMAL PROCESSES IN BALL LIGHTNING.

S3.1. State of substance.

Analysis carried out in previous chapter convinces us, that method of storing energy in ball lightning - chemical. We come to this, comparing the observed lifetime of ball lightning with the characteristic conversion time of the corresponding form of energy into thermal, which is caused by the rates of processes taking place in this case. Since the lifetime of ball lightning exceeds the characteristic times of the collision of molecules in atmospheric air to many orders, not any process can be such slow that the internal energy of system would be retained as such for long. This fact makes it possible to significantly taper the circle of the phenomena, which can compose the base of ball lightning.

Relatively long lifetime, however, not only surprising property of ball lightning, another such property is its form. Ball lightning in the larger part of the observed cases has spherical or close to it form. In this case it is significant that the form and sizes of ball lightning are retained in entire period of observation or, at least, during its significant part. It is obvious that the comparison of this observed fact with the physical representation, which ensues from the specific assumptions about nature of ball lightning, also can be informative.

We analyze from this point of view hypothetical ball lightning, whose active material is mixture of gases or separate aerosols (solid or liquid particles of small sizes), which are found in atmospheric air.

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The physical picture of the phenomenon in question can be visualized as follows. In a certain region of space chemical reaction with the participation of active material occurs. Heat release due to the chemical reaction raises the temperature of air and active material in this region, which leads to the acceleration of chemical reaction. In the zone the gradient of the density of active material and the flow of active material into the zone of reaction are created.

This physical picture is described by steady-state solution of Franck-Kamenetskiy [41], which corresponds to conditions, under which zone of chemical reaction is considerably less than region, occupied by active material. Further we will give this solution for the case of active material, which is found in atmospheric air. In this case it is possible to consider that the region of glow coincides with the combustion zone, and since field distribution of temperatures is spherically symmetrical, under the conditions in question will be observed the region of the glow of spherical form.

Equations of balance for temperature T of air and density N of active particles take form

$$c_p\rho\frac{\partial T}{\partial t}=\varkappa\Delta T+\frac{N\Delta\varepsilon}{\tau}, \tag{3.1}$$

$$\frac{\partial N}{\partial t}=\mathscr{D}\Delta N-\frac{N}{\tau}. \tag{3.2}$$

Here c_p - heat capacity, ρ - mass density, κ - coefficient of the thermal conductivity of air. We consider for simplicity that a quantity of active material is relatively small, i.e., it does not noticeably affect the parameters of air. Further, $\Delta\epsilon$ - energy, isolated by one particle of active material, $\mathscr{D}$ - the coefficient of diffusion of active particles in air, τ(T) - the time of the current of chemical reaction. It is significant in this case which τ sharply depends on the temperature:

$$\tau=\tau_0\exp(E_a/T), \tag{3.3}$$

where E_a - energy of the activation of process.

Us interests steady-state solution of equations (3.1), (3.2), i.e., case, when left sides of these equations are equal to zero. Utilizing boundary conditions $T(\infty)=T_0$, $N(\infty)=N_0$, storing equations (3.1) and (3.2), having preliminarily multiplied the second of them on $\Delta\epsilon$, in this case it is not difficult to obtain

$$\varkappa(T-T_0)=\mathscr{D}(N_0-N)\Delta\varepsilon. \tag{3.4}$$

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We analyze solution of equations (3.1), (3.2). We consider that the reaction proceeds to the region with size of $r \sim r_0$, while the active material occupies much larger region - with size $R_0 \gg r_0$. The heat release can be disregarded out of the scope of reaction, since equation (3.1) will take form $\Delta T=0$, and its solution will be

$$T = T_0 + \frac{\mathcal{P}}{4\pi \varkappa r}, \quad r \gg r_0. \quad (3.5)$$

Here $\mathcal{P}$ - power of heat release, moreover was used the fact that heat flux $q = -\varkappa \nabla T$ out of the scope of reaction was connected with the power with relationship/ratio $4\pi r^2 q = \mathcal{P}$. Analogously the density of active particles in this region is given by the expression

$$N = N_0 - \frac{\mathcal{P}}{4\pi \mathcal{D} \Delta \varepsilon r}. \quad (3.6)$$

This formula can be obtained both from the solution of equation (3.2) and from relationships/ratios (3.4), (3.5).

Let us designate through T_1 temperature in center, T - temperature at a distance of r_0 from center, similarly through N_1 and N - density of active particles in center and at a distance of r_0 from center. Since r_0 is the size of the region, in which the reaction occurs,

$$\frac{E_a}{T} - \frac{E_a}{T_1} \sim 1,$$

i.e.

$$T_1 - T \sim \frac{T_1^2}{E_a} \quad (T \ll E_a).$$

Further from equations (3.1) and (3.2) it follows

$$\varkappa(T_1 - T) \sim \frac{\mathcal{P}}{r_0}, \quad \mathcal{D}(N - N_1) \sim \frac{N_1 r_0^2}{\tau}.$$

Hence taking into account formulas (3.5) and (3.6) we obtain

$$T_1 - T_0 \sim \frac{\mathcal{P}}{\varkappa r_0} > \frac{T_1^2}{E_a}, \quad \frac{r_0^2}{\mathcal{D}\tau} \leqslant 1. \tag{3.7}$$

Stable steady-state solution of these equations gives estimate $r_0^2 \sim \mathcal{D}\tau$.

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The account of numerical coefficient in this relationship/ratio in the case, when active material is gas, for $\tau \sim 1$ s gives value of g_0 of the order of centimeters, that does not contradict observational data.

One additional estimate, which also follows from formulas (3.7), relates to temperature differential in zone of reaction. For the power of heat release $\mathcal{P} \sim 10$ W we obtain $T_1 - T_0 \sim 100$ K. An increase in the power of heat release leads to a change in the character of heat withdrawal, so that formula (3.7) ceases to work. The new mechanism of heat withdrawal leads to the decrease of temperature differentials in comparison with the value, determined by formula (3.7). Therefore for the estimate it is possible to consider that also at the higher power of heat release temperature differential in the zone of reaction composes several hundred degrees.

With drop/jump in temperatures (~100 K) in question and sizes of active region (~10 cm) movement of air with admixture/impurity of active particles becomes convective. Let us estimate the parameters of convective motion in the zone of reaction. Let us assign the size of elementary vortex/eddy l $(l \ll R_0)$ and the temperature differential in the active region ΔT. The size of unit cell can be found from the condition that the number of Rayleigh 1) for the unit cell of the order of critical value $R_{кр}$.

FOOTNOTE 1). The pure number of Rayleigh for the gas, which is located in the gravitational field, is given by relationship/ratio [42]

$$R = \frac{\Delta T}{T}\frac{gL^2}{\nu\chi}.$$

Here ΔT - temperature differential on the vertical size L; T - mean temperature of gas; g - free-fall acceleration; ν - kinematic viscosity; χ - coefficient of thermal diffusivity. Rayleigh number is convenient to represent in the form $R = A\Delta T L^3$, moreover the numerical coefficient A for air at the atmospheric pressure is equal to 91 $cm^{-3}\cdot K^{-1}$ with T=300 K, A=8.9 $cm^{-3}\cdot K^{-1}$ with T=500 K and 2.1 $cm^{-3}\cdot K^{-1}$ with T=700 K. ENDFOOTNOTE.

The critical value of Rayleigh number, which corresponds to the threshold of the onset of convection in the cell in question, depends on boundary conditions [42-44] and with an accuracy to factor 2 is equal to 600. Utilizing this fact, for air at the atmospheric pressure and T=500 K we have

$$l^3 \frac{\delta T}{T} \sim 0{,}1 \text{см}^3,$$

where δT - temperature differential within this cell.

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Introducing ΔT - the temperature differential in the active region, so that

$\delta T \sim \frac{l}{R_0} \Delta T,$ let us represent this relationship/ratio in the form

$$\frac{l^4}{R_0} \frac{\Delta T}{T} \sim 0{,}1 \text{см}^3. \quad (3.8)$$

Analogous relationship can be obtained also from following considerations. Let us record Rayleigh number for the entire active region. In accordance with the conditions of Rayleigh's problem it is equal [to 42-44]

$$R = \frac{\left(k^2 R_0^2 + \pi^2 n^2\right)^3}{k^2 R_0^2}.$$

Introducing in accordance with the solution of the problem of Rayleigh $kR_0 = \pi/\sqrt{2}$, $n = R_0/l$, we find

$$R = \frac{2\pi^4 R_0^4}{l^4}.$$

On the other hand, at a temperature T=500 of K, for which we give estimate, according to the note made recently we have

$$R \approx 4 \cdot 10^{3} \frac{\Delta T}{T} R_{0}^{3},$$

where value R_0 is given in the centimeters. Equalizing these values, we obtain

$$\frac{l^{4}}{R_{0}} \frac{\Delta T}{T} = 0{,}05\,\text{см}^{-3}. \quad (3.9)$$

As is evident, formulas (3.8) and (3.9) take identical form, but they are characterized by factor in right side. This disagreement is completely natural, since used for obtaining of these formulas relationships/ratios are valid only as estimates.

After accepting temperature differential in active region equal to ΔT~10 K, from (3.8) and (3.9) we find l~1 cm, i.e., $l \ll R_0$. Thus, with the sizes in question and at the poweres of the heat release the motion of gas in the active region carries turbulent character. Thus our initial concept about the fact that ball lightning is the region, where chemical reaction occurs, moreover active material is assembled into this zone from the large space, proves to be invalid. This representation is disrupted, since air ceases to be motionless. However, it is possible to attempt "to save" the fundamental side of this model.

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Let air with the active material in the zone of reaction be found in the turbulent motion, and it is motionless out of this zone. This "turbulent machine" works due to the energy, isolated in the presence of the chemical reaction. In the final analysis this motion will connect entire surrounding air, until to this it is be sufficient energy. But since mixing turbulent and motionless regions occurs relatively slowly, it is possible to hope that the lifetime of this system will be sufficient to large in comparison with the duration of the observed phenomenon.

We analyze model of "turbulent sphere in question" [45]. The rate of the flow of gas v_l in the unit cell let us find from the condition that Reynolds number for this motion of the order of critical, which let us place [42] $\mathrm{Re}_{\text{кр}} \sim 10^3$. This gives with T=500 K for atmospheric air $v_l l \sim 400$ $\mathrm{cm^2 \cdot s^{-1}}$, whence $v_l \sim 400$ cm/s. From the law of Kolmogorov-Obukhov [42] $v_\lambda^3/\lambda = \mathrm{const}$ we will obtain for the rate of motion in large cell $v_R \sim v_l (R_0/l)^{1/3} \sim 10^3$ $\mathrm{cm \cdot s^{-1}}$.

Let us note that heat withdrawal out of "turbulent sphere" can be caused by emission. For example, in the model examined in work [45] active material in this system is dust, and heat withdrawal is created by the emission of dust. In this case the heat flow of from within sphere to its surface $q \sim c_p \rho v_R \Delta T$ (c_p - the heat capacity of mixture, ρ - its mass density). For the parameters $q \sim C\Delta T$ in question, where $C \sim 0.1$ $\mathrm{Vt \cdot cm^{-2} \cdot K^{-1}}$, moreover a drop/jump in temperatures ΔT in the turbulent region is restored from the equality of this flow to emitting flow from the surface of sphere. For example, for T=600 K emitting flow $\sigma T^4 = 0{,}7$ W·cm⁻², which gives ΔT~10 K.

Lifetime of turbulent sphere in question is determined by time of mixing. Air from the motionless region flows in into the space between the vortices/eddies and further it is seized into the turbulent region. As a result the mass of turbulent sphere increases, and the region occupied by it increases together with this. In order of flow value of stagnant air into turbulent region $j \sim \rho v_l$, where ρ - mass air density, v_l - the rate in the small-scale vortices/eddies. Taking into account numerical coefficient in this formula ($j \approx 0{,}1\ \rho v_l$ [45]), let us record changes in the radius of the turbulent sphere:

$$\frac{dR_0}{dt} = \frac{j}{\rho} = 0{,}1 v_l.$$

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Hence we find that the characteristic time of a change in the radius of sphere τ~0.1 s.

This result forces us to forego model of turbulent sphere as model for ball lightning for two reasons. First, the lifetime of this system is much less than the observed lifetimes of ball lightning. In the second place, very dynamics of this phenomenon will not be coordinated with the observed facts. A radius of turbulent sphere in the course of time increases until this sphere decomposes. Ball lightning, as a rule, does not change its sizes in the period of observation. These contradictions lead us to the conclusion that gas, aerosols or dust, i.e., the system of the noninteracting particles, cannot compose the active material of ball lightning.

Thus, carried out analysis attests to the fact that active material of ball lightning must be connected. In this plan it is possible to propose two alternatives for the model of ball lightning. In one of them the active material is found in the form of film, similar to the soap bubble, in another the active material is web from the entangled filaments, so that entire system is similar to Eryngium. The explanation to the first model includes the large set of problems. First, liquid will leak off on the film from top to bottom, which n the final analysis can lead to the destruction of film, if it will not rapidly rotate. In the second place, chemical processes on the film lead to its essential heating. This places film in the rigorous conditions: it must retain its form with elevated temperatures and convective movement of air on its surface, on which, at the same time, occur chemical transformations. Although we do not prove the groundlessness of this model it is apparent that it is very difficult to demonstrate its reality. Therefore we give the preference of the second model, proposed in work [46]. This model at first glance seems exotic, but more careful analysis confirms the reality of this system, especially because it is capable of explaining the observed properties of ball lightning [46]. Therefore further we will proceed from this model and our problem will consist of her comprehensive analysis.

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S3.2. Character of chemical interaction.

Analysis carried out earlier led us to conclusion that power engineering of ball lightning was connected with chemical processes, and very active material of ball lightning has filamentary structure 1).

FOOTNOTE 1). The analysis of the process of the formation of the body of ball lightning represented further shows that it has a structure of fractal cluster. However, for the fundamental properties of ball lightning is unessential the difference between the structure of fractal cluster and the filamentary structure. Let us note also that although during the analysis of chemical processes on the surface the shape of surface of active material is approximated by filament, final formulas are valid for the arbitrary type of surface. ENDFOOTNOTE.

In order to obtain the more detailed picture of energy processes, let us continue this analysis. First of all, let us explain how the chemical reaction, which leads to the heat release, occurs. Two versions are here possible. In one of them the reaction occurs with the participation of molecules, which are found in the gas phase. In other - the reacting components are located within the filaments.

Let us examine first version. The activated molecules of gas phase approach the surface of filament and on it enter into the chemical reaction. Let in this case to each reacting molecule be isolated energy $\Delta\epsilon$. Let c - concentration of activated molecules. Let us calculate, to what extent the temperature of filament in comparison with the temperature of surrounding air rises. We have for the flow of the activated molecules

$$j = -\mathcal{D} N \nabla c,$$

where $\mathcal{D}$ - coefficient of diffusion of activated molecules in air, N - molecular air density. The heat flux

$$q = -\mathcal{D} N \Delta\varepsilon \nabla c$$

is formed due to this flow of molecules on the surface of filament,

Since filament in this case is heated, inverse heat flux into surrounding air, which determines temperature differential between surface of filament and surrounding air, is created. Let us examine the case, when this return flow is determined only by the thermal conductivity of gas; obtained in this calculation temperature differential can serve as upper boundary for this value.

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From the condition of the equality of heat fluxes we have

$$q = -\mathcal{D} N \Delta\varepsilon \nabla c = \varkappa \nabla T.$$

This gives equation [40]

$$\frac{dT}{dc} = -\frac{\mathcal{D} N \Delta\varepsilon}{\varkappa}.$$

Considering that the right side of the equation does not depend on temperature, from its solution we will obtain for a drop/jump in temperatures ΔT between surface of filament and air far from it

$$\Delta T = \frac{\mathcal{D}N\Delta\varepsilon}{\varkappa}(c_0 - c_1), \quad (3.9a)$$

where c_0 and c_1 - concentration of activated molecules in air far from the filament and on its surface respectively.

Table 3.1 gives values of drop/jump in temperatures, which relate to processes on surface of filament with participation of molecules of ozone. In this case it is assumed that each molecule of ozone, which falls on surface, enters in the chemical reaction, so that in formula (3.9a) is accepted that $c_1=0$, and $c_0=1\%$. Utilizing for the diffusion of ozone in air at the atmospheric pressure of value $\mathcal{D}N = 4{,}3 \cdot 10^{18}$ $cm^{-1} \cdot s^{-1}$ (where $\mathcal{D} = 0{,}16$ $cm^2 \cdot {}^{-1}$ when $T = 273$ K). $\varkappa = 2{,}4 \cdot 10^{-4}$ $Vt \cdot cm^{-1} \cdot K^{-1}$ and considering that relation $\mathcal{D}N/\varkappa$ does not depend on temperature, we have for the process of the transfer of ozone in atmospheric air

$$\mathcal{D}N/\varkappa = 0{,}25. \quad (3.10)$$

On the basis of this were obtained the values ΔT in Table. 3.1.

Processes with participation of ozone, included in table, can be multistage.

Table 3.1. Reactions on the surface of filament with the participation of ozone.

(1) Процесс	(2) Δε, эВ	ΔT, K
$2O_3 \rightarrow 3O_2$	1,1	32
$3C_{Tb} + O_3 \rightarrow 3CO$	4,5	130
$3C_{Tb} + 2O_3 \rightarrow 3CO_2$	7,1	210

Key: (1). Process. (2). Δε, eV.

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This disrupts the assumption about the complete utilization of chemical energy of each molecule of ozone upon its incidence to the surface and leads to the decrease of upper boundary for value ΔT. However, an increase in the surface temperature, at least, during the first stage of process, is necessary for organizing the chemical process, which effectively occurs at elevated temperatures. Actually this increase in the temperature must comprise, at least, several hundred degrees. Analyzing data of Table 3.1, it is possible to arrive at the conclusion that such conditions in the example examined can be carried out with the high concentration of ozone in air, and also if chemical processes on the surface continue effectively. However, we do not have the reasonable reserve, which guarantees the effectiveness of the use of activated molecules. Therefore there are no guarantees, that the method of conducting the chemical process in question can actually be carried out.

Emergent difficulties are caused by fact that activated molecule must be supplied into zone of reaction. In this case constraint for temperature differential is associated with the fact that for the time, during which activated molecule is supplied into the zone of reaction, in air, through which it is transported, heat flux is propagated. As is evident, this problem will be removed, if we from the very beginning place molecule into the zone of reaction, i.e., to combine combustible with the oxidizer [1]).

FOOTNOTE [1]). This conclusion about the coincidence of fuel with the oxidizer ensues also from requirement so that the specific energy release in the chemical process would correspond to that observed in ball lightning (see S2.5). ENDFOOTNOTE.

This will take the losses, connected with the delivery/procurement of activated molecules into the zone of reaction. The reacting components are combined, for example, in the explosives, where is required the rapid course of chemical reaction, which creates detonation wave in the substance. The chemical processes of the circle of phenomena in question proceed much more slowly than in the explosives, although the specific energy of heat release can be above. Therefore, although these processes can sometimes end by blast, this blast is not detonation wave, but thermal wave, which is propagated with subsonic speed.

Coincidence of reacting components in active material can be reached by two methods.

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With the first the reacting components can be included in substance in the form of the small grains, agitated with each other. This occurs in the explosives and the pyrotechnic materials, moreover both components in this case are found in the form of solid phase. With the second one of the reacting components is porous substance, and another - gas.

Charcoal and ozone is good example of this system. Since charcoal has large internal surface, it can sorb the large number of gas molecules to it. At room temperature the charcoal sorbs approximately 0.3 g of ozone on 1 g of carbon [48, 49]. Although in the first version of the coincidence of the reacting components their relationship/ratio can be regulated, the second method also deserves attention, since it makes it possible to sorb the reacting component from the gas phase and in the case of its small concentration in the gas.

S3.3. Special features of the process of heat release.

Process of heat release in the presence of chemical reaction in ball lightning has series of special features, which superimpose on it specified conditions. On one hand, this is intense process. For guaranteeing the observed parameters of ball lightning the relatively high values of specific energy release are necessary. If the energy reserve of ball lightning is utilized for heating the active material of ball lightning and air, in which this substance is located, then in this case their general temperature will rise, in any case, by several thousand degrees. It is possible to arrive at this conclusion, being based at the analysis of the observed facts, and also the numerical estimates, which will be made in the following chapter. On the other hand, this high intensity of process must be combined with the slowness of its course - it must occur for the time of the order of the observed lifetime of ball lightning.

Combination of such properties for process of heat release (intensity and slowness) can be made not for any process. Further we will present the simplest process of heat release, which phenomenologically can be examined as single-step process, and let us show that this is not made for it.

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Time of heat release in single-step process can be represented in the form of Arrhenius's formula:

$$\frac{1}{\tau} = \frac{1}{\tau_0} \exp\left(-\frac{E_a}{T}\right), \quad (3.11)$$

where T - temperature, E_a - as before energy of activation of process. In the case in question, when the reacting molecules are located by series with each other, pre-exponential factor is the characteristic time of their approach and in order of magnitude is $1/\tau_0 \sim 10^{12} \div 10^{13}$ s⁻¹. In this case the long time of the course of process, which corresponds to the lifetime of ball lightning can be explained by the high value of the energy of the activation of process E_a. Let us require, for example, so that with T=300 K the time of heat release τ would be equally to 10 s. Then for the activation energy we obtain value $E_a == 18$ kcal·mole^{-1}. This completely reasonable value, since for the processes of combustion the activation energy is [41] $E_a = 30 \div 40$ kcal·mole^{-1}, the activation energy is below for other processes.

Let us continue our reasonings. Since the process of heat release - intense, we will consider that it leads to heating of active material on 100 K. Then reaction rate increases in accordance with formula (3.11), moreover

$$\tau(300)/\tau(400) = 4 \cdot 10^3.$$

In this case basic part of the heat release will occur at a temperature, close to the maximum, and the time of heat release will correspond to this temperature, i.e., there will be less than the hundredth fraction of a second. Hence it follows that the character of the heat release in the case in question carries explosive character, and fundamental heat release occurs during short times, determined by the final temperature of system.

Thus, simple single-step process cannot be simultaneously and intense and slow. This example can be questioned the existence of the process of the heat release, which possesses the combination of these properties. Investigations [50, 51] made it possible to find an example of this process, the process of the combustion of charcoal in ozone is it. Ozone is partially adsorbed by carbon, and partially is supplied into the combustion zone in the gas phase.

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The process in question is described by the following phenomenological diagram:

$$C \ldots O_3 \xrightarrow{t_3} X \xrightarrow{v} Y \xrightarrow{1/\tau} Z \xrightarrow{\omega} CO_2, CO. \qquad (3.12)$$

The parameters, which characterize the rates of the corresponding stages of process, are given above the arrows. The values of the time of the slow stages of process corrected below attest to the fact that in the investigated temperature range the characteristic values of the time of the course of process correspond to several minutes.

T, K	300	400	500	600	700
$1/v$, c (1)	330	190	140	110	90
$1/\omega$, c (1)	740	170	70	40	26

Key: (1). s.

Carbon dioxide is the basic product of process (3.12), relative yield of CO much lower depends on a temperature, at which occurs the saturation of charcoal by ozone. For the temperature of saturation 225-230 K relative yield of CO composes approximately 15% [50, 51], and specific energy release - approximately 30 kJ on 1 g of carbon, which coincides with the specific energy release with the complete combustion of carbon in oxygen (Fig. 3.1-3.3).

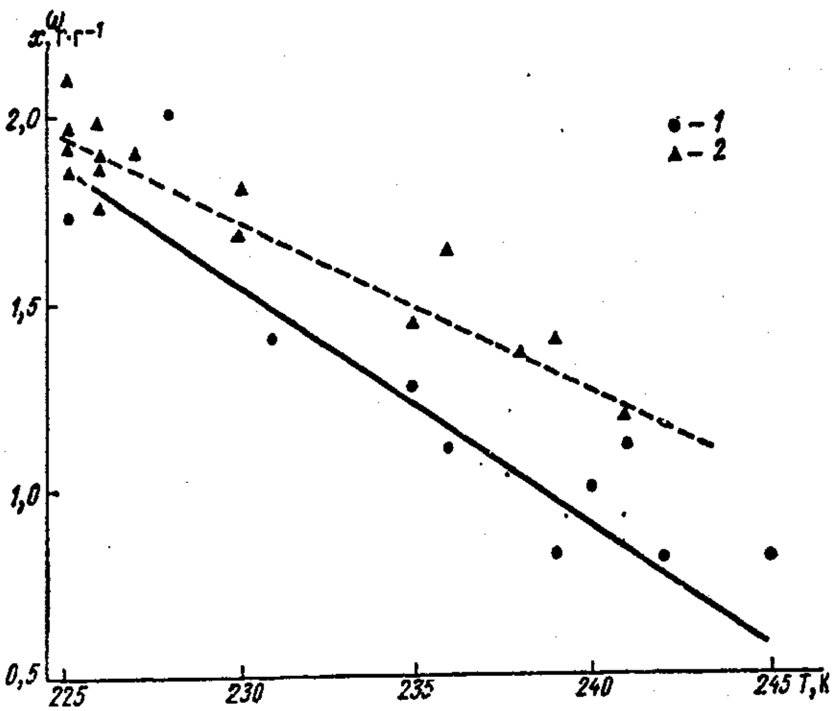

Fig. 3.1. Quantity of ozone x, absorbed by specks of charcoal with average particle sizes of 3 μm (in grams of ozone to gram of dust) depending on temperature T of saturation: 1 - direct measurements; 2 - restorat /reduction in quantity of formed after resolution ozone CO and CO_2. Continuous and dash straight lines - statistical processing of these data.

Key: (1). $g \cdot g^{-1}$.

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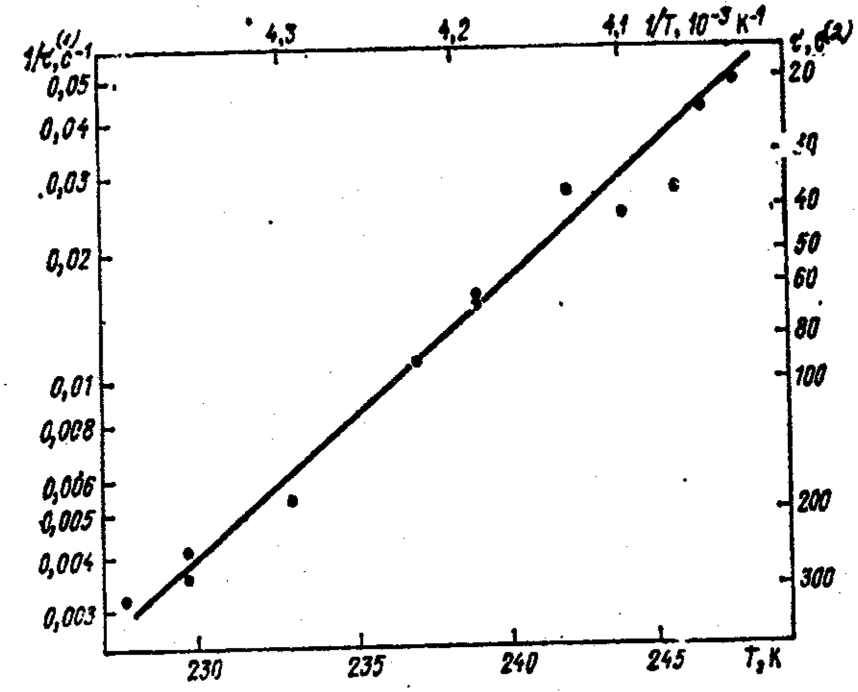

Fig. 3.2. Temperature dependence of rate of bonding of absorbed ozone by specks of charcoal with average sizes of 3 μm.

Key: (1). s^{-1}. (2). s.

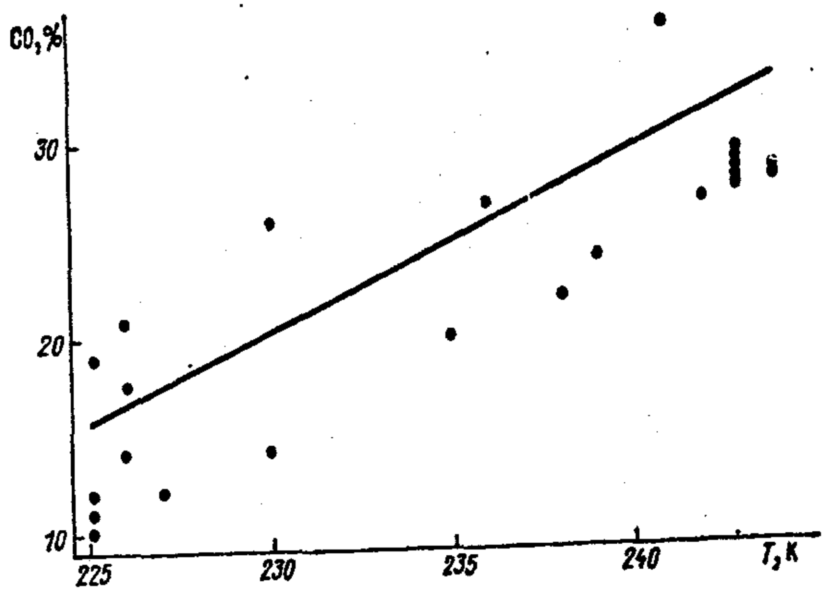

Fig. 3.3. Relative percentage CO among products of combustion of dust of charcoal in absorbed by it ozone (basic product of combustion - CO_2) depending on temperature of saturation of sample by ozone. Average size of specks - 3 μm.

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Let us note special features of process in question. First of all, process this - multistage, that is characterized by induction period. Therefore the noticeable heat release in this process occurs with the delay into several minutes after the saturation of sample by ozone. In this induction period the sample does not undergo external effects. In the second place, this process begins with the low, including the room, temperatures, at which usual combustion does not occur. This process causes the heating of substance, which offers the possibility of the course of high-temperature chemical processes.

Thirdly, the process in question is characterized by high heat-liberation value.

According to analysis, which will be carried out below (in Chapter 6), temperature of zone of glow exceeds 2000 K. Despite the fact that process (3.12) proceeds at lower temperatures, it has fundamental value. Actually, to these high temperatures we start from the room, so that it is necessary to have also another process, which would make it possible to heat substance to such temperatures. Further, glow in ball lightning appears a certain time after the necessary conditions for the existence of this phenomenon are created. Diagram (3.12) shows that it is possible to fit real chemical process with the sufficiently large induction period. Furthermore, this is slow process with the high specific energy release. The latter fact testifies about the possibility to heat active material due to this process to sufficiently high temperatures.

Thus, process (3.12) can be considered as model process, critical for inflammation of active material of ball lightning. Actually, chemical process in ball lightning can be composed of two elements: the first answers the inflammation of active material with a certain delay, the second - to combustion at a high temperature and to glow. In a fundamental sense the first is most complicated. Model process (3.13) convinces us, that the inflammation with the characteristic time of the order of the lifetime of ball lightning is completely actual.

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Chapter 4.

FORMATION AND GAS DYNAMICS OF BALL LIGHTNING.

§4.1. Association of spherical aerosols in the gas and the plasma.

Analysis of form of ball lightning carried out above attests to the fact that filamentary structure [46] is most probable structure of substance in ball lightning. In this case heating air due to the heat release during chemical processes, which occur in ball lightning, does not disrupt its structure. We further analyze the possibility of the formation of this structure during the relaxation of aerosol plasma, i.e., the weakly ionized gas, which contains aerosols.

Special feature of association of solid aerosols, which leads to consolidation of aerosols, is connected with the fact that under some conditions formable larger aerosols have cylindrical form. These aerosols are called chain units and are the sufficiently propagated object in physics of aerosols [52, 53]. Experiment shows that the chain aggregates/units effectively are formed in the presence of external fields or with the participation of the charged aerosols. As an exponential example of this effect let us give results [54, 55], according to which the fume, formed during the combustion of magnetic tape, contains the aerosols of magnesium oxides of spherical form, whereas in the fume of the same composition, obtained from the arc discharge, filamentary aerosols are present. Are empirically clear conditions, with which it is possible to expect the formation of filamentary aerosols. So that it would be possible to carry out this analysis with the aid of the formulas, let us derive relationships/ratios for the rate constants of the association of aerosols, which occurs due to the different mechanisms.

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Association of aerosols in air can go along three channels: 1) association due to diffusion of aerosol particles in gas; 2) approach and association of oppositely charged aerosols as a result of Coulomb interaction between them; 3) approach and association of neutral aerosols in internal field due to interaction of induced by field charges. In order to compose the common physical picture of the association of aerosol particles in the plasma, let us examine serially each of these mechanisms and will find the value of rate corresponding to it.

Let us examine association of spherical aerosols, caused by their diffusion in air. During the diffusion of aerosols in air comes such moment, when their surfaces are contacted. Then due to interaction, and also chemical processes on the surface, aerosols are adhered, i.e., their association occurs. Let a radius of one type of aerosols be equal to r_1, a radius of another - r_2. Let us examine at first the case, when one aerosol of the first type rests, so that diffusion flow of the aerosols of the second type comes to its surface. The full current of aerosols at a distance of r from the center of test aerosol is equal to

$$J = 4\pi r^2 j = -4\pi r^2 \mathcal{D} \frac{\partial N_2}{\partial r},$$

where $\mathcal{D}$ - coefficient of diffusion of second type aerosols, N_2 - their density. Since the aerosols are not absorbed in the space, current does not depend on distance of r, i.e., $J =$ const. This gives

$$N_2(r) = N_2^{(0)} - \frac{J}{4\pi\mathcal{D}r}.$$

Here $N_2^{(0)}$ - density of second type aerosols far from the absorbing center. Further, with distance $r = r_1 + r_2$ occurs the association of aerosols, i.e., $N_2(r_1 + r_2) = 0$. Hence we obtain Smolukhovsky's formula for the current:

$$J = 4\pi\mathcal{D}N_2^{(0)}(r_1 + r_2).$$

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Equation of balance for density of associated aerosols takes form

$$\frac{dN_1^{(0)}}{dt} = -k_{12}N_1^{(0)}N_2^{(0)} = -JN_1^{(0)},$$

where $N_1^{(0)}$ - density of first type aerosols, k_{12} - rate constant of association, which in accordance with obtained relationships/ratios is equal to

$$k_{12} = 4\pi\mathcal{D}(r_1 + r_2). \quad (4.1)$$

In formula (4.1) parameter $\mathscr{D}$ is the coefficient of diffusion of second type aerosols when the diffusion of first type aerosols can be disregarded. However, in the general case should be considered the fact that the association is determined by the character of a change in the relative distance between the aerosols. With the diffusion character of the motion of each of the aerosols for the average from the square of the relative distance between the aerosols we have

$$\overline{(\mathbf{r}_1-\mathbf{r}_2)^2}=\overline{r_1^2}+\overline{r_2^2}-2\overline{\mathbf{r}_1\mathbf{r}_2}=6(\mathscr{D}_1+\mathscr{D}_2)t,$$

where $\mathscr{D}_1, \mathscr{D}_2$ - diffusion coefficients for the appropriate aerosols in air, t - time, furthermore, it was assumed that each aerosol diffuses in air independent of other. From the obtained relationship/ratio it follows that relative motion of two aerosols is determined by the effective diffusion coefficient, which is equal to the sum of the diffusion coefficients for each of the aerosols in air. Taking into account this in formula (4.1), we will obtain expression for the rate constant of the association of the spherical aerosols:

$$k_{12}=4\pi(\mathscr{D}_1+\mathscr{D}_2)(r_1+r_2). \quad (4.2)$$

Let us represent expression for coefficient of diffusion of spherical aerosol in air for case, when radius of aerosol considerably exceeds mean free path of molecules of air. Then the resisting force of aerosol will be determined by Stokes's formula and during the motion of the aerosol of radius r_0 with rate v it will be equal to

$$\mathscr{F}=6\pi r_0\eta v,$$

where η - viscosity of air. Let us give the test charge e to aerosol. Then, according to Einstein's formula, the connection of the coefficient of diffusion and mobility K of particle after determining the relationship/ratio

$$K = e\mathcal{D}/T,$$

here T - temperature of air.

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In accordance with the determination of mobility in this case we have K-v/F (where $\mathcal{F} = eF$, and F - electric intensity). From these relationships/ratios for the coefficient of diffusion of aerosol finally we will obtain

$$\mathcal{D} = \frac{T}{6\pi r_0 \eta}. \quad (4.3)$$

Let us note that the last formula is valid when $\lambda \ll r_0$ (λ - mean free path of the molecule of air). In the general case, introducing the number of Knudsen $\mathrm{Kn} = \lambda/2r_0$ and taking into account opposite limiting case, we can represent approximating formula for the coefficient of diffusion of aerosol in the gas in the form

$$\mathcal{D} = \frac{T}{6\pi r_0 \eta}(1 + 3{,}12\mathrm{Kn}).$$

In particular, for air at the atmospheric pressure and T=300 K this formula takes the form

$$\mathcal{D} = \frac{\mathcal{D}_0}{r_0}\left(1 + \frac{0.14}{r_0}\right), \qquad (4.4)$$

where $\mathcal{D}_0 = 1{,}2 \cdot 10^{-7}$ $cm^2 \cdot s^{-1}$, and r_0 is expressed in μm.

Substituting (4.3) in (4.2), we will obtain for rate constant of association of two aerosols:

$$k_{\text{диф}} = \frac{8}{3}\frac{T}{\eta}\varphi, \quad (4.5)$$

where $\varphi = {}^1/_2 + {}^1/_2\langle r\rangle\langle 1/r\rangle \approx 1$, and triangular brackets indicate averaging of distribution of aerosols over sizes. Value φ is close to unity. If all aerosols of strictly intended sizes, then $\langle r\rangle\langle 1/r\rangle = 1$ and $\varphi=1$. But if we have the self-similar function of the distribution of aerosols according to the sizes, which corresponds to the asymptotic (on the time) distribution of liquid aerosols, then $\langle r\rangle\langle 1/r\rangle = 1{,}21$ and formula (4.5) takes the form

$$k_{\text{диф}} = 2{,}95\frac{T}{\eta}. \quad (4.6)$$

Further, we will utilize this formula. For air with T=300 K gives $k_{\text{диф}} = 6{,}6 \cdot 10^{-10}$ $cm^3 \cdot s^{-1}$. It is significant that the value of the rate constant of the association of aerosols with this mechanism of association does not depend on the type of aerosols. For the demonstration of this fact table 4.1 gives the values of the rate constant of the association of the aerosols of different types undertaken from book [53].

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The average statistical of these data is equal $(6{,}1 \pm 1{,}3) \cdot 10^{-10}$ $cm^3 \cdot s^{-1}$, which in the limits of error coincides with the value corrected above.

Let us examine now association of charged aerosols. Let one of the aerosols have charge q_1, another - a charge q_2. Then with distance of r between them the force of the mutual attraction is equal to q_1q_2/r^2. This force is counterbalanced by Stokes's force, so that the positively charged aerosol moves towards negatively charged with a speed of

$$v_+ = \frac{q_1q_2}{6\pi r_+ \eta r^2},$$

where r_+ - radius of the positively charged aerosol. Similarly moves the negatively charged aerosol, so that the rate of their approach will be equal to

$$v = v_+ + v_- = \frac{q_1q_2}{6\pi\eta r^2}\left(\frac{1}{r_+} + \frac{1}{r_-}\right).$$

For determining rate constant of association of oppositely charged aerosols as test let us select, for example, positively charged aerosol. Let us pass into the coordinate system, connected with this aerosol, and let us conduct around it the sphere of the arbitrary radius r. The frequency of association for the positively charged aerosol in question is a product of the area of the selected sphere to the flow of the negatively charged particles, which intersect it.

Table 4.1. Values of the rate constant of the association of the aerosols of different types in the standard air.

(1) Сорт аэрозоля	$k_{\text{диф}}$, 10^{-10} (2) $\text{см}^3 \cdot \text{с}^{-1}$
Хлорид аммония (3)	6,0
Окись железа (4)	6,6
Окись магния (5)	8.3
Окись кадмия (6)	8,0
Стеариновая кислота (7)	5,1
Олеиновая кислота (8)	5.1
Смола (9)	4,9
Парафиновое масло (10)	5.0
n-ксилолазо-β-нафтол (11)	6,3

Key: (1). Type of aerosol. (2). ... $cm^3 \cdot s^{-1}$. (3). Chloride of ammonium. (4). Iron oxide. (5). Magnesium oxide. (6). Cadmium oxide. (7). Stearic acid. (8). Oleic acid. (9). Resin. (10). Paraffin oil. (11). n-xyleneazo-β-naphthol.

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The frequency of the association of the aerosols

$$\nu = 4\pi r^2 N_- v = \frac{2q_1q_2}{3\eta}\left(\frac{1}{r_+} + \frac{1}{r_-}\right) N_-,$$

where N_- - density of the negatively charged aerosols. Let us introduce the rate constant of the association of the charged aerosols in accordance with the equation of the balance:

$$\frac{dN_+}{dt} = -\nu N_+ = -kN_+N_-.$$

For the rate constant of association this it gives

$$k = \frac{2q_1q_2}{3\eta}\left(\frac{1}{r_+} + \frac{1}{r_-}\right). \quad (4.7)$$

Comparing formulas (4.7) and (4.6), it is possible to arrive at conclusion that diffusion mechanism is essential for large-size aerosols:

$$r_0 \gg q^2/T.$$

In this case the Coulomb energy of two aerosols with the contact is considerably less than their thermal energy.

Let us examine now association of two aerosols in external electric field. Electric field induces on the aerosols dipole moments, and answers interaction of these dipole moments with some of their three-dimensional/space layouts the attraction of particles. In this case interaction leads to approach and association of aerosols.

Potential of interaction of two particles with dipole moments D_1 and D_2 is equal to

$$U = \frac{1}{r^3}[\mathbf{D}_1\mathbf{D}_2 - 3(\mathbf{D}_1\mathbf{n})(\mathbf{D}_2\mathbf{n})],$$

where n - unit vector along direction, which connects particles, r - distance between particles. This formula is recorded for the case, when the distance between the particles considerably exceeds their sizes. Since in the case in question the dipole moments of aerosols are induced by external field, $D=\alpha F$ (α - component of the tensor of the polarizability of aerosol in the direction of electric field F).

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They coincide in accordance with the condition for problem, direction of electric field and induced dipole moments. Taking into account this, we have

$$U = -\frac{\alpha_1\alpha_2 F^2}{r^3}(3\cos^2\theta - 1),$$

where α_1, α_2 - component of the tensor of the polarizability of the corresponding aerosol in the direction of field, one of the principal values of the tensor of the polarizability of aerosol, θ - angle between the directions, which connect aerosols. As is evident, the attraction of aerosols takes place in the small region of angles $(0 < \theta < \arccos 1/\sqrt{3})$. Such layouts in the mutual arrangement of aerosols create the fundamental contribution to the association of aerosols under the action of electric field.

For force, which operates on interacting aerosols at large distances between them, let us record

$$\mathcal{F}_r = \frac{3F^2\alpha_1\alpha_2}{r^4}(1 - 3\cos^2\theta),$$

$$\mathcal{F}_\tau = -\frac{3F^2\alpha_1\alpha_2}{r^4}\sin 2\theta.$$

As is evident, together with force $\mathcal{F}_r$, directed along the line connecting nuclei, appears transverse force $\mathcal{F}_\tau$ in the direction perpendicular to it. This force n the final analysis changes angle θ and in the region of attraction attempts to decrease it. Tangential force accelerates the association of aerosols thus. With $\theta=0$, when the attraction of aerosols is maximal, $\mathcal{F}_\tau = 0$, at the angles, at which the association occurs most effectively, the tangential component of force is unessential. Taking into account this fact, for simplification in the calculations subsequently we will disregard it. This will lead to the error in the numerical coefficient for the rate of association - final result with the made simplification will be somewhat understated.

Disregarding tangential force, we find that value θ does not change in process of approach of aerosols and enters into expression for time of association as parameter. Taking into account this and representing the resisting force of gas during the approach of aerosols in the form

$$\mathcal{F} = 6\pi\eta R \frac{dr}{dt} = \frac{3F^2\alpha_1\alpha_2}{r^4}(1 - 3\cos^2\theta),$$

let us determine the time of the association:

$$t = \frac{2\pi\eta R r^5}{5F^2\alpha_1\alpha_2(3\cos^2\theta - 1)}. \quad (4.8)$$

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Here η - coefficient of the viscosity of gas, $R = (1/r_1 + 1/r_2)^{-1}$, where r_1, r_2 - effective radius of the resistance of the corresponding aerosol. In particular, for the spherical aerosol of radius r_0 we have $r_1 = r_0$.

For computing rate of association of aerosols it is convenient to isolate volume element near test aerosol in such a way that surface of this space would provide identical values of time of association of aerosols. The equation of this surface in the case in question depends on angle θ and takes the form

$$r = r_* \left(\frac{3\cos^2\theta - 1}{2}\right)^{1/5}, \quad \cos\theta > \frac{1}{\sqrt{3}},$$

where r_* - distance to the surface with $\theta=0$. The value of the volume element, limited by this surface, is equal to

$$V = \int d\cos\theta \cdot 2\pi r^2 dr = \\ = \frac{2\pi r_*^3}{3} \int_{1/\sqrt{3}}^{1} d\cos\theta \left(\frac{3\cos^2\theta - 1}{2}\right)^{3/5} = 0{,}518 r_*^3,$$

Let us introduce probability dW of fact that in element of surface, which limits given space V, aerosol is located, whereas in space itself it is absent. We have

$$dW = \exp(-NV)\, d(NV),$$

here N - density of aerosols. This the value

$$\bar{t} = \int t \exp(-NV)\, dNV = 2{,}82 \frac{\eta R}{\alpha_1 \alpha_2 F^2 N^{5/3}},$$

gives for the mean time of the association of aerosols In this case we used expression (4.8) for the case of the association of aerosols, which are located at a distance of r_* with $\theta=0$:

$$t_0 = \frac{\pi\eta R r_*^5}{5\alpha_1\alpha_2 F^2},$$

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Hence for the rate constant of the association of aerosols under the action of electric field it is possible to obtain the relationship/ratio

$$k_{эл} = \frac{1}{tN} = 0{,}354 \frac{F^2 \alpha_1 \alpha_2 N^{2/3}}{\eta R}. \qquad (4.9)$$

In particular, for the spherical aerosols of radius $r_0 (\alpha = r_0^3)$ this formula gives

$$k_{эл} = 0{,}71 \frac{F^2 \langle r_0^2 \rangle \langle r_0^3 \rangle N^{2/3}}{\eta}. \qquad (4.10)$$

Here triangular brackets indicate averaging over radius r_0 of aerosols. As is evident, the value of the rate constant of association depends on the density of aerosols.

Let us compare values of rate constant of association of neutral aerosols, which occurs as a result of diffusion in air (4.6), also, under action of external electric field (4.10). Considering that all aerosols in air have a radius r_0 we have

$$\frac{k_{эл}}{k_{диф}} = 0{,}24 \frac{F^2 r_0^5 N^{2/3}}{T}.$$

Let us give expression for electric intensity F, with which rate constants for mechanisms in question are equal to:

$$F = F_0 x^{-1/3} \left(\frac{\rho}{\rho_0}\right)^{1/3} \left(\frac{a}{r_0}\right)^{1/3}, \qquad (4.11)$$

where x - quantity of aerosol in air in grams of aerosol on 1 g of air, ρ - substance density in aerosol, r_0 - radius of aerosol on the assumption that all aerosols - one size. After selecting the values of the numerical dimensional parameters equal to a=1 μm, ρ_0=1 g·cm^{-3}, we will obtain with T=300 K value F_0=1.9 kV·cm^{-1}.

S4.2. Formation of filamentary aerosols.

Obtained above expressions of rate constants of association of spherical aerosols make it possible to explain conditions, with which is possible formation of filamentary aerosols. Filamentary aerosols more effectively are formed during the association in the external electric field. since in this case the direction of mutual approach during the association of aerosols isolated is determined by the direction of external field.

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In accordance with this let us conduct further following comparison. Let there be in air the set of the spherical aerosols of radius r_0 and let among them be located the simplest filamentary aerosol - cylindrical. Let us compare the rates of the association of this aerosol with the spherical. If association due to the diffusion motion of aerosols rather occurs, then the adhesion of spherical aerosols to the cylindrical will occur along entire surface, and as a result cylindrical aerosol will lose its form. But if association is determined by external electric field, then spherical aerosols will adhere to the ends of the cylindrical and association product will not have compact structure.

Rate constant of association of aerosols due to their diffusion can be determined according to formula of Smolukhovsky (4.1). In this case the diffusion of cylindrical aerosol is considered small in comparison with the diffusion of spherical aerosol and we disregard it. Furthermore, in this case instead of the sum of radii of spherical aerosols in formula (4.1) should be utilized body capacitance, formed by the center of the second aerosol, when the first aerosol is motionless, and their surfaces are contacted. It is not difficult to see that for two spherical aerosols with radii of r_1 and r_2 this value is equal to r_1+r_2, which is in complete agreement with formula (4.1). In the case of cylindrical aerosol with the length $2l$ and by radius r_0 and spherical aerosol with radius r_0 the capacity/capacitance is equal to [56]

$$C = \frac{l}{\ln(l/r_0)},$$

where $l \gg r_0$. Accordingly Smolukhovsky's formula for the rate constant of the association of aerosols taking into account expression (4.3) for the coefficient of diffusion of spherical aerosol is reduced to the form

$$k_{\text{диф}} = \frac{2Tl}{3\eta r_0 \ln(l/r_0)}. \quad (4.12)$$

Value of rate constant of association of aerosols as a result of interaction of dipole moments, induced by external electric field, is given by formula (4.9). Let us accept in it as a radius of resistance radius of the spherical aerosol $R=r_0$, and let us also consider relationships/ratios for the polarizabilities of spherical and cylindrical aerosols $\alpha_1 = r_0^3$, $\alpha_2 = l^3[3\ln(l/r_0)]^{-1}$.

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For the rate constant of association this gives

$$k_{эл} = \frac{0,12F^2 l^3 (Nr_0^3)^{2/3}}{\eta \ln(l/r_0)}. \qquad (4.13)$$

Utilizing formulas (4.12) and (4.13), we find that rate constant associations, which occurs due to two processes in question, become equal at field strength, determined by relationship/ratio

$$Fl = \frac{U_0}{x^{1/3}} \frac{\rho}{\rho_0} \left(\frac{a}{r_0}\right)^{1/3}, \qquad (4.14)$$

where x - quantity of spherical aerosol in air in grams of aerosol on 1 g of air, ρ - substance density of aerosol. Selecting the values of the numerical parameters in this formula equal to $\rho_0=1$ $g\cdot cm^{-3}$, a=1 μm, we will obtain $U_0 = 0,22$ V. Let us focus attention on the fact that formula (4.13) is valid under condition $Nl^3 \ll 1$ (where N - density of spherical aerosols). Specifically, this condition made it possible to utilize the relationship/ratio for the dipole-dipole interaction of aerosols, which became the basis of the derivation of formula (4.9) for the rate constant of the association of aerosols under the action of electric field. With the disturbance of this condition of formula (4.13) and (4.14) overstate result.

Let us conduct evaluation/estimate according to formula (4.14). Let us select the parameters equal to: $\rho=\rho_0=1$ g·cm^{-3}, x=0.1 q·g^{-1}, a=1 μm; l=100 μm. For the electric field we will obtain the boundary value of F≈50 of V·cm^{-1}. This value easily is attained at the thunderstorm phenomena in the atmosphere. As is evident, during the association with the participation of cylindrical aerosol the role of electric field proves to be more essential than during the association of two spherical aerosols. Of this it is possible to be convinced, comparing electric intensity $F_{\text{сф}}$. assigned by expression (4.11), with the strength of field $F_{\text{цил}}$, which is determined by formula (4.14). According to these formulas we have

$$\frac{F_{\text{сф}}}{F_{\text{цил}}}=0{,}9\frac{l}{r_0}, \quad (4.15)$$

and since $l \gg r_0$, then in the case of the association of cylindrical and spherical aerosols external field influence is developed earlier than in the case of the association of two spherical aerosols.

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Taking into account anisotropism of interaction of induced dipole moments, we considered that as a result of association of cylindrical and spherical aerosols of close radii spherical aerosol is attached toward the end of cylindrical, i.e., that this process leads to increase in cylindrical aerosol. Let us show this. Let us trace for this the character of interaction of aerosols in the case, when the distances between them are compared with the sizes of cylindrical aerosol, but they considerably exceed a radius of the spherical aerosol r_0. In this representation spherical aerosol possesses point induced dipole moment $\mathbf{D}_1 = r_0^3\mathbf{F}$, and its interaction with the cylindrical aerosol is determined by interaction of this dipole with the distributed charge on the surface of the cylindrical aerosol, induced by external field. In this case the interaction energy of aerosols is equal to

$$E = -\mathbf{D}_1\mathbf{F}',$$

where F' - electric intensity, created by the induced charge of cylindrical aerosol.

Further we will consider [56] that electric charge, induced on cylindrical aerosol under action of external field, varies in proportion to to distance from center of aerosol. For the electric intensity, created by chain unit in its surrounding space (coordinate of the ends of the aggregate/unit $\rho=0$, $z=\pm l$) this it gives

$$F' = \frac{3D_2}{2l^3}\int_{-l}^{l}\frac{z'(z-z')\,dz}{[(z'-z)^2+\rho^2]^{3/2}},$$

where $D_2=\alpha F$ - dipole moment, induced on the cylindrical aerosol by external electric field for the interaction energy of aerosols. As a result we will obtain

$$E = \frac{3\alpha_1\alpha_2F^2}{2l^3}\int_{-l}^{l}\frac{z'(z'-z)\,dz'}{[(z'-z)^2+\rho^2]^{3/2}}.$$

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In particular, at large distances between aerosols ($\rho, z \gg l$) hence we have

$$E = \alpha_1\alpha_2F^2\frac{(\rho^2-2z^2)}{(z^2+\rho^2)^{5/2}},$$

which corresponds to the potential of interaction of the induced dipole moments, which are located at large distances from each other.

Calculating unknown integral, for potential of interaction of aerosols we have

$$E = \frac{3\alpha_1\alpha_2F^2}{2l^3}\left[\frac{l}{\sqrt{(l+z)^2+\rho^2}}+\frac{l}{\sqrt{(l-z)^2+\rho^2}}-\ln\frac{\left(\sqrt{(l+z)^2+\rho^2}+l+z\right)}{\left(\sqrt{(l-z)^2+\rho^2}+z-l\right)}\right]. \quad (4.16)$$

This expression describes interaction of spherical aerosol with the cylindrical aerosol in the case, when the distances between their surfaces considerably exceed r_0. Since these distances are compared with the sizes of cylindrical aerosol, the obtained formula makes it possible to present the character of the association of aerosols.

Fig. 4.1 shows position of boundary of the region of space around cylindrical aerosol, where interaction energy reverses sign. As is evident, the regions of attraction converge to the ends of the cylindrical aerosol.

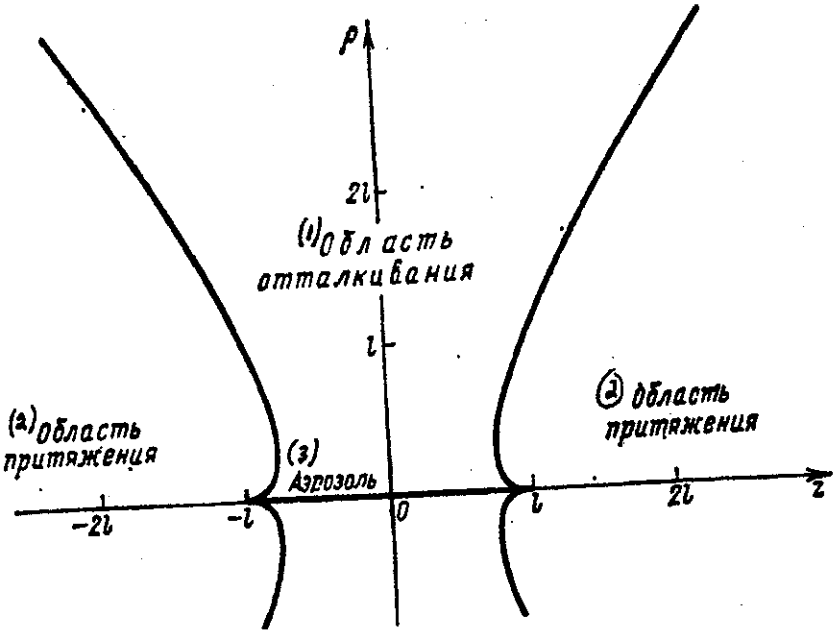

Fig. 4.1. Character of interaction of cylindrical and spherical aerosols, which are located in external electric field. Dipole moment is induced on the spherical aerosol, the distributed charge appears on the cylindrical. Figure reflects the character of interaction of this distributed charge with the field of dipole.

Key: (1). Region of repulsion. (2). Region of attraction. (3). Aerosol.

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Hence it follows that during the motion in the external electric field the spherical aerosols n the final analysis will fall on the end of the chain aggregate/unit. This means that the association of cylindrical aerosol with the spherical aerosols under the action of electric field leads to an increase in the cylindrical aerosol.

Let us pause at one more part of picture in question. We implicitly assumed that during the investigation of the association of cylindrical and spherical aerosols in the electric field the axis of cylindrical aerosol was directed along the electric field. It is interesting to explain, with what electric intensities this occurs. The function of the distribution of cylindrical aerosols on the angles ϑ between the axis of aerosol and the direction of electric field is determined by Langevin formula and is proportional to the factor

$$\exp\left(-\frac{\alpha F^2}{2T}\cos^2\vartheta\right),$$

where α - polarizability of aerosol.

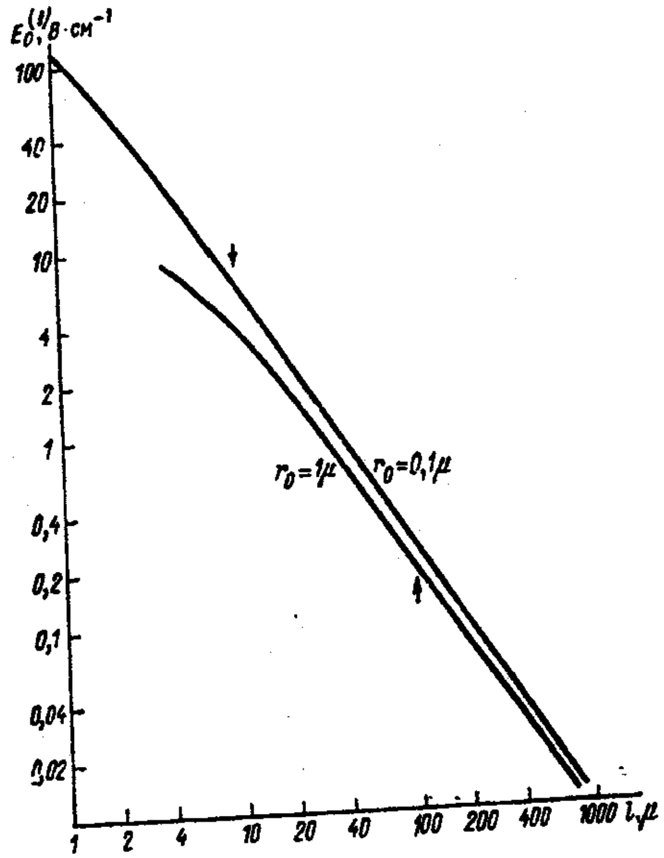

Fig. 4.2. Electric intensity, for which potential of interaction with cylindrical aerosol is compared with thermal energy $(\alpha_{\parallel} E_0^2=T)$. Arrows noted the lengths of aerosol, equal to 100 to its diameters.

Key: (1). $V\cdot cm^{-1}$.

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In Fig. 4.2. are given the values of the strength of field F_0 in the case $\alpha F_0^2/2T = 1$ for T=300 K. In this case it is assumed that the length of aerosol is considerably more than than the radius, so that polarizability in the transverse direction can be disregarded. The analysis of data of Fig. 4.2 shows that the orientation of cylindrical aerosols occurs actually in the static atmospheric conditions, where there are fields with strength $1\ V\cdot cm^{-1}$.

Thus, carried out analysis shows that association of solid aerosols in electric fields of moderate strength can lead to formation of filamentary aerosols. In this case the effectiveness of the effect of electric field for the creation of filamentary aerosols substantially grows with an increase in radius and size of the associated aerosols, and also their density. In particular, the onset of the aerosols in question can effectively occur with the electrical breakdown near the surface. Breakdown is accompanied by the evaporation of the material of surface and by the subsequent formation from it of aerosols.

§4.3. Structure of ball lightning and fractal cluster.

We for that reason have accepted concept about filamentary structure of ball lightning, that this is virtually only structure of ball lightning, which does not contradict observed facts. The subsequent analysis showed that during the association of solid aerosols in the electric field is a tendency to form filamentary aerosols. These aerosols further are interwoven and is formed the lump of filaments. In this case it is necessary to understand, that this representation about the structure of ball lightning is model, since this system is formed from the particles of the different sizes, which are retained within the system. Therefore the structure of the obtained formation must be more complicated.

It is significant that authors of filamentary structure of ball lightning arrived at their model, being based on its experiments on relaxation of vapors of metals, which indicates reality of such structures.

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It is clear that the analysis of the structures, formed during the relaxation of vapors of metals and during the association of solid particles, is useful for understanding of the structure of ball lightning. Therefore further let us pause at the analysis of such structures.

Fig. 4.3 presents photograph, carried out on electron microscope for structure, which is formed during relaxation of vapors of iron [57]. During cooling of vapors the solid particles first are formed, and further are united into clusters. Average particle diameter under the conditions for the described experiment is 7-8 nm. The represented structure possesses correlation properties [58], which make it possible to relate it to the class of the so-called fractal clusters (see [59]).

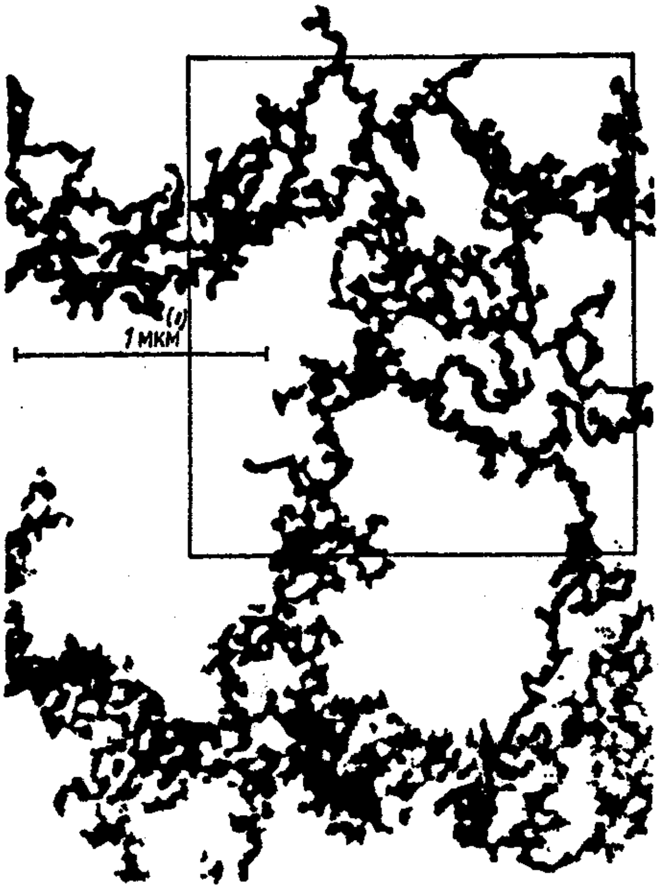

Fig. 4.3. Projection of fractal cluster of iron, obtained with the aid of electron microscope [57]. A radius of single particles is equal to 3.5 nm with the standard deviation of 1.5 nm. The framework limits the part of the cluster - by the calculation of the number of particles within the framework of different size was determined the fractal dimensionality of cluster; furthermore, it was restored from the correlation function for the density of cluster. The average value of fractal dimensionality for the cluster of iron is equal to $D = 1{,}61 \pm 0{,}08$

Key: (1). μm.

The system with the filamentary structure examined is a special case of fractal cluster.

Fractal cluster - system of connected solid particles, which possesses internal symmetry. Let us conduct around the isolated points of the cluster of the circumference of radius r, which considerably exceeds the sizes of single particles. Then the masses of the pieces of cluster within these spheres on the average are identical. To this property of "self-similarity" of the elements of cluster should be added one additional important property. If we increase a radius of the limiting sphere, then the average density of substance within it will fall according to the law

$$\rho(r) = \rho_0 \left(\frac{r_0}{r}\right)^{3-D}, \quad (4.17)$$

where r_0 - significant dimension of the particles, which form part of cluster, ρ_0 - value of the order of material density of cluster, D - fractal dimensionality of cluster, which is its characteristic. Formula (4.17) reflects the fact that in proportion to an increase in the radius of the limiting sphere within it prove to be the voids large-size all that it leads to a drop in the average density of material within it.

Connecting fractal clusters, which have sizes of order R, with each other, it is possible to obtain object of more general structure. In particular, object with this structure is the aerogel (S8.2), and also the gel, obtained during the association of particles, that are located in the closed volume. This object possesses the properties of fractal cluster (4.17) in the region of the sizes

$$r_0 \ll r \ll R, \quad (4.18)$$

where R - maximum size of voids - pores.

In recent years fractals were subject of intense experiments (see survey [59]). As a result of these investigations general laws governing such structures and character of their formation are understood. It was shown that the fractal dimensionality of the formable cluster depends on the character of particle motion during the association and the character of an increase in the formable cluster. In this case the cluster can increase both as a result of the consecutive connection to it of single particles and as a result of the association of clusters.

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Table 4.2 gives the values of the fractal dimensionality of the cluster, formed under the appropriate model assumptions about the process of association. Data of table relate to the mode of the association, when with the contact of particles or clusters their association occurs with the noticeable probability. This mode will be examined further during the estimate of the rate of formation of cluster (§4.4). At the same time, can be realized the maximally conflicting mode, when the probability of the association of particles and clusters is small. It occurs if particles and clusters are charged, so that Coulomb repulsion limits their approach. Then the process of forming the cluster occurs considerably slower, and cluster has more compact structure with the fractal dimensionality, equal to approximately 2.1. (Theory [133] gives in this case $D = 2{,}00 \pm 0{,}08$.)

Depending on conditions of cluster formation is feasible transition from one mode to another. Thus, experimental investigations [124-127] of formation in the appropriate solutions of clusters from the particles of gold and dioxide of silicon with the radius, equal to 4-11 nm, showed that if the time of the formation of cluster is seconds, then its fractal dimensionality is equal to 1.75-1.8. This corresponds to a cluster-cluster association, when their approach is limited by diffusion (last case table 4.2). But if the rate of formation of the cluster of the order of days, then the fractal dimensionality of the formable cluster is close to 2.1.

Rate of formation of cluster is controlled by acidity of solution. A change in the acidity of solution leads to a change in the particle charge, which affects the probability of their approach and adhesion. The structure, formed in the slow mode, apparently, is more stable.

Table 4.2. Fractal dimensionality of cluster D, formed during the association of solid particles in the three-dimensional space.

(1) Модель ассоциации	D
(2) Линейная траектория, кластер — частица	3
(3) Броуновское движение, кластер — частица	2,46±0,05
(4) Линейная траектория, кластер — кластер	1,94±0,08
(5) Броуновское движение, кластер — кластер	1,77±0,03

Key: (1). Model of association. (2). Linear trajectory, cluster - particle. (3). Brownian motion, cluster - particle. (4). Linear trajectory, cluster - cluster. (5). Brownian motion, cluster - cluster.

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Investigations [126] with the gold particles (radius 4 nm) showed that in the fresh solution is formed the cluster with the fractal dimensionality, equal to approximately 1.75. However, through several days its fractal dimensionality increased, reaching value of 2.20. Let us note that the fractal dimensionality of the cluster, formed in the slow mode, is close to the fractal dimensionality of the aerogel (see S8.2).

S4.4. Formation of fractal cluster during the association of solid aerosols.

In order to explain channels, on which it occurs formation of structure of ball lightning, and also characteristic parameters of this system, it is necessary to obtain numerical values for rates of association of solid particles into cluster in actual air. Further we will conduct such calculations for two possible channels of association. In the first of them fractal cluster increases as a result of the consecutive connection of single particles. The secondly - the particles are united into the clusters and the subsequent association of clusters leads to an increase in their sizes and the decrease of their number in the chosen space. In this case for convenience in the examination we will consider that the solid particles have a spherical form and one and the same radius r_0 for all particles.

Let us examine first case, when cluster increases upon consecutive connection to it of single particles. This process occurs both due to the diffusion particle motion and due to the motion of cluster under the action of gravitational force. In the second case the rate of cluster is small in comparison with the thermal particle speed, so that as a result the connection/attachment of particles occurs due to their diffusion 1) and the fractal dimensionality of cluster in both cases is identical.

FOOTNOTE 1). In atmospheric air at room temperature for the fractal cluster with a radius of R in question, which consists of particles with a radius of r_0, this condition takes form $r_0^2 R^{1,5} \ll 10^{-13}$ cm^{3,5}. ENDFOOTNOTE.

In the calculations we utilize the rounded value of fractal dimensionality for these cases: D=2.5.

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Taking into account both processes equation of balance for number of particles in cluster n takes form

$$\frac{dn}{dt}=\nu_{\text{д}}+\nu_{\pi r}$$

where $\nu_{\text{д}}$ - frequency of adhesion of particles to cluster with diffusion particle motion, value $\nu_{\text{л}}$ calculates motion of cluster on the basis of linear trajectory. In the first case, considering that a radius of cluster is sufficiently great $(R\gg r_0)$, according to formula (4.2) we have

$$\nu_{\text{д}}=4\pi\mathcal{D}RN, \quad (4.19)$$

here $\mathcal{D}$ - a coefficient of diffusion of particles in air, N - their density. In the second case the frequency of the adhesion of particles to the cluster is equal to

$$\nu_{\text{д}}=\pi R^2 vN \quad (4.19б)$$

(v - rate of the motion of cluster under the action of gravitational force). It follows from this formula that each particle, which falls into the region of the determination of cluster, adheres to it, although completes the diffusion motion. We utilize a relationship for the rate of the incidence/drop in the cluster in the gravitational field. In this case we will consider that the resisting force during the motion of cluster is the same as during the motion of the sphere

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Let us examine case, when $\nu_0 \gg \nu_1$. For atmospheric air and room temperature this inequality is fulfilled in the case $r_0 \ll 1$ µm. Under this condition the fundamental time of an increase in the cluster occurs when contributions of both mechanisms are compared. With the subsequent increase in the size of cluste. the number of particles in it increases with the acceleration. Taking into account this, let us calculate the total time of an increase in the cluster to such sizes, until particle density is changed. We have from equation (4.23) for D=2.5:

$$t = \int_0^\infty \frac{dn}{\nu_0 n^{\frac{1}{D}} + \nu_1 n^{1+\frac{1}{D}}} = \frac{\pi}{\sin\frac{\pi}{D}\,\nu_0^{\frac{1}{D}}\,\nu_1^{\frac{D-1}{D}}}. \qquad (4.24)$$

Let us conduct numerical calculations according to this formula for atmospheric air D=2.5 at room temperature for material density of dust ρ=2 g·cm^{-3} and for the dust content in air (ratio of the mass of dust, which is contained in the element of volume, to the mass of air in this space) m=1 g·g^{-1}. With r_0=0.1 µm we have t=11 s, and with r_0=10 nm we obtain t=2.8 s. The dependence of the time of an increase in the cluster on the particle size in this case takes form $t \sim r_0^{0.6}$, while dependence on the dust content in air - inversely proportional: t~1/m.

Let us examine another case, when formation of cluster occurs of clusters of smaller sizes, as a result of their consecutive association. In this case the clusters can be adhered both due to the diffusion motion and due to ordered motion along the linear trajectories. In the first mechanism the fractal dimensionality of the formable cluster is approximately 1.8, the second - about 1.9 (see Table 4.2). We will further consider for simplicity that both mechanisms lead to the identical fractal dimensionality of the formable cluster: D=1.85. We will assume air resistance to cluster of radius R equal to the sphere drag of the same radius. Then for the rate constant of the association of the clusters of radius R_1 and R_2 in accordance with formula (4.5) it is possible to record the expression

$$k_{\text{диф}} = \frac{2T}{3\eta}\left(2 + \frac{R_1}{R_2} + \frac{R_2}{R_1}\right). \quad (4.25)$$

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We will further consider that at each moment of time function of distribution of clusters according to number of particles in them takes form

$$df = \frac{dn}{n_0}\exp\left(-\frac{n}{n_0}\right), \quad (4.26)$$

where n_0 - average number of particles in cluster, and connection of number of particles in cluster with its radius is given by formula (4.20). Then for atmospheric air at room temperature we obtain $k_{\text{диф}} = 6{,}9 \cdot 10^{-10}$ $\text{cm}^3 \cdot \text{s}^{-1}$. Taking into account that their density falls in proportion to association and consolidation of clusters and its value comprises N_0/n_0 (where N_0 - initial particle density), for the first we will obtain addend in the equation balance (4.19a)

$$\nu_{\text{диф}} = \frac{\nu_0}{n_0}, \quad \nu_0 = k_{\text{диф}} N_0.$$

Second term in equation of balance is determined in complete agreement with formula (4.19b) by expression

$$\nu_{\text{л}} = \pi\left(R_1^2 + R_2^2\right)|v_1 - v_2|\,N, \tag{4.27}$$

where rate of each cluster is given by formula (4.21). Formula (4.27) should be averaged over the sizes of cluster, for which the kinetic equation of Smolukhovsky let us record for the function of the distribution of clusters according to the sizes:

$$\frac{\partial f(n,t)}{\partial t} = \int \nu(n-n', n')\, f(n-n', t)\, f(n', t)\, dn' - \\ - f(n,t)\int \nu(n, n')\, f(n', t)\, dn'.$$

Let us multiply this equation by n and will integrate on DN. We will obtain (taking into account $n_0 = \int f(n,t)\, n\, dn$):

$$\frac{dn_0}{dt} = \int \nu(n_1, n_2)\, n_1 f(n_1, t)\, f(n_2, t)\, dn_1 dn_2 = \\ = \left\langle \nu(n_1, n_2)\frac{(n_1+n_2)}{2}\right\rangle.$$

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Utilizing a function of distribution (4.26) and relationship (4.20) between the size of cluster and the number of particles in it, it is possible to record

$$\left\langle v_a(n_1, n_2)\frac{(n_1+n_2)}{2}\right\rangle = v_1 n_0^{1+\frac{1}{D}},$$

where

$$v_1 = \frac{2\pi\rho g r_0^4}{9\eta} N_0 J,$$

$$J = \left\langle \left(x_1^{\frac{2}{D}} + x_2^{\frac{2}{D}}\right)\left|x_1^{1-\frac{1}{D}} - x_2^{1-\frac{1}{D}}\right|\frac{(x_1+x_2)}{2}\right\rangle,$$

$$x_1 = n_1/n_0, \quad x_2 = n_2/n_0.$$

Making averaging with the function of distribution (4.26), we find J=2.7.

Thus, for average number of particles in cluster we obtain equation

$$\frac{dn_0}{dt} = v_0 + v_1 n_0^{1+\frac{1}{D}}.$$

We will consider that $v_0 \gg v_1$. As in the preceding case, beginning from the moment, when the number of particles in the cluster is equal

$v_1 n^{1+\frac{1}{D}} \gtrsim v_0$, cluster increases with the acceleration. Hence we obtain, that the total time of an increase in the large cluster (with D=1.85) is equal

$$t = \int_0^\infty \frac{dn_0}{v_0 + v_1 n_0^{1+\frac{1}{D}}} = \frac{\pi D}{(D+1)\sin\frac{\pi}{D+1}\, v_0^{\frac{1}{D+1}} v_1^{\frac{D}{D+1}}} =$$

$$= \frac{2{,}3}{v_0^{0{,}35} v_1^{0{,}65}}. \quad (4.28)$$

For atmospheric air at room temperature, density of the material of particles $\rho=2$ g·cm^{-3} and dust content in air x=1 g·g^{-1} on the basis of formula (4.29) we have for $r_0=0.1$ μm t=4.7 with and for $r_0=10$ nm t=1.9 s, moreover $t \sim r_0^{0.4}$ and t~1/x.

Let us note that in obtaining of formula (4.28) we approximated clusters during their motion in air by spherical particles of corresponding radius. This approximation is reasonable for the optically dense cluster, which possesses the fractal dimensionality D>2. In the case in question this leads to the decreased values of the coefficient of diffusion and mobility of cluster, so that the obtained values of the time of an increase in cluster (4.28) should be considered as upper estimate for the real time.

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Further, if process proceeds in the electric field and with the participation of the charged particles, then during the first stage this leads to the formation of cylindrical aerosols, which will be reflected both in the structure of the formable clusters and in the rate of process.

Formula (4.28) is valid if maximum radius of correlation of cluster R (see formula (4.18)) it considerably exceeds significant dimensions of cluster

$r\sim r_0\left(\frac{\nu_0}{\nu_1}\right)^{\frac{1}{D+1}}$, with which rate of association of clusters is minimum. Utilizing an expression for a maximum radius of the correlation of cluster, let us represent this condition in the form

$$\nu_0\gg\nu_1\left(\frac{\rho}{\bar{\rho}}\right)^{\frac{D+1}{3-D}},$$

where ρ - material density of cluster, $\bar{\rho}$ - average density of substance in the space, occupied by cluster. The disturbance of this condition with fulfillment $\nu_0\gg\nu_1$ means that the association of cluster concludes before the second mechanism of association begins to work. In this case the characteristic time of assembly of cluster is evaluated according to the formula

$$t\sim\frac{1}{\nu_0}\left(\frac{R}{r_0}\right)^D\sim\frac{1}{\nu_0}\left(\frac{\rho}{\bar{\rho}}\right)^{\frac{D}{3-D}}. \qquad (4.29)$$

In the real case from formulas (4.28), (4.29) should be utilized that, which gives the shorter time of the formation of cluster. Table 4.3 gives the values of the time of the formation of cluster in atmospheric of air at room temperature for ρ=2 g·cm^{-3} with the different values of a radius of particles r_0 and different content of particles in air x.

Table 4.3. Time of the formation of cluster (s).

(1) r_0, нм	(2) Время, с	
	(3) $x=1$ г·г$^{-1}$	③ $x=0{,}1$ г·г$^{-1}$
1	$5{,}2 \cdot 10^{-4}$	0,014
3	0,014	0,360
10	0,520	14,0
100	4,700	47,0
1000	12,0	120,0

Key: (1). r_e, nm. (2). Time, s. (3). $x=1$ g·g^{-1}.

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These data testify about critical dependence of the time of formation on the content of substance in air and on a radius of particles.

Analyzing obtained results, we come to conclusion that both channels of formation of fractal cluster examined are completely acceptable from point of view of times of association. Nevertheless second channel (association of clusters) is more natural, when cluster is formed from the gas, gritty. The first channel is realized in the case, when the structure, which consists of the filaments, grows upon the connection to itself of solid particles.

§4.5. Gas dynamics.

Of aforesaid it above follows that active material of globular lightning has noncompact structure, which can be simulated by lump of filamentary aerosols or by fractal cluster. This structure causes some phenomena, which we will examine below. One their base is connected with gas dynamics of the movement of air, which takes place through this structure and creating lift. Nature of this phenomenon is such. The chemical processes, which occur in the active material of globular lightning, lead to heating of substance and surrounding air. As it follows of the estimates carried out earlier, this heating causes the movement of air in the zone of heat release convectively. Heated air will exceed the limits of the region, occupied by active material, rising in this case upward. Instead of it, from below and assembly into the region, occupied by active material, will approach cold air. Being heated in the zone of heat release, this air then will be headed upward. Thus, under the effect of the source of heat release will appear ordered motion of air, which as a result rises very cluster of filaments, which is heat source.

Our problem consists of analysis of gas dynamics of system in question. It is necessary to determine the power of heat release, required for maintaining this temperature of air, and also the lift, which creates this motion. We will consider during the solution of this problem that the system works stationarily, what is natural simplification in this problem.

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Furthermore, we will investigate the movement of air far from the active region, where it behaves similarly to the motion of fume from the tube. The asymptotic solution for the movement of air in this region will make it possible to restore/reduce only the dependence of motion characteristics on the parameters of the problem. The common picture of the motion being investigated is given in Fig. 4.4. It is evident that above the active region is formed the cone with the convective movement of air, in which occurs ordered motion.

Problems of value of Grashof number are small for characteristic parameters, so that motion is laminar. We analyze the character of motion in the region, distant from the zone of heat release. During the determination of the parameters of the movement of air far from the active region we will follow the work of Zeldovich [60], presented in book [42], (problem 4 in §56). From the equation of Navier - Stokes follows the relationship/ratio

$$\frac{u^2}{z} \sim \beta g \Delta T, \quad \frac{\nu u}{R^2} \sim \frac{u^2}{z\mathrm{Re}} \ll \frac{u^2}{z}, \qquad (4.30)$$

where u - vertical component of gas velocity, z - vertical distance from the lump to observation point, R - a transverse radius of cone in the observation point, ν - kinematic viscosity of gas, $\mathrm{Re} = R_0 u/\nu$ - Reynolds number, g - free-fall acceleration, ΔT - difference in temperatures in observation point relative to surrounding air, β - coefficient of the thermal expansion of air. Since

$\beta = \frac{1}{\rho}\frac{\partial\rho}{\partial T}$, under the conditions of constant pressure from Clapeyron's in question equation we have $\beta = 1/T$ (here T - temperature of surrounding air).

Together with equation (4.30) we will use condition of constancy of heat flow P in considered cone at a distance z from active region:

$$P = \rho' c_p \Delta T u \pi R^2. \qquad (4.31)$$

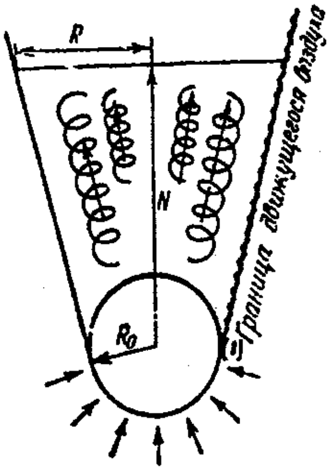

Fig. 4.4. Picture of movement of air through cluster of filamentary aerosols, which are heated under action of internal heat release.

Key: (1). Boundary of moving air.

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Here c_p - heat capacity per unit of the mass of air at a constant pressure, ρ' - mass density of heated air.

From relationship/ratio (4.30) we obtain

$$u \sim \sqrt{gz\frac{\Delta T}{T}\frac{R_0^3}{R^3}}. \qquad (4.32)$$

Formula (4.32) makes it possible to obtain the average/mean air speed in the region, where active material is located. We will assume that for this the distance from the cluster is equal to its radius R_0. This it gives

$$u = A\sqrt{gR_0\frac{\Delta T}{T}}. \qquad (4.33)$$

The numerical factor A with this method of obtaining the formula remains indefinite, and formula itself gives correct dependence on the parameters of the problem at condition $\Delta T \ll T$, which was used for its obtaining.

Lift, which operates on design in question, is equal to

$$\mathcal{F} = C\rho u^2 S,$$

where C - numerical coefficient, ρ - mass density of elapsing gas, S - projected area of design on flow direction. This formula is valid, if for Reynolds number Re is fulfilled relationship/ratio $\mathrm{Re} = R_0 u/\nu \gg 1$ (here ν - kinematic viscosity of air). Under the conditions ($u \sim 1$ $m \cdot s^{-1}$ in question, $R_0 \approx 10$ cm) we have $Re \sim 10^3$, so that this formula is valid. Utilizing in this formula relationship/ratio (4.33), for the lift, which appears due to structure heating, we will obtain the formula

$$\mathcal{F} = a\rho g R_0 \frac{\Delta T}{T} S. \quad (4.34)$$

This formula connects the lift, which appears under the action of heating during the chemical processes in globular lightning, with the design parameters and the temperature of heating. The numerical parameter a is here indefinite. It can be restored/reduced directly from the experiment. Such measurements were carried out in work [61], where and simulation experiment was utilized the tungsten wire with a radius of 4 and 7 μm.

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From it was made the lump of a radius of 0.8-2 cm and with the mass of 20-200 mg. Lump was irradiated with the aid of the laser, an increase in its temperature with respect to room temperature of air comprised $\Delta T = 10 \div 300$ K. Simultaneously was measured the lift of lump, which allowed on the basis of formula (4.34) to restore/reduce the value of parameter A. During the statistical processing of more than 100 measurements is obtained value a=11±5.

Formula (4.34) gives, that globular lightning can "float" with relatively high content of active material. Let us present the condition for the "floating up" of globular lightning (lift is equal to the structural weight) in the limiting cases. For the optically opaque fractal cluster (D>2) this condition takes the form

$$x = \frac{m}{M} = 8\frac{\Delta T}{T_0}, \quad (4.35)$$

where m - mass of active material, M - mass of air within the body of ball lightning. In other limiting case of the optically transparent body of ball lightning floating condition takes the form

$$\frac{r_0}{R_0} = 5\frac{\rho_{н}}{\rho}\frac{\Delta T}{T_0},$$

where $\rho_{н}$ - mass air density, ρ - material density of body, r_0 - radius of filaments. As is evident, the condition for the floating up of the body of ball lightning easily is reached.

It should be noted that maintenance of gas-dynamic mode in question requires essential power expenditures. Let us show this.

The power, spent on the maintenance of this heat engine, is given by formula (4.31). Utilizing, furthermore, formula (4.33) for the average/mean air speed into the region of lump and the value of parameter A=3.3, obtained from the experiment, we find

$$p = \frac{P}{V} = p_0 \frac{\Delta T^{3/2}}{T_0^{1/2} T}. \tag{4.36}$$

Here

$V = \frac{4}{3}\pi R_0^3$ - the space of active region, T_0 - the temperature of surrounding air, T - the temperature of air in the zone of heat release $\Delta T = T - T_0$. $p_0 = \frac{3}{4} A c_p \rho_0 T_0 \sqrt{g/R_0}$.

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For a radius of average globular lightning R_0=14 cm we have p_0=7.2 Vt·cm^{-3}. Whence it follows even number power expenditures for the maintenance of gas-dynamic motion must be considerable.

We will consider that energy release and heat exchange in globular lightning carry stationary character. The specific power of heat release according to data of Table 1.5 comprises $10^{-0.25 \pm 0.75}$ Vt·cm^{-3}. Then on the basis of formula (4.36) it is possible to find an increase in the temperature of air within the body of ball lightning: $\Delta T = 10^{1.8 \pm 0.6}$ K. Although the real processes in ball lightning carry transient character, this value (about 100 K) gives representation about the average heating of air within the design of ball lightning.

Let us estimate weight of body of ball lightning on basis of formula (4.35) and condition that ball lightning sails. Utilizing obtained result $T = 60\ \mathrm{K} \cdot 10^{\pm 0.6}$ it is obtained: $x \sim 1 \cdot 10^{\pm 0.8}$. Thus, the average specific weight of body - the order of the specific weight of atmospheric air.

Summing up results to analysis, carried out in this chapter, we obtain, that during association of solid aerosols can arise structures of fractal cluster, and also structures, which are cluster of filamentary aerosols. The characteristic times of the formation of such structures are seconds. The designs in question form the body of ball lightning. Heating body due to the chemical processes taking place in it causes the movement of air through it and creates lift. In this case the maintenance only of motion in air is connected with the high power expenditures [1]

FOOTNOTE [1]. Let us note that good model of ball lightning in the plan of its thermal interaction with the surrounding air is electric iron. In order of magnitude it has the same power, the same sizes and the same temperature of heating relative to surrounding air, as average/mean ball lightning. It is possible, in particular, to ascertain that with the aid of electric iron the sensation of heat from average/mean ball lightning can be discovered only at close (~10 cm) distances from it. ENDFOOTNOTE.

CHAPTER 5.

ELECTRICAL PHENOMENA IN BALL LIGHTNING

§5.1. The electrical properties.

Ball Lightning develops electrical properties. This follows from observed interaction of ball lightning with the metallic objects and electrical instruments [9], and also from the character of the effect of ball lightning on the man, which it is similar to the defeat of man by electric current. All these examples attest to the fact that ball lightning bears electric charge. The presence of electric charge is substantial for the fractal structure of ball lightning - it creates the surface tension of the body of ball lightning, without giving to it "to collapse" [46]. At the same time the contribution of electrical energy to the total internal energy of ball lightning is unessential (see §2.4).

Question arises, whence electric charge of ball lightning is taken and further - to what electrical phenomena it leads presence of this charge. Our subsequent presentation will be connected with the analysis of these problems. This schematically appears as follows. Solid particle, which is located in the weakly ionized atmosphere, is charged, since the mobility of positive and negative charge carriers different or in the plasma is the uncompensated for electric charge. The charged solid particles associate, so that cluster formable in this case proves to be charged. The electric charge of cluster is stored on its surface and is created the surface tension, which guarantees the stability of design.

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High electric fields at the ends of the cluster cause the electric currents, which lead to its discharging. In more detail these questions will be examined below.

For quantitative analysis of electrical properties of ball lightning let us conduct estimates of its electrical parameters. In this case for the certainty we will consider that the surface tension α of ball lightning coincides with the surface tension of water at room temperature (0.073 $J \cdot m^{-2}$). This assumption, apparently, will give upper estimate for the electrical parameters of ball lightning [1]).

FOOTNOTE [1]. The close values of the electrical parameters of ball lightning gives the account of that fact that ball lightning is attracted to metallic objects, i.e., the force of interaction of the electric charge of ball lightning with its representation/transformation - order of the weight of ball lightning. **ENDFOOTNOTE.**

The surface tension of the charged sphere it is possible to record in the form

$$\alpha = \frac{q^2}{4\pi R_0^3} = \frac{F^2 R_0}{4\pi},$$

here q - complete electric charge, R_0 - a radius of sphere, F - electric intensity on its surface. Hence for average ball lightning (R_0=14 cm) we have F=2.4 $kV \cdot cm^{-1}$, $q = 5.3 \cdot 10^{-7}$ C; in this case the electric potential of ball lightning is equal to 34 kV. Electrical energy of ball lightning q^2/R_0 in this case is 0.02 J, that six orders lower than energy of average ball lightning [2]).

FOOTNOTE [2]. Let us note that the lethal dose during the defeat of man by electric current answers the passage through the man of the electrical energy, which exceeds 2 kJ [137]. ENDFOOTNOTE.

Surface charge creates a pressure on the surface of ball lightning α/R_0, equal to 0.5 Pa. If we consider further that the mass of the body of ball lightning coincides with the mass of air, which is located within it at room temperature, then we will obtain that the specific charge of the body of ball lightning comprises $3.5 \cdot 10^{-8}$ $Kl \cdot g^{-1}$. These estimates we utilize below during the analysis of electrical phenomena in ball lightning.

S5.2. Charging of aerosol particles and the weakly ionized gas.

Since ball lightning possesses electrical properties because of the fact that its body is formed from charged aerosol particles, we investigate further charging of aerosol particles in ionized gas.

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Let us examine first unipolar plasma, i.e., gas, which contains the admixture/impurity of the ions of one type and charged it is equal. We will consider that the aerosol is the solid spherical particle of radius r_0, moreover we will first examine to examine case $r_0 \gg \lambda$ (where λ - mean free path of ions in the gas). Falling on the surface of aerosol, ion transmits its charge to it, i.e., ion flow to the surface of aerosol particle creates the current, which loads it. Let us determine the strength of this current.

In case $(r_0 \gg \lambda)$ in question ion current to aerosol particle is composed of diffusion and hydrodynamic currents, created by action of electric field:

$$J = 4\pi r^2 \left(- \mathscr{D} \frac{dN}{dr} + KFN \right) e. \qquad (5.1)$$

Here N - density, e - the ion charge, K - mobility, $\mathscr{D}$ - the coefficient of diffusion of ions in gas, r - distance to the center of aerosol, F - the electric intensity of aerosol.

We will use relationship/ratio of Einstein between coefficients of diffusion and ion mobility $e\mathscr{D} = KT$ (T - temperature of gas) and formula for electric intensity of aerosol $F = Ze/r^2$, where Z - charge of aerosol in units of electronic charges. substituting them into equation (5.1), we will obtain

$$J = 4\pi r^2 \mathscr{D} \left(\frac{dN}{dr} - \frac{Ze^2}{Tr^2} N \right) e. \qquad (5.2)$$

Since ions are not absorbed in space, value of ion current to aerosol does not depend from distance of r to aerosol. Therefore relationship/ratio (5.2) can be considered as equation for the ionic density N(r). Solving this equation with boundary conditions $N(\infty) = N_0$, $N(r_0) = 0$, we obtain the formula of Fux [52]:

$$J = \frac{4\pi \mathscr{D} N_0 Z e^3}{T\left[\exp\left(Ze^2/r_0 T\right) - 1\right]}. \qquad (5.3)$$

Formula (5.3) gives the following asymptotic relations for the ion current to the aerosol particle.

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If particle charge is relatively small, i.e., if $Ze^2/r_0 T \ll 1$, for ion current to neutral macroparticle of radius r_0 we obtain Smolukhovsky's formula:

$$J_0 = 4\pi \mathscr{D} r_0 N_0 e. \qquad (5.4)$$

In other limiting case, when the charge of aerosol particle has a sign, to the opposite charges of ion (Z<0), and very particle charge is sufficiently great, $|Z| e^2/r_0 T \gg 1$, we will obtain Langevin's formula:

$$J = 4\pi \mathscr{D} N_0 |Z| \frac{e^3}{T} = 4\pi K |Z| e^2, \qquad (5.5)$$

where the ion mobility in gas $K = e\mathscr{D}/T$.

Let us further examine for simplicity case, when ion charge is relatively small $(Ze^2/r_0T \ll 1)$. but we will use more general boundary condition, introducing probability γ of fact that ion, which encounters area of the particle, transmits its charge by it. Then for the current of charges to the area of the particle we have

$$J=\gamma\pi r_0^2\sqrt{\frac{8T}{\pi M}}\,N(r_0)\,e=j_0\frac{N(r_0)}{N_0}. \qquad (5.6)$$

Here $j_0=\gamma\pi r_0^2\sqrt{8T/\pi M}\,N_0e$, $N_0=N(\infty)$; M - mass of ion, so that $\sqrt{8T/\pi M}$ - average/mean thermal velocity of ions; $N(r_0)$ - ionic density on the area of the particle (earlier we considered that $N(r_0)=0$). We solve equation (5.2) on condition that $J=\mathrm{const}$, and by boundary conditions (5.6), and also taking into account that $N(\infty)=N_0$. In the limiting case in question we disregard second term in equation (5.2). The solution of equation will take the form

$$N(r)=A-B/r.$$

In this case $A=N_0$, $A-B/r_0=N_0J/j_0$, i.e. $B=N_0r_0(1-J/j_0)$. Hence we find

$$J=\left(\frac{1}{j_0}+\frac{1}{J_0}\right)^{-1}, \quad (5.7)$$

where j_0 is assigned by formula (5.6), and J_0 - by formula of Smolukhovsky (5.4.).

Let us examine now another, conversion opposite case, when mean free path of ion is great in comparison with size of aerosol particle. Let energy of ion be equal to E, and upon the entry to the area of the particle it transmits by it charge with the probability γ.

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The connection between the impact parameter ρ, under which the ion moves to the center of particle, and the distance of closest approach r_0 is given by the known relationship/ratio:

$$1-\frac{\rho^2}{r_0^2}=\frac{Ze^2}{r_0E}.$$

Hence we find the capture cross section of ion to the surface of the aerosol particle:

$$\sigma=\pi\rho^2(r_0)=\pi r_0^2\left(1-\frac{Ze^2}{r_0E}\right),$$

which gives for the rate constant of capture, when ion charge is transmitted to aerosol particle,

$$k=\gamma\sqrt{\frac{2E}{M}}\pi r_0^2\left(1-\frac{Ze^2}{r_0E}\right).$$

For the current the surface of aerosol particle we obtain the expression

$$J=kN_0e=\gamma\left\langle\sqrt{\frac{2E}{M}}\pi r_0^2\left(1-\frac{Ze^2}{r_0E}\right)\right\rangle N_0e.$$

Here brackets indicate averaging over the Maxwellian distribution of ions on the rates. Carrying out this averaging, we will obtain

$$J = j_0 \frac{Ze^2/r_0T}{\left[\exp\left(Ze^2/r_0T\right) - 1\right]}, \tag{5.8}$$

where

$$j_0 = \gamma\pi r_0^2 \sqrt{\frac{8T}{\pi M}}. \tag{5.9}$$

Formulas (5.3) and (5.8) answer two asymptotic relations between radius of aerosol particle r_0 and mean free path λ of ions in gas. Uniting these formulas taking into account (5.7), we will obtain the following expression for the ion current to the aerosol particle:

$$J = \frac{J_0 \cdot Ze^2/r_0T}{\left(1 + J_0/j_0\right)\left[\exp\left(Ze^2/r_0T\right) - 1\right]}. \tag{5.10}$$

This formula taking into account the fact that the charge of the aerosol particle Z can be different signs, unites all limiting cases examined.

Let us note interesting fact.

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I to the problem enter three parameters, that have the dimensionality of the length: a radius of the aerosol particle r_0, the mean free path of ion in the gas λ and the Coulomb length Ze^2/T, which characterizes the size of the region of the strong interaction of the charged particle with the ion. At the same time general result depends only on the relation of parameters λ/r_0 and Ze^2/r_0T, and, as it follows from formula (5.10), dependence on these dimensionless parameters is developed in the separate factors of general expression.

Obtained expressions are valid for ion currents of one type. Let us examine the quasi-neutral plasma, when the charged aerosol is located with the plasma in the equilibrium. If the size of aerosol particle is sufficiently great, then from the equality of the currents of positive and negative ions to it we will obtain for the equilibrium charge of the aerosol:

$$Z = \frac{r_0 T}{e^2} \ln\left(\frac{\mathcal{D}_+}{\mathcal{D}_-}\right), \quad r_0 \gg \lambda, \quad r_0 \gg e^2/T. \tag{5.11}$$

Last inequality arose from the condition that an increase in the charge of aerosol particle by one in principle will not change the character of charging. For room temperature this inequality takes form $r_0 \gg 0.06$ μm. If particle size is noticeably less, then one should consider that the probability of the appearance of aerosol particles with the charge, greater than one, is proportional to exponential curve $\exp(-e^2/r_0T)$ and it is small. Actually, for example, the probability of the entry of ion to the aerosol particle, which has charge Z and the same sign, contains factor $\exp(-Ze^2/r_0T)$, which expresses the probability of the approach of ions to the area of the particle. Eliminating from the examination of particle with the charge, and comparing the currents of the charging of neutral and discharging of the once charged aerosol particles, for the relative percentage of the charged particles in this case we will obtain the relationships/ratios

$$\frac{n_+}{n_0} = \frac{1}{x}\sqrt{\frac{M_-}{M_+}}, \quad \frac{n_-}{n_0} = \frac{1}{x}\sqrt{\frac{M_+}{M_-}}, \quad r_0 \ll \lambda, \qquad (5.12a)$$

$$\frac{n_+}{n_0} = \frac{\mathcal{D}_+}{\mathcal{D}_- x}, \quad \frac{n_-}{n_0} = \frac{\mathcal{D}_-}{\mathcal{D}_+ x}, \quad r_0 \gg \lambda, \qquad (5.12b)$$

large of one where n_0, n_+, n_- - densities of neutral and also once (positively and negatively) charged aerosol particles; $x = e^2/r_0 T \gg 1$.

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The average/mean charge of aerosol particles, according to formulas (5.12), is equal to

$$\bar{Z} = \frac{n_+ - n_-}{n_0} = \begin{cases} \dfrac{M_- - M_+}{x\sqrt{M_- M_+}}, & r_0 \ll \lambda, \\[2ex] \dfrac{\mathcal{D}_-^2 - \mathcal{D}_+^2}{\mathcal{D}_+ \mathcal{D}_- x}, & r_0 \gg \lambda. \end{cases} \qquad (5.13)$$

Since $x \gg 1$, that we obtain $\bar{Z} \ll 1$.

Let us examine character of establishment of equilibrium charge in quasi-neutral plasma, counting for simplicity, that parameters of positive and negative ions in plasma are close. A change of the charge of aerosol particle in the case $Z \gg 1$ takes the form of the equation

$$\frac{dq}{dt} = J_+ - J_-,$$

where $q=Ze$; J_+ and J_- - currents of positive and negative ions to the particle. Utilizing expression (5.3) for the ion currents in the case $r_0 \gg \lambda$ and formula (5.11) for the average/mean charge, we will obtain the solution of this equation:

$$q = q_0\left[1 - \exp\left(-\frac{t}{\tau_{\text{зар}}}\right)\right],$$

where, according to (5.11),

$$q_0 = \frac{r_0 T}{e}\frac{\Delta\mathcal{D}}{\mathcal{D}}$$

$$\left(\mathcal{D} = \frac{1}{2}(\mathcal{D}_+ + \mathcal{D}_-),\quad \Delta\mathcal{D} = \mathcal{D}_+ - \mathcal{D}_-,\quad \Delta\mathcal{D} \ll \mathcal{D}\right).$$

The time of the establishment of the equilibrium charge of aerosol particle comprises

$$\frac{1}{\tau_{\text{зар}}} = \frac{4\pi\mathcal{D}N_0 e^2}{T} = 2\pi\Sigma,\quad \frac{e^2}{Tr_0} \ll 1, \tag{5.14}$$

here Σ - plasma conductivity.

Let us examine now limiting case, when $e^2/r_0 T \gg 1$. Since we consider the parameters of positively and negatively charged ions close ones, according to formulas (5.12) in this case $n_+/n_0 = n_-/n_0 = 1/x$.

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The equation of balance for the charged aerosol particles takes the form

$$\frac{dn_\pm}{dt} = n_0 k_0 N_i - n_+ k_{\text{рек}} N_{i}$$

where k_0; $k_{\text{рек}}$ - rate constant of the transmission of charge from the ion to aerosol particle, moreover in the first case particle is neutral, and the second has the charge, to the opposite charges of ion. With this $N_1 k_0 = J/e$. where J - ion current to the neutral aerosol particle - it is determined by formula (5.7), $k_{\text{рек}} = k_0 e^2/Tr_0$. It will be the solution of the equation of balance

$$n_+ = n_0 \frac{r_0 T}{e^2} [1 - \exp(- t/\tau_{\text{зар}})],$$

the expression for the time of charging in accordance with formula (5.12) taking the form

$$\frac{1}{\tau_{\text{зар}}} = \frac{4\pi \mathcal{D} N_0 e^2}{T} \left(1 + \frac{4\mathcal{D}}{\gamma r_0 \sqrt{\frac{8T}{\pi M}}}\right)^{-1}. \qquad (5.15)$$

In the extreme case $\lambda \ll r_0$ this formula will pass into formula (5.14).

Process of adhesion of ions to aerosol particles leads also to drop in ionic density in plasma, i.e., to decay of plasma. The equation of balance for the density of positive ions N_+ in the case in question, after was established the equilibrium between the charged and neutral aerosol particles in the plasma, has the form

$$\frac{dN_+}{dt} = - n_0 k_0 N_+ - n_- k_{\text{рек}} N_+ = - \frac{N_+}{\tau_{\text{расп}}},$$

where the time of decay of the plasma

$$\frac{1}{\tau_{\text{расп}}} = n_0 k_0 + n_- k_{\text{рек}} = 2 n_0 k_0 =$$
$$= \frac{8\pi \mathcal{D} n_0 e^2}{T} \left(1 + \frac{\mathcal{D}}{\gamma r_0 \sqrt{T/2\pi M}}\right)^{-1}. \qquad (5.16)$$

The obtained formulas make it possible to estimate the parameters of the process of the charging of aerosol particles in the real plasma.

Let us examine real atmosphere. The composition of ions, which are found in real atmosphere, depends on humidity and temperature of the atmosphere, from the admixtures/impurities being present in it and usually it includes several molecules of water. The diffusion coefficient comprises: according to data [62] $\mathcal{D}_+ = 0{,}029$. $\mathcal{D}_- = 0{,}043$ of $cm^2 \cdot s^{-1}$ (moreover the mass of ions $M_-=101$, $M_+=140$); according to data [63] $\mathcal{D}_+ = 0{,}028$, $\mathcal{D}_- = 0{,}036$ $cm^2 \cdot s^{-1}$.

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Taking into account these data formulas (5.11) and (5.13) for aerosol particles, which are located in the atmosphere at room temperature, can be represented in the form

$$Z/r_0 = (-6 \pm 1)\ \overset{(1)}{\text{мкм}}{}^{-1}. \quad (5.17)$$

Key: (1). mkm^{-1}.

In this case the characteristic time of charging (5.14) for the average ionic density in the atmosphere ($N_0 = 300$ cm^{-3}) is lower $\tau \approx 10$ min, which can serve as upper boundary for the lifetime of ball lightning in the atmosphere. Discharging the body of ball lightning in the atmosphere and its destruction occurs during such times.

Charging of aerosol particles in the atmosphere can occur, also, under nonequilibrium conditions. Let us examine the case, when in the zone of the determination of aerosols electrical discharge occurs. Electric intensity in this region is sufficiently great and negative charge is connected with the electrons. The mobility of thermal electrons in atmospheric air is approximately $1.4 \cdot 10^4$ $cm^2 \cdot (V \cdot s)^{-1}$, which considerably exceeds the mobility of molecular positive ions to atmosphere 2-2.5 $cm^2 \cdot (V \cdot s)^{-1}$. In this case formula (5.11) at room temperature for the charge gives

$$Z/r_0 = -160 \,^{(1)}\text{мкм}^{-1}. \quad (5.18)$$

Key: (1). mkm^{-1}.

The respectively characteristic time of the establishment of this charge according to (5.14) comprises $\tau N_0 = 40$ $s \cdot cm^{-3}$.

Formula (5.17) makes it possible to estimate maximum size of aerosol particles, which form part of body of ball lightning. Given in §5.1 estimate for the specific charge of ball lightning ($4 \cdot 10^7$ $Kl \cdot g^{-1}$) for the characteristic particle density $\rho = 2$ $g \cdot cm^{-3}$ according to formula (5.17) correspond to a radius of particles $r_0 = 2$ μm. Since the subsequent processes of the formation of the body of ball lightning can be accompanied only by the loss of charge, it is possible to consider that the particles, entering the body of ball lightnings, have a radius $r_0 < 2$ μm.

§5.3. Assembly of the charged cluster and the separation of the charge of plasma.

Let us examine character of assembly of body of ball lightning from solid aerosols. Since the particles are charged, as a result of the association of solid particles the charged cluster is formed. In this case necessarily that in the process of the assembly of cluster would be satisfied the following conditions.

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First, if charge rapidly overflows to the surface of cluster, then the assembly of cluster can occur during a cluster-cluster association, moreover the charged ends of one cluster are connected with the uncharged part of another. Otherwise surface charge will block the assembly of large cluster. In the second place, the value of the equilibrium charge of the cluster considerably lower than sum of the equilibrium charges of the associated particles. Therefore the high charge of cluster corresponds to nonequilibrium conditions, so that ion current to the cluster leads to its discharging.

We will consider that association of similarly charged particles in principle does not differ from association of neutral particles, which can be made, if parameter β is subordinated to following condition:

$$\beta = Z^2e^2/2r_0T \ll 1 \quad (5.19)$$

(here Z - average/mean particle charge). This condition means that repulsive energy of two contacting particles not more than than their thermal energy.

We will use formule (5.17), then for room temperature formula (5.19) will give value $r_0 \ll 2$ μm. Thus, we will obtain the same estimate for the maximum radius of particles, as in the preceding paragraph. One should, however, note that these estimates proceed from the different physical considerations.

Let us give values of rates of electrical processes in real atmosphere. The highest value corresponds to the charging of particle by electrons. Taking into account that electron mobility in air comprises $1.4\cdot10^4$ $cm^2\cdot(V\cdot s)^{-1}$, on the basis of formula (5.18) we will obtain for time τ_e of charging and discharging of particle by electrons (N_e - electron density) the value

$$\tau_e N_e = 40\ \overset{(1)}{\text{с}}\cdot\text{см}^{-3}, \quad r_0 \gg 0{,}06\ \overset{(2)}{\text{мкм}}. \qquad (5.20a)$$

Key: (1). s·cm⁻³. (2). μm.

Let particles be united into cluster. The equilibrium charge of cluster is determined by formula (5.17), where instead of a radius of particles r_0 should be utilized a radius of cluster. It is not difficult to see that the equilibrium charge of cluster is substantially less than the sum of equilibrium particle charges, which compose cluster. Therefore its discharging under the action of the current of positive ions on the cluster occurs in proportion to an increase in the cluster.

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The characteristic time of this process in the atmosphere, which contains quasi-neutral plasma, according to formula (5.14) is equal

$$\tau_{\text{зар}} N_i = 4\cdot10^5\ \overset{(1)}{\text{с}}\cdot\text{см}^{-3}, \quad r_0 \gg 0{,}06\ \overset{(2)}{\text{мкм}}. \qquad (5.20б)$$

Key: (1). s·cm⁻³. (2). μm.

Recombination of charged particles in space occurs together with processes of charging and discharging of particles in weakly ionized gas. In real atmosphere - this is the recombination of positive and negative ions with the participation of the molecules of air. Recombination coefficient weakly depends on the type of these ions and at the atmospheric pressure is [64, 65] $\alpha = 2 \cdot 10^{-6}$ $\text{cm}^3 \cdot \text{s}^{-1}$. Hence for the time of recombination $\tau_{\text{рек}}$ we obtain

$$\tau_{\text{рек}} N_i = 5 \cdot 10^5 \, {}^{(1)}\text{с} \cdot \text{см}^{-3}. \qquad (5.20c)$$

Key: (1). $\text{s} \cdot \text{cm}^{-3}$.

As it follows from formulas (5.20b) and (5.20c), the rates of discharging cluster and recombination of charges in air are close. This means that in the recombining plasma of air the effective discharging of cluster occurs. If we consider that also after recombination in the space in the zone of cluster remains the uncompensated for positive charge, then let us arrive at the conclusion that the recombination of charges in the plasma cannot avoid discharging cluster.

Thus, assembly of body of ball lightning must occur in unipolar plasma, i.e., when in space of ball lightning is uncompensated for charge of one sign. Hence it follows that the assembly of cluster must precede the separation of the charge of plasma or charge of plasma and particle charge. Let us note the fact that the charge density in ball lightning is relatively greater. ually, if we use estimates S5.1 and to subdivide the value of the electric charge of ball lightning for the space of average ball lightning, then we will obtain the average density of the charge of ball lightning in the unit charges of electrons $3 \cdot 10^8$ cm^{-3}, that approximately six orders higher than density of atmospheric plasma in the near-surface layer of the Earth. Since there are no mechanisms of the strong concentration of the charge of atmospheric plasma, hence it follows that the charging of aerosol particles must occur in the plasma, which has the density, high in comparison with the density of atmospheric plasma. At the same time to the assembly of the cluster of charge in the plasma it must be divided.

Let us show that separation of charge in ball lightning cannot occur as in cloud, under action of gravitational forces.

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In the cloud the negatively charged drops of water fall under the action of their weight and thus they create atmospheric electricity. In our case this mechanism is impossible, since here particle sizes are small, and the necessary electric fields are great in comparison with the atmospheric. Actually, the solid particles, which further form cluster, they have sizes not more than 1 μm. The rate of a drop in the particle of a radius of 1 μm with a density of 2 $g \cdot cm^{-3}$ under the action of gravitational force in atmospheric air is equal to

$v = 0{,}014$ $cm \cdot s^{-1}$. Since $v \sim r_0^2$ the small particles fall more slowly. A drop in the particles creates the negative current in the atmosphere, under action of which appears the electric field with strength F, which causes the drift of positive ions in the atmosphere. At equilibrium the current of positive ions is equal to the current of negative charge, so that $v/Z=KF$.

Mobility of positive ions in real atmosphere $K \sim 1\ cm^2 \cdot V \cdot s^{-1}$, so that electric intensity $F \sim 0.1\ V \cdot cm^{-1}$, that several orders lower than expected values in ball lightning. The presence of negative ions in the atmosphere leads to a certain drop in this value. The presence of large-size particles could ensure larger effect; however, this would lead to the fact that the charge of cluster was small.

Thus, we come to conclusion that separation of charge before assembly of body of ball lightning occurs not under action of gravitational fields, but it is caused by external electric fields. In this respect electrical phenomena in ball lightning do not have an analog in the electrical machine of the Earth's atmosphere.

Let us conduct estimates for system in question. Electric intensity $F \sim (1-10)\ kV \cdot cm^{-1}$ will cause the motion of ions at a rate of $v \sim (10^3-10^4)$ of $cm \cdot s^{-1}$, so that the distance of the order of the size of system (10 cm) pass during the times of order $(10^{-3}-10^{-2})$ s; for this time it occurs the separation of charge. Solid particles possess relatively small mobility, so that their movements in this case can be disregarded. Thus, for the separation of charge is necessary the presence of the high electric fields, which exist during several milliseconds. Further, after the drift of the positively charged particles from the space, these fields are fixed on the material of ball lightning.

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It is significant that the characteristic time of the separation of charge is noticeably less than the times of the association of solid particles into the cluster.

For analysis of processes of forming charged cluster let us examine simple model of creation of initial conditions for this cluster. Let from air through the surface of material flow the electric current, which further evaporates the surface of material and is created the plasma, gritty. From the continuity condition of electric current we have $F_1\sigma_1 = F_2\sigma_2$ (where F_1, F_2 - electric intensity in air and material, σ_1, σ_2 - conductivity of air and material respectively). It is evident that in view of the different conductivity of air plasma and material of surface on the interface is created the jump of electric intensity ΔF, i.e., surface charge appears at the interface.

Model in question lies in the fact that surface charge is located in thin layer and during evaporation is taken away into air plasma. Then is formed plasma with the predominance in it of the charges of the specific sign. In proportion to the formation of solid particles the plasma ions transmit their charge to these particles during relatively short times. By there very during the first stage of the formation of cluster we have air, which contains the charged solid particles; moreover total particle charge is different from zero.

Let us conduct estimates on the basis of represented model. We will consider for simplicity that the conductivity of the air plasma considerably lower than conductivity of material, so that a drop/jump in the electric intensity on the interface coincides with the field strength in air F_1. Further, we will consider that the interfacial area, on which is formed the plasma, considerably exceeds the section of ball lightning, i.e., we will be restricted to the one-dimensional case. Then, according to Poisson's equation, we have

$$F_1 = 4\pi e \int N\,dx,$$

where N - the bulk density of charge on the interface, x - direction, perpendicular to interface. Let R - size of plasma after the evaporation of material. Then the density of the uncompensated for charge in it

$$N = F_1/4\pi eR.$$

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If we isolate from this plasma the space of radius R, then charge within it is equal to $q = {}^4/_3\pi R^3 N e = F_1 R^2/3$. We will consider that the solid particles were combined into the cluster of radius R. Then this cluster has a charge q, for which the estimate, is obtained, and electric field is created on its surface with the intensity

$$F = q/R^2 = F_1/3.$$

Thus, electric intensity, created by cluster, is compared several times of less than the electric intensity in air, when electric current flows over it. In order to obtain electrical parameters of ball lightning used earlier, necessary, in order to initial electric intensity in air, which creates electric current and causes the evaporation of material in air, comprised $F_1 \sim 10$ kV·cm^{-1}.

Separation of charge is accompanied by complicated gas dynamics of system in question, which includes gas, dust and plasma. In this case, since the values of characteristic electrical energy of the uncompensated for charge in this case are relatively small (order 0.02 J), separation of charge cannot influence gas dynamics of process.

Carried out analysis and estimates make it possible to represent physical picture of formation of charged cluster as a result of association of solid charged particles. Particle charge does not affect the character of their association, however, so that the cluster in the process of its increase/growth would not be discharged, it is necessary that the ionic density in the zone of its formation would be substantially less than with the charging of particles. Consequently, the process of the association of the solid charged particles into the cluster precede the process of the charging of particles in the plasma, and also the process of the separation of the particle charge and charge of plasma. Last process occurs under the action of external electric fields.

In order to obtain quantitative picture of electrical processes with assembly of body of ball lightning examined, table 5.1 gives characteristic values of time of course of corresponding processes. The given parameters, as the values of radii of particles used, are adequate for the conditions of ball lightning. Let us comment data of table 5.1.

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As is evident, most rapid process - adhesion of ions to aerosol particles. Ionic density in the plasma considerably lower than that, which they can accept to itself aerosol particles. Therefore all ions adhere to the particles, which leads to the disappearance of plasma in the space. The process of the separation of charges in the plasma precedes this process. Thus the inclusion of aerosol particles into the plasma occurs at that moment, when plasma bears electric potential and charges in it they are divided. Aerosol particles, seizing ions, fix this potential of plasma. The association of aerosol particles into the cluster further occurs. During the times of the order of the time of association or during smaller times occurs the neutralization of the opposite charges, which can have particles. The formed cluster bears on itself only the excess charge of plasma. Discharging cluster in the atmospheric plasma occurs in the relatively larger period and it leads to the decay of cluster itself.

Table 5.1. Characteristic times of the course of electrical processes.

(1) Процесс	(2) Расчет по формуле	(3) Время 1), с	
		(4) при r_0=3 нм	(5) при r_0=0,1 мкм
(6) Установление равновесного заряда на частице	(5.15)	$2,5 \cdot 10^{-3}$	$5 \cdot 10^{-4}$
(7) Распад плазмы за счет прилипания ионов к частицам	(5.16)	$3 \cdot 10^{-10}$	$4 \cdot 10^{-6}$
(8) Рекомбинация положительных и отрицательных ионов в объеме	(5.20c)	$5 \cdot 10^{-4}$	
(9) Разделение зарядов плазмы	—	$10^{-3} \div 10^{-2}$	
(10) Ассоциация частиц в кластер	(4.29)	$0,01 \div 5$	
(11) Разрядка кластера в атмосферной плазме	(5.15)	10^3	

Key: (1). Process. (2). Calculation according to formula. (3). Time s. (4). with r_0=3 nm. (5). with r_0=0.1 μm. (6). Establishment of equilibrium charge on particle. (7). Decay of plasma due to adhesion of non-ion particles. (8). Recombination of positive and negative ions in space. (9). Separation of charges of plasma. (10). Association of particles into cluster. (11). Discharging cluster in atmospheric plasma.

FOOTNOTE [1]. It is accepted that initial density x_i of ions in the plasma is 10^{9} cm^{-3}, and the average density of substance in the space is equal to the density of atmospheric air at room temperature. ENDFOOTNOTE.

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§5.4. Electrical processes in the charged cluster.

Let us examine electrical phenomena, which occur with charged cluster, which is located in the atmosphere. As before we will be while conducting of estimates oriented toward the cluster with a radius of average ball lightning (14 cm) and the surface tension, equal to the surface tension of water. The electric charge of this cluster in the unit charges of electron will comprise order $4 \cdot 10^{12}$, whereas according to formula (5.17) its equilibrium charge in the atmosphere is close to 10^{6}. As a result under the action of ion current discharging cluster will occur. The characteristic time of discharging in real atmosphere with the average density of the charged particles (300 cm^{-3}), according to formula (5.14), will be 20 min. Consequently, electrical processes in the atmosphere must be examined in the limits of these times.

Formation of cluster is accompanied by overflowing of charge to its surface, which creates stability of cluster. Let us explain how charge is distributed at the ends of the cluster. We utilize a model, by considering that its ends - this of the filament of the radius, which coincides with a radius of the particles, of which is comprised the cluster. Let us determine characteristic of which it is comprised cluster. Let us determine the reference length of the end of the filament l, on which is concentrated the charge. This magnitude estimate can be obtained from the condition that electrical energy of interaction of charges, which are located on the end of this filament, must be of the same order as as interaction energy of these charges with the electric field of cluster. Hence for the unknown value l we will obtain

$$l \sim R_0/\sqrt{n}, \quad (5.21)$$

here R_0 - a radius of cluster, n - the number of filaments on the surface. On the basis of formula (5.21) we obtain

$$l/r_0 \sim \sqrt{\rho/\rho_{cp}}, \quad (5.22)$$

where r_0 - radius of the associating particles, ρ - mass density of the material of cluster, ρ_{cp} - the average mass density of cluster, i.e., the ratio of the mass of cluster to the space, which it occupies. Since $\rho \gg \rho_{cp}$, that we obtain $l \gg r_0$; in particular, for those utilized earlier the parameters of cluster (m=3 g, R_0=14 cm, ρ=2 $g \cdot cm^{-3}$) we have $l/r_0 \approx 100$.

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Since electric charge of cluster in the final analysis is stored near ends of cluster, this leads to onset of electric fields of high strength. On the surface of the charged section the electric intensity comprises

$$F_{\max} = 4\pi\sigma = F\frac{2R}{r_0\sqrt{n}} \sim F\sqrt{\frac{\rho}{\rho_{cp}}}, \quad (5.23)$$

where σ - surface charge at the end of the filament, F - average electric intensity on the surface of cluster. In the example examined this corresponds to the local increase of the field strength more than to two orders in comparison with the average value. In the example examined the field strength near the charged filament reaches 5 MV•cm^{-1}. Such fields are caused by the sample of atmospheric air, if they are concentrated in the not very small spaces. In connection with this it is necessary to establish, under what conditions the breakdown of air near the charged ends of the cluster and the onset in this region of the corona discharge are possible.

Condition of onset and maintaining corona discharge near charged filament takes form [66]

$$\int_{r_0}^{\infty} \alpha dr = \ln\left(1+\frac{1}{\gamma}\right), \quad (5.24)$$

where α and γ - first and second coefficients of Townsend. In atmospheric air we will approximate the first coefficient of Townsend with dependence [66, 67]

$$\alpha = \alpha_0 \exp(-F_0/F),$$

here $\alpha_0 = 1{,}1 \cdot 10^6$ m^{-1}; E$_0$=2.8 MV•m^{-1}. Since $E=E(r_0)r_0/r$, the condition (5.13) for atmospheric air will take the form

$$\alpha_0 r_0 Z e^{-z} = \ln(1+1/\gamma), \quad (5.25)$$

where $z=F(r_c)/F_0$. Fig. 5.1 presents dependence on a radius of filament for the electric intensity on the surface of filament, with which it is realized by a sample of atmospheric air. results relate to the values γ=0.1; however, it follows that they weakly depend on this value.

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Analysis of figure and given estimates show that conditions of onset of corona discharge in system in question are difficultly attained. In particular, in the example examined the corona discharge occurs with $r_0>8$ µm (see Fig. 5.1), which is deliberately higher than the possible particle sizes in the cluster. However, high fields near the ends of the cluster affect the character of the currents of discharging. In atmospheric air in the electric fields with $F>3$ MV·m^{-1} negative ions are broken down and negative charge in this case is connected with the electrons. Electron collision with the molecules of air causes their excitation and glow, but the energy, spent on this process, is very small. Thus, in the example in question created due to this process glow, in any case, is not more intense than the glow of night insects. It is difficult to expect due to low electrical energy of cluster that the electrical phenomena are capable of causing noticeable glow.

Since cluster in question bears electric charge, it can interact with conductors. In order to explain, how this a interaction is substantial, let us make estimate for the force of interaction of the cluster with the massive metallic object in question, on which it induces the charge of opposite sign. Considering that this interaction does not cause the redistribution of charge, we find the force of interaction

$$\mathcal{F} \sim \frac{q^2}{4R_0^2} \sim 30\ \mathrm{H}_1^{(1)}$$

Key: (1). N.

q - the charge of cluster, R_0 - its radius. As is evident, the force of interaction in this example is compared with the weight of cluster. This bears out the fact that interaction of the charged cluster with the conductors can substantially affect the character of its motion, which follows also from the observations of ball lightning.

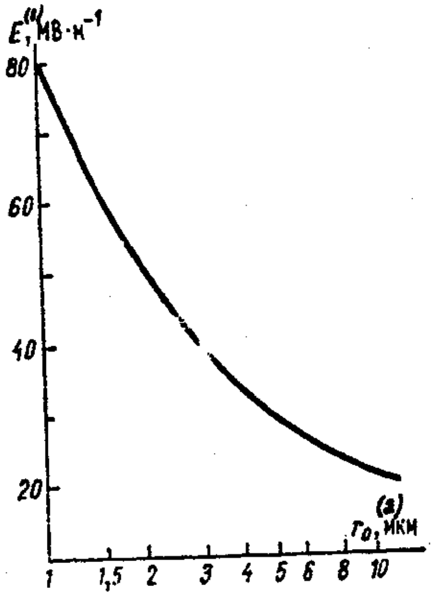

Fig 5.1. Dependence of electric intensity E on surface of charged filament, necessary for maintaining corona discharge in atmospheric air, on radius of filament r_0.

Key: (1). MV·m⁻¹. (2). µm.

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Similar estimate makes it possible to find maximum charge, which can bear body of ball lightning. For this let us examine the process of the association of the charged clusters into the large cluster. According to the mechanism of association, represented in §4.4, with the not very small sizes of clusters their approach occurs due to the incidence/drop in the heavier cluster on the lighter under the action gravitational force. Hence it is apparent that the Coulomb pushing apart of clusters does not interfere with their approach, if the force of Coulomb interaction is less than the difference in the weights of clusters. This gives the following estimate:

$$q^2/R_0^2 \ll mg, \quad (5.26)$$

where R_0, m - significant dimension and the mass of ball lightning. Substituting in (5.26) a radius of average/mean ball lightning, and also the charge, which provides the surface tension, equal to the surface tension of water, on the basis of formula (5.26) we obtain $m \gg 10$ g. As is evident, the characteristic electric charge of ball lightning selected earlier for the estimates answers the average specific weight of the body of ball lightning, which the order of the specific weight of air.

Thus, carried out analysis shows that processes, which occur in weakly ionized air with solid particles, lead to electrical charging of these particles. For forming the charged cluster during the association of the charged particles in weakly ionized air, necessary that in the process of association in air there would be an excess electric charge, i.e., the region, where association occurs, must be located in the heterogeneous electric field. In this case it is prevented the discharge of cluster in the process of its assembly. The high electric fields near the ends of the cluster, which appear as a result of the overflowing of the electric charge of cluster to its surface, are insufficient for the onset of the corona discharge; however, they are capable of causing weak glow during discharging of cluster. Electrical interactions of the charged cluster with the conductors can influence the character of its motion.

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CHAPTER 6.

GLOW OF BALL LIGHTNING.

56.1. Mechanisms of emission.

As it follows from analysis of observational data, ball lightning is source of light of average intensity. The glow of ball lightning can be different colors and, apparently, carries transient character. In order to obtain quantitative representation about the brightness of ball lightning and to analyze the mechanisms of its emission, let us compare ball lightning as radiation source with the equilibrium emitter. This equilibrium emitter is sphere with a radius of ball lightning and emits from the surface as blackbody. The average luminous flux, emitted by ball lightning, composes

$1400\,{}^{+800}_{-500}$ lm. Let us explain, at what temperature equilibrium emitter emits the same luminous flux. We will obtain the temperature of the blackbody: $T = 1360 \pm 30$ K.

Another comparison let us conduct for luminous efficiency - ratio of luminous flux to power expendable in this case. According to data of Table 1.5 the luminous efficiency of ball lightning [1]) is equal to $10^{-0,2\pm 0,65}$ lm·W^{-1}.

FOOTNOTE 1). The luminous efficiency of electric lamp is 14 lm·W^{-1}, solar radiation - 96 lm·W^{-1}. ENDFOOTNOTE.

The temperature of blackbody with the radius of ball lightning, whose luminous efficiency coincides with the value indicated, composes 1800±300 K.

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It should be noted that effective temperature of radiating particles of ball lightning must be higher than given estimates give, since in first case emission of ball lightning is created in narrow region of the spectrum, and the second - fundamental energy losses of ball lightning are connected with gas-dynamic escape of heat. Therefore it is possible to expect that effective temperature of the radiating particles in ball lightning $T \geq 2000$ K.

Special features of emission of ball lightning are connected with its structure and character of energy release. The glow of ball lightning due to heating of its body is possible. In this case it is necessary to consider that if the sizes of the particles, of which is comprised the body of ball lightning, are small, then this introduces corrections into the spectrum of the emitted emission. Specifically, the flow of the emitted emission at wavelengths, which exceed particle sizes, it is considerably less than in the case of emitting the extended surface from the same material and at the same temperature.

Together with thermal radiation of body of ball lightning emission of atoms and molecules in gas phase is possible. Excited atoms or molecules can be formed from the active material of ball lightning as a result of chemical reactions, or be excited under the action of the high temperature, created in the zone of reaction. The second mechanism of emission is more interesting than the first, since depending on the type of the radiating atoms or molecules it can give the different of color.

Should be emphasized special features of this mechanism of emission. First, since it occurs in atmospheric air, essential proves to be the quenching of the radiating atoms and molecules during the collision with the molecules of air. In the second place, energy release occurs due to the chemical reactions. Therefore the temperature of the formable gas in the zone of reaction is bounded above and it hardly exceeds 3000 K.

Let us further examine each of mechanisms of emission of ball lightning indicated in more detail.

S6.2. Emission of aerosol particles.

Heated macroscopic particle of large (in comparison with reference length of emitted light) sizes emits in accordance with optical properties of its surface. In particular, if this particle consists of absolutely black material, the emitted by it radiant flux is equal to σT^4 (here T - the surface temperature, σ - Stefan-Boltzmann constant). Isolated atom or molecule - macroscopic particles - can emit the set of photons with the strictly assigned frequencies.

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These spectral lines appear upon transfers between the specific states of macroscopic particle. It is obvious that the separate spectral lines in the spectrum of its emission will be widened in proportion to the association of molecules and formation of them of macroscopic particle and as a result they will create the continuous spectrum, which with the large particle sizes will depend on the surface properties, but not from its sizes. Further we will examine the case of the intermediate sizes of such particle, when the wavelength of the emitted emission exceeds her sizes.

Dependence of radiation spectrum on sizes of aerosol particles will be revealed in such a case, when their sizes are small in comparison with characteristic wavelength of emission. Then in the radiation spectrum of particle the long-wave part of the spectrum with the wavelengths, which considerably exceed particle size, will be absent. Let us determine radiation spectrum for the aerosol particles. The total power of the emission of single particle is equal to

$$\mathcal{P} = \int_0^\infty \frac{\hbar\omega^3}{\pi^2 c^2} \left(\exp\left(\frac{\hbar\omega}{T}\right) - 1\right)^{-1} \sigma_{\text{погл}}(\omega)\, d\omega, \qquad (6.1)$$

where $\sigma_{\text{погл}}(\omega)$ - absorption cross-section by the particle of light at the frequency ω. If absolutely black particle has large sizes, then the absorption cross-section, averaged in the directions of photons, does not depend on frequency and equally

$$\sigma_{\text{погл}} = S/4, \quad (6.2)$$

here S - total surface area of particle. For the power of particle radiation this it gives

$$\mathcal{P}_0 = S\sigma T^4,$$

$$\sigma = (4\pi^2 c^2 \hbar^3)^{-1} \int_0^\infty x^3 dx\,(e^x - 1)^{-1} = \frac{\pi^2}{60 c^2 \hbar^3}.$$

In the general case the absorption cross-section of light with particle to equal [56]

$$\sigma_{\text{погл}}(\omega) = 4\pi \frac{\omega}{c} \operatorname{Im} \alpha(\omega), \qquad (6.3)$$

where α - polarizability of particle.

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Let us further examine case, when one of particle sizes is small in comparison with wavelength of emission and dielectric constant of material of particle $\varepsilon(\omega)$ ~1. Last condition gives, that the depth of penetration of light considerably exceeds particle sizes, i.e., the field of electromagnetic wave within the particle does not depend on depth. This condition is used for writing of formula (6.3), in which is excluded the dependence of dielectric constant on the wave vector.

For the polarizability of spherical particle in the case of [56] in question we have

$$\alpha(\omega)=\frac{\varepsilon(\omega)-1}{\varepsilon(\omega)+2}r_0^3. \quad (6.4)$$

Representing in (6.4) the dielectric constant in the form $\varepsilon(\omega)=\varepsilon'(\omega)+i\varepsilon''(\omega)$. for the absorption cross-section of light with the spherical particle of a small size we will obtain

$$\sigma_{\text{погл}}(\omega)=\frac{1}{4}S\frac{\omega r_0}{c}f_{\text{сф}}(\omega), \qquad (6.5)$$

where

$$S=4\pi r_0^2, \quad f_{\text{сф}}(\omega)=\frac{12\varepsilon''(\omega)}{\{[\varepsilon'(\omega)+2]^2+[\varepsilon''(\omega)]^2\}}.$$

If aerosol particle is chain aggregate/unit, i.e., it has filamentary structure, then, simulating by its cylinder with length of $2l$ and by radius r_0 (moreover $r_0 \ll l$), we have [56] for polarizability of particle:

$$\alpha_{\perp}=r_0^2 l\left[\frac{\varepsilon(\omega)-1}{\varepsilon(\omega)+1}\right], \quad \alpha_{\parallel}=\frac{r_0^2 l}{2}[\varepsilon(\omega)-1], \qquad (6.6)$$

where indices ⊥, ∥ indicate perpendicular and parallel directions of intensity of electromagnetic field with respect to axis of cylinder. Averaging over the directions for the absorption cross- section of absorption we will obtain the formula

$$\sigma_{\text{погл}}=\frac{1}{4}S\frac{\omega r_0}{c}f_{\text{цил}}(\omega), \qquad (6.7)$$

where

$$f_{\text{цил}}(\omega)=\frac{4}{9}\varepsilon''(\omega)\left\{1+\frac{8}{[\varepsilon'(\omega)+1]^2+[\varepsilon''(\omega)]^2}\right\},$$

and $S = 4\pi r_0 l$ - surface area of aerosol particle.

As is evident, formulas (6.5), (6.7) contain as factor low parameter $\omega r_0/c$ - ratio of sizes of aerosol particle to wavelength of emission.

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Due to this factor occurs cutting the contribution of long-wave radiation in the radiation spectrum of aerosol particle. For this reason the total flux of emission from the surface of the heated aerosol particle is noticeably less than flow from the surface of the massive particle of the same material. In this case the radiation spectrum of a small aerosol particle is displaced into the short-wave region in comparison with the radiation spectrum of massive particle.

Considering that value f in formulas (6.5), (6.7) weakly depends on frequency, let us calculate total power of emission of aerosol. Substituting formulas (6.5), (6.7) in (6.1), we will obtain for the power of radiation of the aerosol particle

$$\mathcal{P} = \mathcal{P}_0 \beta,$$

$$\beta = \frac{T r_0 f}{\hbar c} \int_0^\infty x^4 \, dx \left(e^x - 1\right)^{-1} = \frac{3{,}83 T r_0 f}{\hbar c}, \qquad (6{:}8)$$

where $\mathcal{P}_0 = S\sigma T^4$ - radiated power from the surface of macroscopic blackbody. Thus, the total power of emission depends on the temperature of aerosol particle according to the law of T^5, and in the region of the applicability of the obtained formula value β is low parameter ($\beta \ll 1$). This formula can be continued, also, into the region of the sizable values of this parameter. For this purpose let us record it in the form

$$\mathscr{P} = \mathscr{P}_0 \frac{\beta}{\beta/a+1}, \quad (6.9)$$

here a - coefficient of the grayness of the material of aerosol particle. Expression recorded in this form gives correct passage to the limit (6.8) when $\beta \ll 1$, and when $\beta \gg 1$ it gives the radiated power from the surface of macroscopic body $\mathscr{P} = \mathscr{P}_0 a$.

In order to obtain representation about quantitative effect of size of aerosol particles on power of their radiation, let us give results of calculating parameter β for carbon particles. Table 6.1 depicts the optical parameters of carbon black [68] (refractive index it is equal to $n+i\varkappa$) and the calculated according to formulas (6.5) and (6.7) values $f(\lambda)$ for the appropriate forms of aerosol.

Let us pause at case of filamentary carbon aerosol, for it in region of wavelengths according to data of table 6.1 in question value $f_{\text{цил}} = 2.5 \pm 0,2$.

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Utilizing this value, we will obtain

$$\beta_{\text{цил}} = 12 r_0 / \lambda_{\max}(T), \quad (6.10)$$

where $\lambda_{max}(T)$ - wavelength, to which the maximum of blackbody radiation with temperature T corresponds, according to Wiens law we have $\lambda_{max}(T)\cdot T=0{,}290$ K·cm. The obtained result shows that the high value of numerical factor in formula (6.10) decreases the effect of the specific character of the emission of aerosol particles. In the case in question cutting the long-wave part of the radiation spectrum is developed only with the sizes of the aerosol particles, when they are more than by an order of value of lower than the characteristic wavelength of the emitted photons. In the case of spherical aerosol particles we have

$$\beta_{\text{сф}}\approx 3{,}7r_0/\lambda_{max}(T), \quad (6.11)$$

i.e. particle size is developed more strongly.

Let us calculate mean free path of photons, if once contains cylindrical aerosols in quantity x of grams of aerosols to 1 gram of air. The mean free path of photons is equal to

$$l=(N\sigma_{\text{погл}})^{-1}, \quad (6.12)$$

here N - number of aerosols per unit of volume, $\sigma_{\text{погл}}$ - the absorption cross-section of separate aerosol. Let the filamentary aerosols in question have a radius r_0 and be distributed in the space arbitrarily. Bearing in mind that the mean free path does not depend on the length of aerosols, we will consider that the length of each aerosol L. Then the mass of separate aerosol will be $m=\rho\pi r_0^2L$ (where ρ - mass density of the material of aerosol).

Table 6.1. Optical parameters of carbon black.

(1) λ, мкм	n	ϰ	$f_{\text{сф}}$	$f_{\text{цил}}$	(1) λ, мкм	n	ϰ	$f_{\text{сф}}$	$f_{\text{цил}}$
0,4	1,80	0,74	1,067	2,46	3,5	2,14	0,72	0,765	2,52
0,6	1,82	0,74	1,005	2,47	4,0	2,18	0,74	0,758	2,61
0,8	1,86	0,70	0,934	2.35	4,5	2,23	0,77	0,751	2,74
1,0	1,90	0,68	0,885	2,30	5,0	2,26	0,77	0,734	2,76
1,2	1,92	0,68	0,871	2,31	5,5	2,28	0,75	0,708	2,70
1,4	1,94	0,66	0,838	2,25	6,0	2,31	0,70	0,655	2,54
1,6	1,96	0,67	0,834	2,29	6,5	2,39	0,71	0,622	2,62
1,8	1,98	0,68	0,831	2,32	7,0	2,34	0,72	0,654	2,63
2,0	2,02	0,68	0,805	2,34	8,0	2,36	0,72	0,644	2,64
2.5	2,08	0,72	0.803	2,49	9,0	2,34	0,82	0,723	2,98
3.0	2,10	0,72	0.790	2,50	10	2,40	1,0	0,792	3,66

Key: (1). µm.

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Since regarding value x we have $\rho_г x = mN$ (here $\rho_г$ - the mass density of gas), hence we will obtain

$$N = \frac{\rho_г x}{\rho \pi r_0^2 L}.$$

In limit, when aerosol has large sizes in comparison with wavelength of photon λ, we have

$$\sigma_{\text{погл}} = \frac{1}{4} S a,$$

where $S = 2\pi r_0 L$ - surface area of aerosol, a - its coefficient of grayness. In this extreme case we will obtain

$$l = \frac{2\rho r_0}{\rho_г x a}. \quad (6.13)$$

It is natural that the result does not depend on the selected length of cylindrical aerosol.

In other limiting case, utilizing formulas (6.5), (6.7) for absorption cross-section, we obtain

$$l=\frac{\rho}{\rho_r x}\frac{\lambda}{\pi f},\quad r_0\ll\lambda.$$

Uniting formulas so that they would be obtained from the general formula in the appropriate limiting cases, it is possible to record

$$l=\frac{\rho}{\pi x\rho_r f}\left(\lambda+\frac{2\pi f r_0}{a}\right). \qquad (6.14)$$

For carbon black (f=2.5) this formula gives

$$l=\frac{0{,}13\rho}{x\rho_r}\left(\lambda+\frac{16}{a}r_0\right). \qquad (6.15)$$

It is evident that the dependence on a radius of aerosol particle is developed in the very small ratio of its radius to the wavelength of photon.

Thus, relative to emissivity of small aerosol particles, prepared from dielectric opaque material, it is possible to make following conclusion. A strong difference in the radiant flux from the surface of these particles in comparison with the radiant flux from the surface of the massive particles of the same type and at the same temperature can be observed only in the case, when particle sizes are very small in comparison with the wavelength of the emitted photons.

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Let us examine emission of metallic aerosol particles, which have other nature of interaction with electromagnetic wave. As a result of the fact that the conductivity of metal its high, dielectric constant for the electromagnetic waves is great, so that interaction occurs in the thin near-surface layer. We will consider that the depth of penetration of electromagnetic wave inside the metal - value, small in comparison with long wave. Then the electromagnetic wave incident to the surface of metal will be reflected from it with the probability, close to one, and the probability of its absorption will be small. Accordingly, the heated surface of metal will emit substantially less than the blackbody, heated to the same temperature. In this case the low parameter, which ensures this physical picture, is equal to

$$\alpha = \sqrt{\frac{\omega}{8\pi\sigma}}, \quad (6.16)$$

where ω - frequency of electromagnetic wave, σ - conductivity of metal. In particular, for copper at the wavelength 1 μm $\alpha = 0{,}012$, i.e. it is actually small.

For massive sample, whose sizes are great in comparison with wavelength, emitted by surface of metal radiant flux at this frequency it is equal to [56]

$$J_\omega = J_\omega^{(0)}\alpha\left(\ln\frac{1}{2\alpha^2} + 1 - \frac{\pi}{2}\right), \quad (6.17a)$$

where $J_\omega^{(0)}$ - radiant flux at this frequency, emitted by blackbody with the same surface temperature. Since the fundamental value has a relationship/ratio between the sizes of aerosol particle and the depth of penetration, but not with wavelength, formula (6.17a) substantially will not change also in the case, when the sizes of aerosol particle are small in comparison with the wavelength of the emission (but they are great in comparison with the depth of penetration of electromagnetic wave). In particular, in the case of the spherical aerosol particle, whose radius is much wavelength (but more than than the depth of penetration) the radiant flux emitted by it is equal to [56]

$$J_\omega = J_\omega^{(0)} 6\alpha, \quad (6.17b)$$

but in the case of cylindrical aerosol particle [56]

$$J_\omega = J_\omega^{(0)} 8\alpha. \quad (6,17c)$$

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Here $J_\omega^{(0)}$ - radiant flux of blackbody, calculated by the formulas, which relate to the massive sample.

Obtained according to formulas (6.17) values of radiant fluxes are close for copper in region of wavelengths on the order of 1 μm. This to utilize a single expression for the emissivity of particles irrespectively of the shape of particles and the relationship/ratio between the size of particles and the wavelength of emission.

On basis of formula (6.17) we have for emitted radiant flux

$$J_\omega = 0{,}086\, J_\omega^{(0)} \sqrt{\lambda_э/\lambda}, \quad (6.18)$$

where $\lambda_0=1\ \mu m$. λ - length of electromagnetic wave.

Let us conduct now calculations for emitting losses of copper aerosol particles. It is significant that these losses are considerably less than in absolutely black aerosol particles. Utilizing formula (6.18) and performing the integration for the frequencies of the emitted photons, for the power of radiation of aerosol particle we will obtain

$$\mathcal{P}=0{,}18\sqrt{T/T_0}\,\mathcal{P}_0, \quad (6.19)$$

where $\mathcal{P}_0=S\sigma T^4$ (here S - surface area of aerosol particle) - the power, emitted by blackbody at the same temperature T and calculated by the formulas, when particle size is considerably greater the wavelength of photons, $T_0=10^4$ K. As is evident, formula (6.19) gives temperature dependence $T^{1/2}$ for the emitted by particle radiated power. Further, for example, with T=1200 K we have $\mathcal{P}=0{,}062\mathcal{P}_0$, the power of radiation of copper particle is considerably less than particle with the same by temperature and sizes, but having non-machined surface.

Using formulas represented above, we analyze further following phenomenon. One of the versions of ball lightning is considered the glowing cluster, which is formed during the short circuit of massive copper wires (for example, tram) or upon the lightning strike in massive metallic conductors. This glowing cluster falls to the earth, it wheels along it, continuing for a while to glow. Such phenomena make a small contribution to the general statistics of the observations of ball lightning and on their manifestation they differ from usual ball lightning, which moves by air, but not on the ground.

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Therefore it should be isolated such phenomena. It is most probable that after the blast of the copper conductor, that is accompanied by the passage of the current through it and plasma resultant in this case, occurs the formation of copper aerosol particles. During the association in the external field they acquire filamentary structure, and as a result of the high density of material the density of filamentary aerosol particles also is sufficiently great; therefore they are interwoven with each other, forming compact cluster.

Separate filaments are not adhered in presence of uncompensated for charge in cluster, i.e., cluster supports its form. If the thickness of separate filaments in the cluster is more than than 10 µm, then it falls to the earth. Cooling this cluster is caused by both the convective heat exchange of air and by emission of filaments. Further during the estimate of the cooling time of this system we will be restricted to heat losses caused by the emission.

Taking into account only emitting losses, let us rewrite equation of heat balance for twine guide of radius r, in the form

$$c_p\rho\frac{dT}{dt}=-\frac{2}{r_0}j(T),$$

where c_p - heat capacity of conductor, ρ - its mass density, j(T) - radiant flux, emitted by surface of conductor. Since $j(T)\sim T^{9/2}$, the solution of this equation can be represented in the form

$$\left(\frac{T_0}{T}\right)^{7/2} = 1 + \frac{7}{2}\frac{t}{\tau_0}, \quad \tau_0 = \frac{c_p \rho r_0 T_0}{2j(T_0)},$$

here T_0 - temperature at the initial moment of time. The parameter τ_0 characterizes the characteristic cooling time of conductor; this time is proportional to a radius of separate filaments. Table 6.2 depicts the values of this parameter for r_0-10 μm. At the same time Table 6.2 gives the values of probability w of the fact that the optical photon with a wavelength of $\lambda<0.75$ μm is emitted at this temperature.

Values represented in Table 6.2 relate to optically rarefied cluster of aerosols. With the disturbance of this condition the radiation losses decrease. Furthermore, chemical processes on the surface of filaments can change the character of heat withdrawal and it is essential to increase the radiated power in the optical region of the spectrum.

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And finally convective heat withdrawal accelerates cooling conductor. The disregarded factors attest to the fact that obtained data can be used only as the estimate. As it follows from Table 6.2, the glow of the cluster of filamentary aerosols in question is possible in the period of the order of second. This confirms the possibility of the phenomenon in question.

On the basis of filamentary structure of ball lightning (or structure of fractal cluster) let us make estimate, which relates to parameters of body of ball lightning. For the effective radiation yield, created within ball lightning, it is necessary that the optical thickness of body would be limited. We will obtain this estimate. Presenting body in the form of the set of the single particles of radius r_0, we have, that the optical thickness of the layer τ of size l is equal to $\tau = l/(N\sigma)$. Here N - particle density, σ - scattering cross section on the single particle, so that $(N\sigma)^{-1}$ - mean free path of photon. According to formula (6.5) $\sigma \sim r_0^3$, and the particle density can be found from the relationship/ratio

$\rho_{cp} = \frac{4}{3}\pi r_0^3 \rho N$, where ρ_{cp} - average density of body, ρ - material density of body. Hence it follows that the optical thickness of body does not depend on a radius of the entering it particles and can be recorded in the form of formula $\tau = \tau_0 \rho_{cp} l$, where τ_0 is the characteristic only of the material of body. The condition presented requires, in order to $\tau \lesssim 1$. Since for the body of ball lightning $l \sim 10$ cm, $\rho_{cp} \sim 10^{-3}$ $g \cdot cm^{-3}$, the this condition gives for the material of body value $\tau_0 \ll 100$ $cm^2 \cdot g^{-1}$. In particular, for the aerogel of silicon dioxide we have [121] $\tau_0 \sim 10$ $cm^2 \cdot g^{-1}$.

Table 6.?. Characteristic cooling time and the portion of the optical radiation of metallic filaments.

T, K	τ, с$^{(1)}$		w
	(2) для меди	(3) для железа	
1200	2,80	1,30	$1,6\cdot10^{-4}$
1400	—	0,74	$9,1\cdot10^{-4}$
1600	—	0,46	$3,2\cdot10^{-3}$
1800	—	0,31	$7,9\cdot10^{-3}$

Key: (1). s. (2). for copper. (3). for iron.

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S6.3. Chemiluminescence in excited air.

As it follows from carried out analysis, glow of heated surface cannot explain entire diversity of colors, observed in ball lightning. Separate of color can be connected with the specific emitting transitions/junctions of atoms or molecules, which are excited during the chemical processes. Very fact of the excitation of the specific electronic states of atoms or molecules is supplementary energy process in the system and does not affect its power engineering in. However, since this process determines the glow of system, it should be analyzed in more detail.

Let us examine first chemiluminescence, i.e., process, in which chemical energy of gas components is converted into energy of glow of excited molecules or atoms. In this paragraph we analyze the effectiveness of the system, which contains ozone and nitrogen oxides. This system is of interest for a number of reasons. First, ozone and nitrogen oxides are present in excited air. In the second place, this is example of one of the most effective processes of chemiluminescence in air. In the third, which is also important, the parameters of elementary processes taking place in this case are relatively well known (Table 6.3), which makes it possible to carry out reliable analysis.

In example in question radiating molecules NO_2 are formed in the presence of reaction NO with molecules of ozone. Then molecules NO_2 have the capability again to become molecules NO during the appropriate process. Thus, we have the chain/catenary process, in which the molecules of ozone are expended and their chemical energy partially is converted into the photon energy, which appear with the luminescence of the excited molecules NO_2. This is in practice only chain/catenary process with the participation of ozone, where appears emission in the optical region of the spectrum. Further our problem consists of the estimate of the conversion factor of chemical energy of ozone into the energy of optical photons. Since fundamental into the energy of optical photons. Since the basic goal - to obtain representation about the character of the phenomenon being investigated, analysis will carried out only for room temperature of mixture. Table 6.3 gives essential for our analysis parameters of fundamental processes, which correspond to room temperature.

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Taking into account the qualitative character of analysis, we do not give all works, in which these parameters were measured, but we give characteristic. The parameters table 6.3 will be assumed as the basis of the conducted analysis.

Probability of converting chemical energy, i.e., probability that resolution of one molecule of ozone will lead to onset of optical photon, it is composed of three factors:

$$w = xyz, \quad (6.20)$$

here x - probability that molecule of ozone will be destroyed in reaction with molecule NO; y - probability that as a result of this reaction it is formed excited molecule NO_2; z - probability that decay of excited molecule NO_2 will be accompanied by emission of photon.

Table 6.3. Rate constants of processes with thermal energy in the mixture, which contains nitrogen oxides and ozone.

(a) № процесса	(b) Процесс	(c) Константа скорости1), см^3·с$^{-1}$	(d) Литература
1	$NO + O_3 \rightarrow NO_2 + O_2$	$1,9 \cdot 10^{-14}$	[69—71]
2	$NO + O_3 \rightarrow NO_2(^2B_2) + O_2$	10^{-15}	[69, 70, 72]
3	$NO_2(^2B_2) \rightarrow NO_2(^2A_1) + \hbar\omega$ ($\lambda = 0,52 \div 0,81$ мкм) (f)	$\tau_1 = 3 \cdot 10^{-6}$ с; (e) $\tau_2 = 28 \cdot 10^{-6}$ с; ⓔ $\tau_3 = 75 \cdot 10^{-6}$ с ⓔ	[73]
4	$NO_2 + O_3 \rightarrow NO_3 + O_2$	$3,2 \cdot 10^{-17}$	[69, 70, 74]
5	$NO + NO_3 \rightarrow 2NO_2$	$1,9 \cdot 10^{-11}$	[75]
6	$NO_3 + NO_2 \rightarrow NO_2 + NO + O_2$	$4,0 \cdot 10^{-16}$	[75]
7	$2NO + O_2 \rightarrow 2NO_2$	$2 \cdot 10^{-38}$ (g) см^6·с$^{-1}$	[76]
8	$2NO_3 \rightarrow 2NO_2 + O_2$	$2,3 \cdot 10^{-6}$	[75]
9	$NO_2 + NO_3 \rightleftarrows N_2O_5$	$K_{равн} = 4,3 \cdot 10^{10}$ см$^{-3}$	[75]
10	$NO_2(^2B_2) + N_2 \rightarrow NO_2(^2A_1) + N_2$	$k\tau = 1,2 \cdot 10^{-15}$ см^3	[77, 78]

Key: (a). No of process. (b). Process. (c). Rate constant, $cm^3 \cdot s^{-1}$. (d). Literature. (e). s. (f). µm. (g). $cm^6 \cdot s^{-1}$.

FOOTNOTE 1). When is given another parameter of the rate of the process in question, its dimensionality is indicated. ENDFOOTNOTE.

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Let us note that with the luminescence of the excited molecule NO_2 appears the emission with the wavelength in the band 0.52-0.81 µm.

Although the tail of this band enters the infrared region, we will conditionally consider the appearing photon optical. Further we analyze each of the factors of formula (5.20).

As it follows from totality of processes, represented in Table 6.3, molecules of ozone perish in reactions with NO and NO_2. Probability that this molecule is broken down in the reaction with molecule NO, is equal to

$$x=\frac{k_1[\mathrm{NO}]}{k_1[\mathrm{NO}]+k_4[\mathrm{NO_2}]},$$

where the indices in the reaction rate constants correspond to the number of process in Table 6.3. Let us record the equation of balance at the density of molecules NO:

$$\frac{d[\mathrm{NO}]}{dt}=-k_1[\mathrm{NO}][\mathrm{O_3}]-k_5[\mathrm{NO}][\mathrm{NO_3}]+ \\ +k_6[\mathrm{NO_2}][\mathrm{NO_3}].$$

In this case we disregarded process of 7, which for the phenomenon in question does not play role. It follows from the quasi-steady-state of process that $\frac{d[\mathrm{NO}]}{dt}=0,$

$$\frac{[\mathrm{NO_2}]}{[\mathrm{NO}]}=\frac{k_1[\mathrm{O_3}]}{k_6[\mathrm{NO_3}]}+\frac{k_5}{k_6}.$$

Substituting this relationship/ratio into the expression for x and using the specific values of the rate constants of processes in accordance with the data of Table 6.3, we will obtain

$$x=\left(1+\frac{k_4[NO_2]}{k_1[NO]}\right)^{-1}=\left(1+\frac{k_4[O_3]}{k_6[NO_3]}+\frac{k_4k_5}{k_1k_6}\right)^{-1}=$$

$$=\left(1+0{,}08\frac{[O_3]}{[NO_3]}+80\right)^{-1}<\frac{1}{80}.$$

Probability that reaction of molecule of ozone with molecule NO will lead to formation of electronically excited molecule $NO_2(^2B_2)$ with thermal energy of collision composes approximately 7%.

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Let us note that the reaction of oscillatorily excited ozone O_3 (001) with probability 8% leads to the formation of electronically excited molecule NO_2 [79], i.e., the quantum yield of the excited molecule NO_2 in the presence of reaction NO and O_3 in principle does not depend on oscillatory molecular excitation of ozone. Thus, accepting y=8%, we have $xy<10^{-3}$.

Question about accuracy of value of probability of quenching of excited molecule NO_2 during collision with molecule of nitrogen, which is given in table 6.3, remains open. Relating to this numeral as to the correct estimate and considering that the quenching of excitation NO_2 in air occurs due to nitrogen, for the probability of emitting this molecule, we will obtain the value

$$z=4\cdot10^{-5}.$$

As is evident, quenching leads to most essential losses in emission. It is not difficult to understand this result - the emitting lifetime of the excited molecule NO_2 is relatively great and according to Tables 6.3 comprises $3 \cdot 10^{-5}$ and $7.5 \cdot 10^{-5}$ (decay time of quantum caused by the lifetimes of the excited molecule τ_1 and τ_2). At the atmospheric pressure the characteristic time of the "damping" collisions with the molecules of air is much less. This determines so low a value of the probability of fluorescence for the excited molecule. Apparently, this is general law - the probability of luminescence for any long-lived excited molecule is small at the atmospheric pressure.

Combining obtained numerals, for probability of transformation of molecule of ozone into quantum of radiation of excited molecule NO_2 we obtain

$$w < 4 \cdot 10^{-8}.$$

The smallness of this value is explained by the smallness of all composite/compound factors. Most essential among them - quenching in the collisions in atmospheric air.

Carried out analysis convinces us, that probability of transformation of chemical energy into energy of glow in atmospheric air in the presence of chemical reaction is very small and this smallness first of all relates to long-lived states. Taking into account that the example examined is one of the most effective cases of chemionization in excited air, on the basis of the carried out analysis we must forego the chemiluminescence as the process, which leads to the emission in ball lightning, and search for other mechanisms of its creation.

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S6.4. Emission of the excited atomic particles in hot air.

Obtained result, connected with high probability of quenching of molecule in atmospheric air, makes it possible to glance at this problem in another way. If the probability of the quenching of the excited molecule or atom is close to one, then in the gas equilibrium (Boltzmann) distribution for the excited particles is established. This means that the number of such particles does not depend on the method of their creation, but it is determined by the local temperature of gas.

It is checked validity of this confirmation for short-lived excited states of atomic particles. Let us calculate the probability of luminescence of the resonance excited atoms of sodium and potassium, which possess short emitting lifetime. Table 6.4 gives the rate constants of quenching for the resonance excited atoms of sodium and potassium the molecules of nitrogen and oxygen in the region 400-2200 K [32, 80]. In the experimentally investigated temperature range these values in limits of accuracy of experiment and coincidence of the results of different measurements virtually do not depend on temperature.

For probability of luminescence of excited atom taking into account obtained expressions we have

$$z = \{[k(N_2)[N_2] + k(O_2)[O_2]]\tau + 1\}^{-1}, \qquad (6.21)$$

where $k(N_2)$ and $k(O_2)$ - rate constants of quenching during collision with molecule of nitrogen and oxygen respectively, τ - emitting lifetime, $[N_2]$ and $[O_2]$ - molecule densities of nitrogen and oxygen.

Table 6.4. The resonance excitation of the atoms of sodium and potassium by the molecules of nitrogen and oxygen.

(1) Возбужденный атом	(2) τ, нс	(3) k, 10^{-10} см$^{3}\cdot$с$^{-1}$	
		N_2	O_2
Na(3^2P)	16	7,0±1,5	12±1
K(4^2P)	25	5,0±1,4	14±3

Key: (1). Excited atom. (2). ns. (3). ... $cm^3 \cdot s^{-1}$.

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Utilizing this formula and data of table 6.4, for the probability of the luminescence of the resonance excited atom of sodium and potassium in atmospheric air at a temperature of 2000 K we will obtain

$$z(\mathrm{Na}) = 0{,}02, \quad z(\mathrm{K}) = 0{,}01,$$

i.e. in this case the probability of the luminescence of photon $z \ll 1$.

As is evident, in examples of resonance excited atoms of sodium and potassium examined probability of luminescence of excited atoms in atmospheric air is small [1]).

[1]). FOOTNOTE [1]). Let us note that the difference between the quenching in the examples with NO_2 and in the case of the atoms of sodium and potassium is caused by the different emitting lifetimes, which differ to more than three orders. As far as the very process of quenching is concerned, the rate constant of the quenching of the excited molecule

NO_2 according to data of table 6.3 is $(2-4)\cdot 10^{-11}$ $cm^3\cdot s^{-1}$, which by an order is lower than the rate constants of the quenching of the atoms of sodium and potassium (see Table 6.4). ENDFOOTNOTE.

Therefore one should refuse from the selective methods of designing of excited states. From the obtained result it follows, for example, that if in atmospheric air at a temperature of 300 K, into which is introduced the admixture/impurity of sodium, sodium atoms are converted into the resonance excited state, then the probability of the transformation of this excitation into the emission composes 0.3%. Remaining excitation will be extinguished as a result of collision [illegible]e molecules of air and will leave into the heat.

Conclusion about presence of thermodynamic equilibrium for excited atoms or molecules in equilibrium air makes it possible to restrict number of atoms and molecules, which can create emission of ball lightning. Actually, the radiating excited states of atoms and molecules must satisfy the following conditions. First, this must be the short-lived excited states, since the less the emitting lifetime, the higher the intensity of the emission of molecules. In the second place, these excited states must be the lower excited states of atoms or molecules, since their number is determined by the local temperature of air, which approximately by an order lower than excitation energy of lower states. And, third, the photons, emitted with the luminescence of the excited states in question, must answer the optical part of the spectrum.

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Limited number of excited atoms and molecules satisfies all these conditions. They all are given on the diagram, represented in Fig. 6.1, where all possible versions are given as the radiating atoms and the molecules in ball lightning.

Examined mechanism of creation of emission in equilibrium atmospheric air with high local temperature is analogous to process of glow of flame (into which is introduced additive) or to emission of illumination means in pyrotechnics. Therefore from the point of view of the glow of ball lightning it is interesting to analyze the illuminating compositions, where optimum conditions for the transformation of chemical energy into the radiant energy are reached.

Let us examine composition of yellow light. This composition includes following chemical constituents [81]: Mg - 30%; KNO_3 - 37%; $Na_2C_2O_4$ - 30%; resin - 3%.

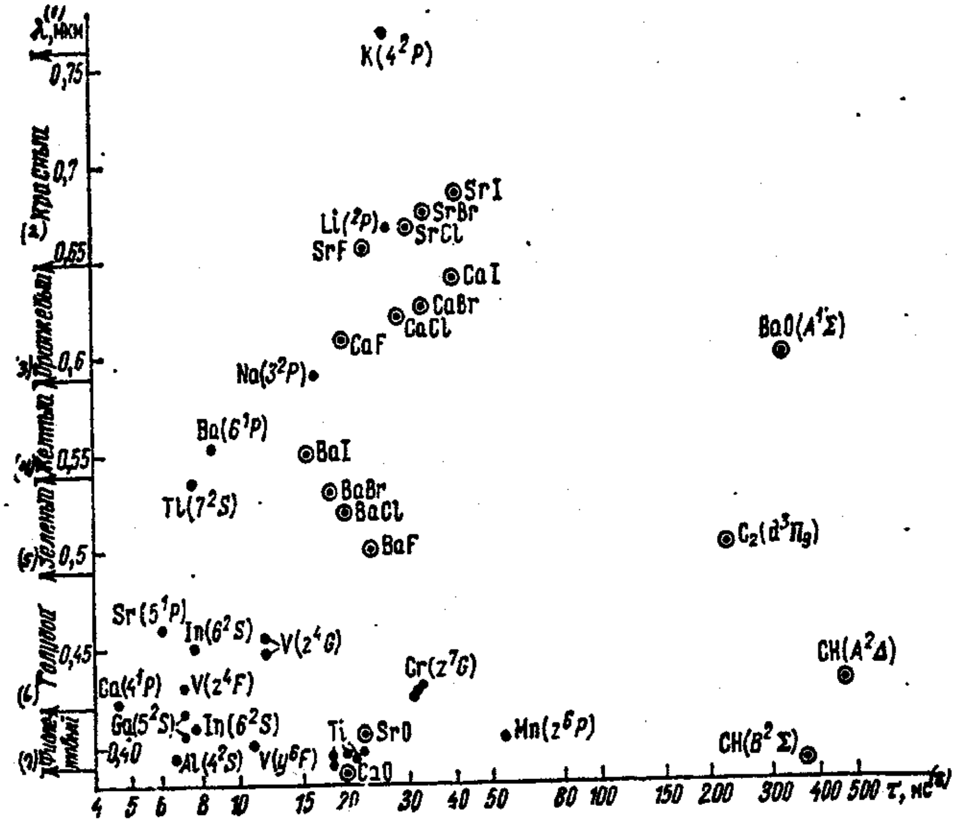

Fig. 6.1. Diagram: wavelength - emitting lifetime for transitions/junctions into ground state for short-lived excited states of atoms and molecules, which radiate in optical region of the spectrum. The position of transition between the fundamental vibrational states of electron transitions is indicated for the molecules.

Key: (1). μm. (2). Red. (3). Orange. (4). Yellow. (5). Green. (6). Azure. (7). Violet. (8). ns.

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The specific energy reserve of this composition of 6 kJrdg^{-1}, maximum combustion temperature 2500-3000 K, and luminous efficiency 8 $lm \cdot W^{-1}$, therefore, conversion factor of chemical energy into the energy of glow by yellow are equal to approximately 1.5%. In this case the glow is created by the excited atoms of sodium and by hot specks.

§6.5. Propagation of the wave of glow.

Let us connect of processes, which lead to glow of ball lightning. As a result of chemical processes the hot zones, which create emission, appear. If we consider that the active material of ball lightning has fractal structure, then the wave of chemical reaction is propagated along the separate branches of cluster. The expanding reaction products create the hot glowing zone; in this case the color of ball lightning is determined by the emission of admixtures/impurities, which are located in the hot zone.

In order to obtain locked physical picture of process of glow, it is necessary to estimate parameters of processes, which determine glow, and to compare them with observed parameters. This analysis will give to us more detailed information about the system being investigated.

It is obvious that hot region cools due to thermal conductivity - the less size of hot region, the greater gradients of temperatures and the rather cooling occurs. Since the emitting losses of hot region strongly do not depend on its sizes, it becomes clear that the less the size of hot region, the lower the luminous efficiency of process - relation of the power of radiation and total power, isolated in the presence of the chemical reaction. The luminous efficiency of process is connected thus with the sizes of the glowing region. But since the values of the luminous efficiency of ball lightning are known from observational data, it is possible to obtain information about the sizes of hot regions in ball lightning.

Let us conduct estimates for model mixture - hot air with additive of sodium. This mixture simulates the emission of ball lightning of yellow. Sodium as one of the propagated elements in nature performs the role of the radiating additive, moreover in ball lightning it glows in the mixture with the reaction products of active material, but.not air as in case examined here.

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The absorption coefficient for the resonance radiation of sodium in the center of line is equal to [82]

$$k_0 = \frac{g_{\text{в}}}{g_0} \frac{\lambda^2}{4} \frac{[\mathrm{Na}]}{\{[\mathrm{N}_2]\, k_{\text{уш}}(\mathrm{N}_2) + [\mathrm{O}_2]\, k_{\text{уш}}(\mathrm{O}_2)\}}, \qquad (6.22)$$

where $g_{\text{в}}$ and g_0 - statistical weights of the excited and ground states, λ - the wavelength of transition/junction, [X] - the density of atoms or molecules of the corresponding component, $k_{\text{уш}}(\mathrm{X})$ - rate constant for the broadening of the resonance line of sodium due to the collision with the molecules X. Accordingly $k_{\text{уш}}(\mathrm{N}_2) = 3{,}6 \cdot 10^{-9}$ $\mathrm{cm}^3 \cdot \mathrm{s}^{-1}$. Considering that the rate constants of the line broadening of sodium due to the different components are located in the same relationship/ratio, that also the rate constant of quenching, we obtain $k_{ym}(O_2) = 6{,}1 \times 10^{-9}$ cm³·s⁻¹. Hence we find for the coefficients of absorption of resonance lines (in cm⁻¹) in the center of the line

$$k_0(3^2S_{1/2} \to 3^2P_{3/2}) = 8{,}5 \cdot 10^6\ c^{(1)}, \qquad (6.23)$$
$$k_0(3^2S_{1/2} \to 3^2P_{1/2}) = 4{,}2 \cdot 10^6\ c^{(1)},$$

Key: (1). s.

here c - sodium concentration, i.e., the ratio of the number of sodium atoms to the number of molecules of air.

On basis c. obtained values let us make following estimate, which will make it possible to obtain representation about parameters of glowing region of ball lightning. Let the glowing region occupy layer near the sphere with the radius, equal to a radius of average ball lightning (14 cm), and give the same luminous density, as average ball lightning (1400 lm). Let us explain, what concentrations of sodium c and thickness of radiation layer l at an assigned temperature T of layer are capable of ensuring the glow of average ball lightning of the yellow (radiant flux it is 10^{-3} W·cm⁻²). For the radiant flux in each resonance line of sodium from the side of radiation layer [31] we have

$$J = \frac{0{,}38\,[\mathrm{Na}^*]\,\hbar\omega l^{1/2}}{\tau k_0^{1/2}}, \qquad (6.24)$$

where [Na*] - density of excited atoms, which is connected with Boltzmann's formula with atom density in the ground state, $\hbar\omega$ - energy of the emitted quantum, τ - emitting lifetime of excited state. According to formulas (6.23), (6.24) $j \sim (lc)^{1/2}$.

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Fig. 6.2 depicts the values of parameter lc in the dependence on the temperature of radiation layer. It follows from the figure that for the reasonable concentrations of sodium ($c \geqslant 10^{-4}$) the value of the thickness of radiation layer relatively little precisely in the temperature range ($T \geqslant 2000$ K) examined. At lower temperatures this value becomes sizable, and this means that in the real case, when instead of radiation layer is a set of regions with the locally high temperature, it is difficult to ensure the observed luminous density of system.

Let us conduct one additional estimate, which will make it possible to estimate size of elementary region of ball lightning with high temperature. We will consider that in a certain small element of volume occurred the chemical reaction, which led to the formation of bubble with the high temperature. This bubble contains reaction products with the admixture/impurity of sodium and cools due to the thermal conductivity, transmitting its energy to surrounding air. Considering that bubble - sphere with a radius of r, let us find its luminous efficiency - the ratio of the radiated power on the atomic lines of sodium to the dissipated power of energy due to the thermal conductivity [1).

FOOTNOTE 1). It is assumed that beyond the limits of bubble sodium is located in the bound state and therefore does not absorb resonance radiation. ENDFOOTNOTE.

Heat flux from bubble is equal to

$$j_{\text{тепл}} = -\varkappa \frac{dT}{dr} = \frac{\varkappa T}{(\alpha + 1) r}, \qquad (6.25)$$

where κ - coefficient of thermal conductivity of surrounding air

$\left(\alpha = \frac{d \ln \varkappa}{d \ln T}\right)$, T - temperature of bubble.

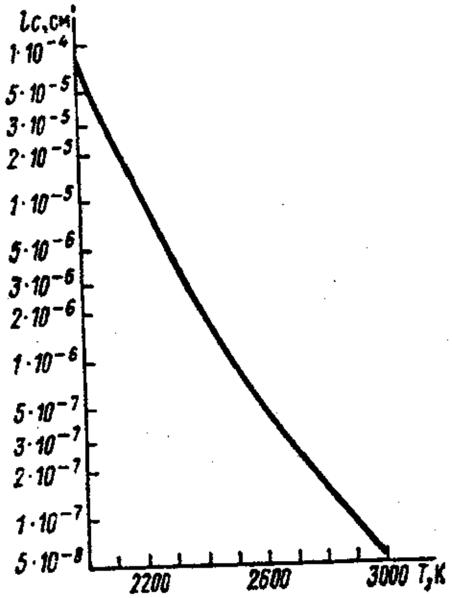

Fig. 6.2. Dependence of parameter $l_c(T)$ in the case, when radius of sphere and emitted by it luminous flux coincide with average characteristics of ball lightning.

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Let us note that convective heat transfer is absent for $r \ll 1$ cm. The luminous flux for each of the atomic lines of sodium is equal to [31]

$$j_{изл} = \frac{0,32\,[\mathrm{Na}^*]\,\hbar\omega}{\tau}\sqrt{\frac{r}{k_0}} \qquad (6.26)$$

(here designation those as in formula (6.24)). This expression is correct for the closed emission in the center of line $rk_0 \gg 1$. Hence for the luminous efficiency we find

$$\eta = \frac{j_{изл}}{j_{тепл}} = \gamma(T)\, r^{3/2} c^{1/2}. \qquad (6.27)$$

Dependence $\gamma(T)$ is represented in Fig. 6.3.

Radiating hot region of gas is formed as a result of chemical reaction, which occurs in zone of contact of reacting particles. With is this more probable that the hot region takes the form of the jet, which contains the heated reaction products with the admixture/impurity of the radiating atoms. Taking into account this, let us conduct calculations for the luminous efficiency of heated tube domain. In this case in formula (6.26) for the radiant flux should be replaced numerical coefficient of 0.32 by 0.39, and formula (6.25) for the heat flux from the cylindrical heated region will take the form

$$j_{\text{тепл}} = \frac{T\varkappa(T)}{(\alpha+1)\,r\ln(l/r)}. \quad (6.28)$$

Here designation - the same as in formula (6.26), l - length of the heated cylinder. In the subsequent calculations for the certainty we will set $l=50$, i.e., $\ln(l/r)=4$.

For luminous efficiency we will obtain formula

$$\eta = A(T)\,r^{3/2}c^{1/2}. \quad (6.29)$$

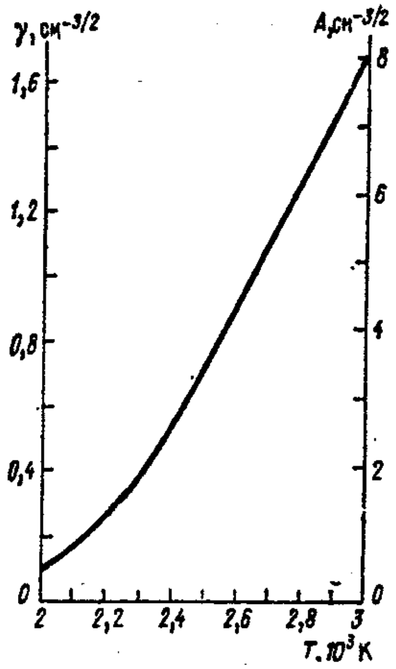

Fig. 6.3. Dependence of parameter γ in formula (6.27) and parameter A in formula (6.29) on temperature T of hot region at its assigned geometry.

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Comparing formulas (6.27) and (6.29), and also expression for the thermal and luminous fluxes in the spherical and cylindrical cases, we find that

$$\frac{A}{\gamma} = \frac{0{,}39}{0{,}32} \ln \frac{l}{r} \approx 5.$$

It is natural that in the cylindrical case the higher luminous efficiency is provided.

For estimate of size of glowing region it is necessary to know, for what concentrations of glowing admixture/impurity it is possible actually to design. For this purpose let us give the values of the abundance of fundamental elements in the surface layer of the earth's crust.

(1) Элемент	O	Si	Al	Fe	Na	K	Ca	Mg	Ti	Ba	Mn	Sr
(2) Содержание, $\text{мг}\cdot\text{г}^{-1}$	480	310	85	35	28	27	25	14	3,6	0,7	0,6	0,35

Key: (1). Element. (2). Content, $mg\cdot g^{-1}$.

Being based on these data, it is possible to consider that for sodium $c\sim10^{-2}$, and since for average ball lightning of yellow $\eta\sim10^{-3}$, we obtain, that in temperature range in question size of hot zone comprises fractions of millimeter. Let us note that the size of hot region exceeds the characteristic distance between the adjacent branches of cluster [1]).

FOOTNOTE [1]). The distance between the adjacent branches of cluster in order of magnitude comprises $l\sim\sqrt{\rho/\bar{\rho}}\,r_0$, where ρ - material density of cluster $\bar{\rho}$ - its average density in the space. Since $l\sim100\ r_0$, and $r_0\sim(0{,}1\div1)$ μm, we have $l\sim(10\div100)$ μm. ENDFOOTNOTE.

On basis of totality of carried out estimates let us construct model of active material of ball lightning. This is - the cluster, which includes the solid particles of both the fuel, and the oxidizer. If we consider that specific energy reserve in it by the same as in the illuminating composition (6 $kJ\cdot g^{-1}$), we will obtain that power engineering of average ball lightning is provided by 3 g of active material. The average mass density of active material in average ball lightning (radius of 14 cm) composes order $3 \cdot 10^{-4}$ $g \cdot cm^{-3}$, i.e., the content of active material in air (0.2-0.3) $g \cdot g^{-1}$.

Glow of cluster occurs as follows. At a certain moment of time the active material enters into the chemical reaction, which affects the separate zones of cluster with the sizes of the order of fraction of millimeter and occurs sufficiently rapidly. The formable hot jets, which include reaction products together with the glowing admixtures/impurities, possess the temperature in the interval of 2000-3000 K.

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Higher temperatures cannot arise as a result of chemical processes, lower will not ensure the observed glow of system. The glow of the heated jets determines the emission of ball lightning.

Let us examine character of propagation of wave of chemical reaction and wave of glow in active material of ball lightning. Phenomenologically these processes can be presented as follows. A certain induction period precedes chemical reaction with large heat-liberation value. After inflammation at the fixed point the wave of combustion is propagated along the active material along the appropriate filaments. Simultaneously reaction occurs at many points of the body of ball lightning. In view of the high temperature of reaction products the chemical process is accompanied by glow, and since simultaneously it occurs in the different parts of ball lightning, this causes the impression of the glow of its entire mass. After reaching the fixed point of body, reaction can be discontinued and at the same time arise at its other points. This creates the transiency of glow.

Let us fulfill numerical estimates, simulating active material with filamentary structure. Let a radius of filament r_0, substance density in it ρ. The reaction products are expanded after reaction, occupying tube domain of radius R_0, the density of reaction products $\rho_{п}$. Since the pressure of reaction products counterbalances air pressure, we have

$$\left(\frac{R_0}{r_0}\right)^2 = \frac{\rho}{\rho_{п}}.$$

Considering that a density of reaction products of the order of air density at temperature (2000-3000) K, we have $R_0/r_0 \sim 100$.

Wave of combustion, which appears in the presence of reaction of active material, is propagated in essence in gas phase due to expansion of reaction products, but wave propagation velocity of combustion is limited with rate of combustion of solid. Let v_0 - wave propagation velocity of combustion on the solid. Then the wave propagation velocity of reaction along the filament comprises

$$v = \frac{R_0}{r_0} v_0 \sim 100\, v_0.$$

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Simulating active material of ball lightning we examine by illuminating composition, we will use fact that wave propagation velocity of combustion comprises order 1 $cm \cdot s^{-1}$ [81]. The wave propagation velocity of chemical reaction and wave of glow in the case in question will be $v \sim 100\ cm \cdot s^{-1}$.

As a result of propagation of wave of chemical reaction along filament of active material heated gas cylinder (it can contain inside and solid particles) appears. This cylinder [1]) glows due to the high temperature and cools under the action of the thermal conductivity of gas.

FOOTNOTE [1]). In reality these are not cylinder, but the cone, which decomposes at the wide end. ENDFOOTNOTE.

The reference length of the cylinder

$$l \sim v\tau,$$

where τ - cooling time:

$$\tau \sim \frac{Q\rho}{j} \frac{\pi r_0^2}{2\pi R_0},$$

here j - heat flux, determined by formula (6.28).

Utilizing parameters of illuminating composition (specific energy reserve $Q=6$ kJ$\cdot$g^{-1}, density of active material $\rho=2$ g$\cdot$cm^{-3}), at $r_0=1$ μm and $T=3000$ K we have $\tau \sim 10^{-3}$ s, in this case $\tau \sim r_0^2$. For these parameters $R_0 \sim 0.01$ cm, $l \sim 0.1$ cm.

Let us determine under given conditions number of simultaneously glowing regions in average ball lightning. The total power of heat release in it on the order of 2 kW, whereas the combustion of separate filament leads to the power of heat release $p \sim Q\rho\pi r_0^2 v \sim 0{,}04$ W. The relation of these values gives the average number of glowing regions: $n \sim 5\cdot10^4$. In this case each glowing cylinder has a surface area $s = 2\pi r_0 l \sim 6\cdot10^{-3}$ cm^2, i.e., the total area of glow $S \sim 300$ cm^2, which is approximately by an order less than the surface area average ball lightning: $S = 4\pi R_0^2 \approx 2500$ cm^2. This means that the emission of each region freely departs beyond the limits of system, without falling into other glowing regions, i.e., not the surface, but volumetric emission of ball lightning occurs.

Let us conduct one additional estimate in order to understand, what role in emission of glowing regions they can play located there aerosol particles.

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We will consider that the size of aerosol particles as small ($r_0 \ll 1$ μm), and we will use formula (6.8) for the power of radiation of single aerosol particle. We will obtain that the total power of the emission of aerosol particles, which are located in the hot region, is proportional to the total space, occupied by aerosol particles, and does not depend on their according to the sizes. In particular, after using data of table 6.1 for the specks of carbon black $(f_{c\phi} = 0,9 \pm 0,1)$ and considering that their content in hot regions on the order of 0.1 g on 1 g of air, we obtain, that during the temperature of the hot regions T=2500 K and estimates for their parameters obtained earlier the total power of emission due to the aerosol particles will comprise order 200 W, which is approximately by an order lower than the total scattered power of ball lightning. In this case in the optical part of the spectrum is emitted by approximately 8 W, and the luminous flux of this source of light - order 2000 lm, i.e., the order of the luminous flux, emitted by average ball lightning.

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Chapter 7.

PHENOMENA OF NATURE, ALLIED TO BALL LIGHTNING.

S7.1. The electrical machine of the Earth's atmosphere.

Analysis carried out above convinces us, that ball lightning is complicated phenomenon of nature, whose understanding requires multiplan investigations. Comprehensive investigations are necessary for the study and other phenomena of nature. Special interest from the point of view of ball lightning for us present electrical and other phenomena in the atmosphere, including lightning and St. Elmo's fire, waters-spout, the volcanic eruptions, aurorae polares.

Interest in these phenomena is caused by following reasons. First, these phenomena on some their manifestations remind of ball lightning. For example, aurora polaris, as ball lightning, is accompanied by glow, and St. Elmo's fire frequently are accepted as ball lightning. In the second place, the part of these phenomena is frequently accompanied by the appearance of ball lightning. Thus, with the volcanic eruptions and during the propagation of waters-spout sometimes are observed ball lightnings. And, thirdly, is a purely systematic interest in these phenomena, which are characterized by the spontaneous character of the onset. In each case the phenomenon of nature in question is the totality of natural processes, also, in each case the possibility of its description and, consequently, also forecast, depends on the degree of its experimental investigation. The comprehension of the results of measurements makes it possible to construct the theoretical models, which describe the phenomena in question, the elaboration of this description depending on the possibilities of experiment itself.

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Difficulties of experimental investigation of phenomena in question are caused by spontaneous character of their onset. Therefore problem substantially is simplified, if there is a possibility of the laboratory simulation of phenomenon itself or its separate sides. With this possibility laboratory investigations make it possible to obtain responses to the presented questions and thus to conduct detailed research of phenomenon in that degree, to which laboratory model answers natural. Certainly, the depth of understanding phenomenon in this case depends on the perfection of utilized experimental techniques, and on the existing representations about those taking place in this case processes. The detailed investigation of phenomenon substantially hinders in the absence of the laboratory model of entire phenomenon or its separate sides.

Among atmospheric phenomena, allied to ball lightning, should be first of all isolated electrical phenomena in the atmosphere. The onset of ball lightning is obliged to electrical processes in the atmosphere and their detailed understanding would contribute to the explanation of the character of the birth of ball lightning. Electrical phenomena in the atmosphere are diverse. Let us further examine only part of them - the overall diagram of the work of the electrical machine of the Earth, and also thunderstorm electricity and St. Elmo's fire.

Our Earth is continuously charged negatively, so that its potential as electrified body comprises [85, 129] about 300 kV and current, which is 1400-1800 A, continuously leaks off to it. This process of the continuous recharging of the Earth is determined by thunderstorm processes in the atmosphere. Assuming that the average/mean charge, transferred by separate lightning, is equal to 25 C, [85, 130, 134], we will obtain that for the realization of the observed current of recharging it is necessary that into the Earth would second-by-second strike approximately 60 lightning bolts, and every day - approximately 5 mln. In this case should be noted a small energy state of the process of the recharging of the Earth. Considering that the average/mean electric potential of cloud is 30 MV, we find that the charging of the Earth answers the electrical power of order $5 \cdot 10^7$ kW. Since the electric potential of the Earth is 300 kV, the process of discharging the Earth due to the current, transferred by atmospheric ions, is $5 \cdot 10^5$ kW.

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For the comparison let us point out that the average power, consumed by man, exceeds $1 \cdot 10^{10}$ kW, the power of the solar radiation, which falls in the atmosphere of the Earth, is $1.7 \cdot 10^{13}$ kW, and the power of infrared radiation, emitted by the Earth's atmosphere into both sides, is equal to $2.7 \cdot 10^{13}$ to kW. As is evident, the capacity of the electrical machine of the Earth substantially less than the power of other natural processes is compared with the power of contemporary atomic power plants.

As is evident, understanding fundamental processes, which lead to formation of charged particles in the atmosphere and realization of recharging of Earth [131], is the main question in investigation of work of electrical machine of Earth. It is considered acknowledged that the charged particles in the atmosphere, which create current to the surface of the Earth, are formed under the action of cosmic rays - the fast particles, which arrive from the direction of the Sun and stars. Maximum ionization, for example, according to measurements [86], occurs at the heights of 11-15 km and composes 35 $cm^{3} \cdot m^{-1}$, total ionization in the column of air is equal to $4.5 \cdot 10^{7}$ $cm^{-2} \cdot s^{-1}$. If we charges formable in this case divide and to release to the earth only the charges of one sign, then the current of recharging will compose $4 \cdot 10^{7}$ A, which to four orders exceeds real current in the atmosphere. Thus, ionization by cosmic rays is sufficient for the realization of the electrical recharging of the Earth.

Subsequent process is connected with separation of charges in the atmosphere. It is clear that in the separation of charge participate the aerosols - microscopic specks or droplets. If the coefficients of diffusion of positive and negative ions are distinguished, then more movable ions with the larger probability adhere to the aerosol and thus they determine the sign of its charge. For example, according to measurements [63] for air with the water vapors the coefficient of diffusion of positive ions (led to standard conditions) is equal to $0.029\ cm^2 \cdot s^{-1}$, and for negative ions $0.036\ cm^2 s^{-1}$. This means that the aerosols will be charged negatively, moreover according to the theory of Fux [52] average/mean charge is proportional to a radius of aerosol. For the data of the parameters and room temperature the average charge of the aerosol of a radius of 1 μm comprises approximately 6e (see formula (5.17)).

Presence of charged aerosols in the atmosphere makes it possible to present circuit of separation of charge in the atmosphere and onset of current of recharging of Earth. The atmosphere contains the charged aerosols, and also positively and negatively charged ions.

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Aerosols under the action of the gravitational field of the Earth have the supplementary rate, directed toward the Earth. This creates the separation of charges in the atmosphere.

Circuit of water in the atmosphere plays important role in process of separation of charges in the atmosphere. On the evaporation of water is expended the power $4 \cdot 10^{13}$ kW, and it is not difficult to visualize that to this powerful heat engine of the Earth is connected the low-power electrical machine, which requires the expenditures of power $5 \cdot 10^7$ kW, which six orders is less. But in this case it can seem that they affect the transfer of charge and other processes, not noticeable against the background of the powerful process of the transfer of water in the atmosphere.

Process of separation of charges in the atmosphere is realized in clouds. This process is well studied and consists of the following (for example, see [87-89, 131, 132]). Water vapors rise in the atmosphere, and at the height of several kilometers, where the temperature is low, they are condensed, forming the aerosols of small sizes. These aerosols - drop in the course of time increase in the sizes and are charged negatively. After achieving sizes of several microns, these drops fall down under the action of gravitational force. As a result appears the charging of cloud - on top positive, from below - negative charge and heavier aerosols prove to be from below. Thus, are created the clouds, whose typical size composes several kilometers, and the divided in them charge composes several ten coulomb. The potential of the lower negatively charged zone of cloud relative to the Earth composes hundreds of millions of volts. Discharging cloud to the earth as a result of lightning stroke is accompanied by the transfer of electric charge to the earth. As a result of this process the Earth is charged negatively.

Thus, Earth is charged negatively as a result of acting thunderstorms. Approximately 10-20% of thunderstorms bear to the earth positive charge, 80-90% - negative [88, 135]. As is evident, the process of the charging of the Earth is determined by the process of the separation of charges in the cloud, which, in turn, accompanies the process of the transfer of water in the atmosphere. It is checked the possibility of the transfer of charge with the rotation of water in the atmosphere. Yearly due to the evaporation through the atmosphere are passed $4 \cdot 10^{14}$ t or by 13 mln. t of water per second. For the realization of the observed current of charging it is necessary that the transfer of charge would be approximately $1.4 \cdot 10^{-10}$ C on 1 g of water.

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The drop located in the cloud with a radius of 2 μm bears on itself the average/mean charge 20e [88], which corresponds to the specific charge 10^{-7} $\mathrm{Kl} \cdot \mathrm{g}^{-1}$ transferred; drop with a radius of 5 μm bears on itself average/mean charge 50 e [88], which answers the specific charge $3 \cdot 10^{-8}$ $\mathrm{Kl} \cdot \mathrm{g}^{-1}$ transferred. Hence it is apparent that the clouds, formed during the transfer of water in the atmosphere, completely can ensure the work of the electrical machine of the Earth, which ensures the electrical charging of the Earth.

Thus, we have following picture of work of electrical machine of Earth. The electrical processes, which lead to the charging of the Earth, are side reactions with the work of the heat engine of the Earth, connected with the evaporation of water and their movement in the atmosphere. At a height of several kilometers water vapors are condensed into the droplets of water - aerosols, which form clouds. These aerosols are charged predominantly negatively due to the different mobility of positive and negative ions in the atmosphere. In this case very positive and negative ions of the atmosphere, which lead to the charging of aerosol-drops, are formed under the action of cosmic rays. The negatively charged drop-aerosols fall down under the action of the gravitational field of the Earth. As a result the lower part of the cloud proves to be under the high potential. Being discharged to the earth under the action of the electrical discharge in the form of lightning, the lower part of the cloud transmits the part of its negative charge to the Earth and it charges it thus. The reverse process of discharging the Earth is realized due to the currents in the atmosphere. In this case average/mean electric intensity on the surface of the Earth is [84, 129] 130 $V \cdot m^{-1}$, average current density above the dry land $2.4 \cdot 10^{-12}$ $A \cdot m^{-2}$, and above the ocean $3.7 \cdot 10^{-12}$ $A \cdot m^{-2}$.

Represented picture of work of electrical machine of Earth gives its only schematic description. More detailed description requires the explanation of the chemistry of the ions, which participate in these processes, and also understanding the microscopic process of the charging of drops. Furthermore, our examination is limited to the fact that the height of the atmosphere, on which can be located the water vapors, composes several kilometers, whereas electrical processes continue also in the more upper levels of atmosphere. In spite of all these deficiencies it is possible to consider that the fundamental elements are here clear. From the point of view of ball lightning the interest in the electrical processes in the atmosphere can consist of the following.

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First, localization of electrical processes can lead to the formation of a sufficient density of the active particles, which give the beginning of ball lightning. In the second place, the charged aerosols play important role in the electrical phenomena. This must cause to them attention, also, in the plan of the formation of ball lightning.

§7.2. Electrical phenomena in the atmosphere.

Let us pause at electrical phenomena in the atmosphere, which are accompanied by emission. Among them we will isolate lightning and St. Elmo's fire. Lightning (for example, see [85, 89]) is powerful short-term cloud-to-cloud discharge and Earth, between two clouds or within the cloud. The length of the channel of this discharge is kilometers.

Description of separation of charges in cloud represented in preceding paragraph shows that large charge, which corresponds to potential into hundreds of megavolts, is stored on lower part of cloud. However, this potential it is insufficient in order to carry out by direct test in air, since breakdown voltage for dry air composes 30 $kV \cdot cm^{-1}$, what to one - two orders exceeds electric intensity, created by the charges of cloud. For this reason the lightning discharge carries more complicated character. Breakdown is realized due to the random heterogeneities, and also the charges and the impurities in air, which reduce breakdown voltage. The role of such admixtures/impurities plays usually dust or aerosol. The first stage of discharge - lightning creates the channel of discharge, this stage is called stepped leader. Stepped leader is the weakly glowing breakdown, which occurs along the separate broken lines, the length of each line composing tens of meters. The characteristic velocity of propagation of stepped leader is 10^5 $m \cdot s^{-1}$, which in order of magnitude coincides with the drift velocity of electrons in air in the fields in question.

Stepped leader transfers only part of charge of cloud. His primary task consists of the creation of the conducting channel. After the creation of the conducting channel through it the current is fixed, the luminous density of channel sharply is raised. This stage is called return shock.

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The velocity of propagation of return shock on the average is [85] $5 \cdot 10^7$ $m \cdot s^{-1}$ and is equal to the velocity of propagation of the front of electric field in the conductor. Return shock lasts in the relatively short period. Its first phase (phase of peak current) lasts microsecond, and entire charge is transferred in return shock less than in the millisecond. The channel does not manage to be expanded for this time, so that output energy proceeds with the heating of channel and the ionization of air in it.

Let us estimate representative temperature of channel. Let the passed through it electricity $Q\sim 2$ C, electric intensity in channel $F\sim 1$ kV·cm^{-1}. Energy chosen per unit of the length of channel composes QF, and a characteristic change in the temperature of air in the channel

$$\Delta T \sim \frac{QF}{c_p \rho S},$$

where $c_p \sim 1$ J·(g·C)$^{-1}$ - heat capacity of the air, $\rho\sim 10^{-3}$ g·cm^{-3} - its density, and $S\sim 10^{2}$ cm^{2} - section the channel (radius of channel it relies by equal on the order of 10 cm). Hence we will obtain: $\Delta T\sim 2\cdot 10^{4}$ K. This is very rough estimate, but it makes it possible to understand that air in the channel of lightning strongly is ionized. Energy losses in the formable plasma to the high degree are connected with the emission, which limits further increase in the temperature. It is usually considered [85, 136] that the temperature in the channel of lightning is 30000 K.

Initial stage of return shock, connected with creation and supersonic expansion of high-temperature channel, is accompanied by propagation of acoustic wave - by thunder. Then is established the equilibrium of high- temperature channel with the surrounding air and during this period of time within the conducting channel is transferred basic part of the charge. The value of the current transferred by channel sharply falls in the course of time, and very stage of return shock, which corresponds to the transfer of basic part of the charge, usually lasts less than 1 ms. The further conducting channel decomposes.

However, if retuning in charge distribution in cloud manages to occur for time of decay of conducting channel, flash of lightning can be carried out again along the same channel. Usually this occurs, if from the time of the previous flash passed not more than 0.1 s.

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New flash begins by the so-called arrow-shaped leader, who according to his manifestation and designation/purpose is passer-by to the stepped leader, but in contrast to it path along the made channel is passed and therefore moves continuously, without being delayed at each stage.. After the passage of arrow-shaped leader return shock follows. The pulse of lightning along the existing channel can be repeated after a certain time. Usually one flash of lightning contains several discharge pulses along one and the same channel.

Lightning is interesting for pass as intense radiation source. Let us explain the effectiveness of the transformation of electrical energy into the radiant energy. For the parameters of lightning in question the energy, isolated with return shock per unit of length, is QF~2 kJ·cm^{-1} (Q~2 C - the passed along the channel charge for the time of return shock, $F \sim 1$ kV·cm^{-1} - electric intensity). If we consider that the channel emits as blackbody with temperature $T \approx 30000$ K, then we will obtain the energy flow of emission with the unit of the area of channel $q = \sigma T^4 = 5 \cdot 10^5$ W·cm^{-2}, and energy flow with the unit of the length of channel $2\pi qR \sim 10^7$ W·cm^{-1} (radius of channel $R \sim 10$ cm). Since in the conducting channel is maintained the temperature in the period $\tau \sim 10^{-4}$ s indicated, the outgoing through the emission energy under the conditions for this estimate composes order 1 kJ·cm^{-1}, i.e., the conversion factor of electrical energy into the radiant energy in the conducting channel of the lightning of order one.

This estimate is overstated, since assumption about radiating channel as about blackbody is too rough. However, it convinces us in the fact that the transformation of electrical energy into the light in the conducting channel of lightning occurs sufficiently effectively. Another special feature of the glow of the channel of lightning is the fact that the large part of the emission corresponds to the ultraviolet part of the spectrum. Actually, for the blackbody with the temperature of 30000 K the maximum radiant energy according to Wiens law corresponds to wavelength 0.1 μm. Although it is actual as a result of the fact that the air plasma is transparent for the vacuum ultraviolet, this maximum is displaced into the region of longer waves, the fundamental emitting losses of the hot air plasma in question are connected with the ultraviolet radiation. In this case, since the ultraviolet radiation effectively is absorbed in the actual air, the radiation spectrum of lightning, recorded at a great distance, proves to be distorted.

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As is evident, physical processes in usual lightning are sufficiently studied and understood [85, 89]. Lightning is intense radiation source, but in comparison with ball lightning the duration of its emission is short and is determined by the lifetime of the conducting channel. In this plan the so-called beaded lightning [12] is more interesting. This lightning is formed from the channel of usual lightning, which separates into the series of vividly glowing spots - "rosary" (Fig. 7.1). The time of the glow of these spots is 1-2 s, i.e., approaches a lifetime of ball lightning. Unfortunately, the existing information on beaded lightning [12] is very limited. And the accumulated factual material on this question, and its analysis is much more limited, than in the case of ball lightning. Therefore information on the pearl lightning cannot aid in the plan of the study of ball lightning.

St. Elmo's fire are interesting electrical phenomenon in the atmosphere. In fact they are the corona discharge in the vicinity of separate conductors in the thunderstorm weather with the high field strength in the atmosphere. In this case near the conductors appear the electric fields of the high intensity, capable of leading to the ionization of the surrounding gas. In the vicinity of these [illegible]tors, the so-called corona layer, are developed the processes of th[illegible]ations of gas, critical for the reproduction of the electrons, which further perish on the electrode or depart to the region with a small strength of the field, where they perish, adhering to the molecules of oxygen. Together with the processes of ionization in the corona layer proceed also the processes of exciting the gas, so that this layer glows. If we look at the corona discharge in the darkness or with a small light, then only the glowing corona layer, which the conductor, surrounds will be visible.

Specifically, thus St. Elmo's fire are received. They are glow in the thunderstorm weather near the crosses of churches, points of buildings, the masts of the ships and other objects.

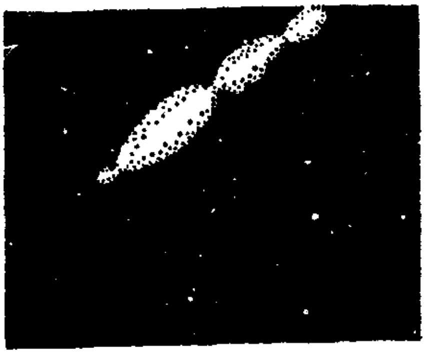

Fig. 7.1. Photograph of pearl lightning.

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Usually this glow is observed, when such objects with a small radius of curvature fall into the bottom edge of clouds, i.e., into the region with the high field strength. Let us give the series of the descriptions of St. Elmo's fire, undertaken from the book of Arago [1]. The first of them is borrowed from the "Notes of Forben".

"At night (in 1696 on parallel of Balearic islands) it suddenly became very dark, lightning began to sparkle and terrible thunder began to thunder. Fearing the storm threatened us, I ordered to retract entire of the sail. More than 30 St. Elmo's fire appeared aboard the ship. One of them, by the way located on to the top of the weathervane of large mast, was greater than three feet. I sent sailor in order to remove it, but when this person approached the mast, then he yelled from there, that the light emits sound, similar to the volume, such as it occurs with the ignition of the moistened powder. I ordered it to be removed and weathervane to go down, but hardly had he touched weathervane from the place, as light passed from it to the mast head and from there it could not be removed. It remained there sufficiently for a long time when little by little entire burned down".

Several other short descriptions of St. Elmo's fire, undertaken from F. Arago's book, make it possible to compose general idea about this surprising phenomenon:

"After thunderstorm, which happened on 14 January, 1824, Maksadorf glanced at cart, loaded with straw and which stood under large black cloud, among field (near Kyoten), it noted that all straws rose upwards and seemed on fire. Even whip of the coachman of heavenly bodies by bright light. This phenomenon, which was continuing about ten minutes, disappeared as soon the wind took away black cloud".

"On sunset on 8 May, 1831, artillery and engineering officers during thunderstorm were missed with exposed heads on terrace of fort Ram-Azun in Algeria. Each of them noted that his comrades on the extremities of the hair raised upwards were the small light brushes. When officers rose hands, then similar brushes were formed also on the extremities of their fingers".

"During thunderstorm on 8 January, 1839, when lightning hammered into tower of Hasseltska church, peasants, who were being located on dam between Tsvolle and Hasselt, in vicinities of last city, noted strange phenomenon.

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They saw for several instants previously the mentioned thunder impact, that their clothing on the fire. Vainly trying to extinguish this fire, they with the horror noted, that the trees and masts shone by the same flame. As soon as thunder impact was heard, flame immediately disappeared".

As can be seen from these descriptions, St. Elmo's fire - mysterious phenomenon of nature, appearance is not predicted. On their manifestation - character and time of glow - the St. Elmo's fire frequently resemble ball lightning. Therefore frequently St. Elmo's fire are accepted as ball lightning. However, there is a vital difference in the external manifestation of these phenomena. St. Elmo's fire are the glow, which appears near the object, whereas ball lightning - moving glowing formation in air.

St. Elmo's fire are corona layer near object, but, as show contemporary investigations [90, 91], it is difficult to explain such intense glow by classical corona discharge. Fundamental role here play the charged water drops, which fall into the corona layer from the surface of conductor and they substantially amplify discharge, increasing the zone of glow. In this case the drops are dislodged from the surface of conductor due to the discharge itself. Although this concept of St. Elmo's fire is insufficiently checked, it attests to the fact that the real physical picture of this phenomenor is complicated and requires attentive investigation.

§7.3. Tornados.

Tornado - complicated phenomenon of nature, whose contemporary understanding very superficially. The tornado (in the USA it is called tornado 1)) is the large vortex, which passes in the atmosphere with the long lifetime.

FOOTNOTE 1). Sometimes tornado is called the atmospheric vortex, which appears above the dry land, and water-spout - similar vortex above the water surface. ENDFOOTNOTE.

Outwardly tornado is developed as follows [92-95]. It appears in the thunderstorm weather, when the front of thermal air is passed through this locality and the air pressure is reduced at a certain height. Usually beginning to it gives the dark cumulus cloud, from which to the earth trips the tornado.

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It can have a form of trunk, funnel, column, etc., and is eddy of air, supported due to pressure difference of air on top and from below.

Let us pause at some statistical data. Most frequently waters-spout are observed in the middle strip of the USA, where the hot and arid climate favors this phenomenon. Yearly above the territory of the country pass about 700 waters-spout, their victims become approximately 200 people (in 1957 as a result of waters-spout perished 864 inhabitants of the USA, in closer 1974 perished 366 people, and during April 1984 - 106 people). The most terrible tornado (tornado of three states) passed on 18 March, 1925, on the states of Missouri, Illinois and Indiana. As a result of this natural calamity perished 695 people, are heavily injured 2027 people, losses were 40 million dollars. The yearly losses of the USA from the waters-spout are evaluated at 500 million dollars. Another known tornado (mettunskiy) carried past above the states of Illinois and Indiana on 26 May, 1917. This tornado existed 7 h 20 min and within this time covered a distance of approximately 500 km. The width of funnel was 400-1000 m, perished 110 people.

In our country waters-spout are observed not so frequently, yes even their destructive force is not so great as in USA. But also here they left the poor memory about themselves. The strongest tornado was observed in Moscow on 29 June, 1904. Although to the American scales it must be related not strong, but to the average waters-spout, its consequences were very perceptible. As a result were destroyed several villages (some are completely eliminated), perished several ten people. Latter from the most memorable waters-spout, Ivanovskiy, it carried past above Ivanovo region on 9 June, 1984. As a result suffered 966 apartment houses, 40 objects of municipal services, 157 enterprises of storages, cattle-breeding farms, about 600 garden houses. Are eliminated about 2 thousand hectares of agricultural sowings, more than thousand hectares of forest. Injured and killed were not communicated about their number.

Relatively large scales of tornado and its destructive effect contribute so that investigation of this phenomenon can be more objective than in the case of ball lightning, which frequently remains unnoticed, and even it is unknown, what part of existing ball lightnings is observed generally.

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But waters-spout, on the contrary, leave about themselves the memory in the form of different destruction on the ground and therefore they can be fixed, even if due to the limited scales of actions, place and time appearances cannot be observed directly. Separate ball lightning, at best, are simultaneously observed by several people, whereas tens become the direct witnesseses of the tornado, sometimes even thousands of people, so that the statistics of observations creates the authenticity of the description of each separate tornado, what you will not say about ball lightning.

However, in spite of possibility of more reliable description of each case of observing tornado, contemporary physical picture of this phenomenon is very schematic. The difficulty of the experimental investigation of the separate parts of tornado limits the possibilities of its complete description. Let us examine the separate sides of this phenomenon and let us present some questions of general character, to which is required convincing response. One of the surprising properties of tornado - high rarefaction of air within the vortex. In combination with the sharp boundary of vortex and the high rate of movement this leads to the strong destructive effect. If the object, filled with air, proves to be within the vortex, then is instantly created pressure difference of air inside, also, out of the object. This leads to the onset of enormous internal stresses, which in the final analysis can lead to the destruction of object. In order to visualize the scale of the acting forces, let us make simple estimate. Let there be the one-room house with an area of 5×5 m^2 and with a height of 2.5 m, which corresponds to the area of its surface of 100 m^2. Assume that further this house instantly proved to be in such atmosphere that the internal pressure exceeds external to 1% (i.e. on 0.01 atm.). It is not difficult to calculate, that this will lead to the fact that on the construction of house the force, equal to 10^5 N will operate (10 t). It is clear that this force is capable of leading to serious destruction.

Onset of enormous internal stresses due to internal air pressure leads to destruction of houses and other construction, which contain air. This destruction carries usually explosive character. It is interesting, however, that there are cases, when the destruction of house, which is accompanied by the dispersion/divergence of its construction to the different sides, did not affect those being located within the inhabitants of house. Even the more surprising cases occurred with hens.

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In the middle strip of the USA, where waters-spout most frequently are observed, there are sufficiently many poultry-breeding economies. As a result of waters-spout chicken coop frequently they are broken down, in this case cases occur, when the chicken coop is broken down and hens remain living and at its places. This as the destruction of houses, it is possible to explain by a sharp drop in the air pressure outside. Were observed the more curious cases, when hens remained at their place, but they were completely plucked. This occurs because the foundation of the pen of hen is located in air bag/follicle, that is found in the skin; it is possible to explain such cases by the blast of air in these bags/follicles.

From aforesaid it is evident that there are diagrams, capable of qualitatively describing tornado and processes, its accompanying. But correct scientific model is obligated to give the quantitative description of phenomenon. In connection with the described cases and their explanation arises the question, as appears so high pressure gradient of air on the boundary of vortex, that the objects instantly prove to be in the zone of reduced pressure; what pressure gradient in the vortex in question can arise and as this will be coordinated with gas dynamics of vortex.

Another special feature of tornado from point of view of gas dynamics of eddy is connected with acting in it forces, caused pressure differentials. The most frequent cases of the partial destruction of houses - tearing roof from them. Analyzing all this

is, it is possible to arrive at the conclusion that the pressure differentials in the tornado are considerably higher than one percent, accepted in the estimate carried out earlier. Actually, let us try to utilize the parameters, placed in this estimate (house with an area of the foundation of 5×5 m^2 and a height of 2.5 m) and we will consider further that the roof is the weakest place for design. Then under the action of internal air pressure roof is elevated and further under the action of forces within the vortex it is taken away or destroyed. The maximum altitude, to which it can be elevated with the assigned air-pressure differential Δp, composes $(\Delta p/p)h$, since $pV = \text{const}$ (p - internal pressure, h - the height of the house, V - the volume of air in it). Using this estimate, we find that for tearing the roof the pressure differential in the vortex must comprise, at least, several percentages.

Fundamental question, which relates to nature of tornado as to gas-dynamic machine, this - how it works.

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It is clear that the basis of the work of tornado composes pressure difference of air and above (taking into account a change in the pressure with the height). The appearing vortex sucks out air from bottom to top. The efflux of water in the tank can be the convenient model, which describes this motion. The air pressure in the tube rises under the action of the emerging water and vortex emerges upward in the form of the rotating funnel. It is evident from this model that eddy of air, which attempts to even pressure in the tube is above, it is in this case stable motion. But this simple model describes only the one side of phenomenon. Passing from this model to the real situation, we immediately must present the question, which serves as the partition between the lower and upper air layers, which does not make it possible to flush pressure by the simple vertical displacement of layers. It is obvious that these functions fulfills the maternal cloud, from which appears the vortex. It is possible to visualize that between lower and upper boundaries of cloud is the pressure differential, which causes the flow of air to its upper end. But then the following question arises - why vortex does not remain at the bottom edge of cloud, but germinates down to ground itself.

It is evident that work of tornado as mechanical machine is determined, first of all, by properties of cloud itself and by processes taking place in it, which, possibly, create continuous draw bar, which supports so prolonged an existence of vortex. In this case the properties of vortex itself on the surface of the Earth are determined by the boundary conditions of vortex at lower boundary of cloud, i.e., are assigned by the processes, which take place in the cloud.

With this formulation of problem and by taking into account some phenomenological boundary conditions of cloud, it is possible to describe gas dynamics of tornado, if these conditions are fitted then so that parameters of tornado, designed on basis of equations of gas dynamics of air, would coincide with those observed. This approach is completely natural and is utilized in the different modifications. However, the quantitative parameters of tornado and, in particular, the supersonic speeds for some elements of air, attest to the fact that real picture even for this part of the tornado is more complicated. These difficulties attest to the fact that the character of the work of tornado is determined not only by gas dynamics of the motion of air and dust in the vortex, but also by thermal and electrical processes in the cloud, including - by processes of formation and condensation of water drops.

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Confirmation to that is the observed fact, according to which the tornado germinates only from the black cloud, i.e., from the cloud with the completely specific composition of drops.

Thus, nature of tornado as ball lightning, is understood still insufficiently and requires complex study. However, the nearness of these phenomena consists not only of the difficulty of their investigation, apparently, some processes are passed to them equally. Ball lightnings frequently are observed for this reason during the motion of tornado.

S7.4. Volcanic eruptions.

Volcanic eruption is one of clearest phenomena of nature, which are sometimes accompanied by onset of ball lightnings. The volcanic activity of the Earth - the ejection of gases, ashes, magma from the terrestrial interiors - is supported due to the internal energy of the Earth. Heat flow outside comprises in average [96, 97] 0.06 $W\cdot cm^{-2}$, which corresponds to the power of heat release throughout the entire Earth, equal to approximately $3.2\cdot10^{10}$ to kW [1]).

FOOTNOTE [1]). The average power, which corresponds to production human activity, little exceeds $1\cdot10^{10}$ kW; this energy release in essence is determined by the combustion of combustible useful minerals - coal, oil, gas, etc. ENDFOOTNOTE.

Approximately 3% of energy, which goes from the interior of the Earth, are isolated with the volcanic eruption. On the Earth there exists the order of 800-900 volcanos, which are considered active [98]. Yearly ejections occur in not more than 20-30 volcanos. In this case on the average yearly the volcanos vent to the atmosphere 3 billion tons of ashes. This relatively is little, and if it is even to distribute ashes over the surface of the Earth, we will obtain density 0.6 $mg\cdot cm^{-2}$. However, if this value is multiplied by the lifetime of the Earth, then for the average quantity of ashes, which fell to the surface of the Earth as a result of volcanic eruptions, we will obtain about 30 $t\cdot cm^{-2}$ that more than 10 km correspond to thickness of the layer. From these estimates it follows that the material of volcanic origin (ashes, magma) composes the noticeable part of the surface layer of the earth's crust. Thus, volcanic activity is reflected in the properties of the material of the earth's crust.

In accordance with internal structure of Earth under its solid surface layer - earth's crust - it is located liquid layer - magma.

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The earth's crust has a thickness of several ten kilometers and consists of the separate plates, which "float" on the liquid magma. In the places of the section of separate plates the magma approaches closely to the surface of the Earth. In such places of terrestial globe and volcanos are located. Volcanic eruption occurs under the action of the gases dissolved in the magma.

Magma is found under large pressure, which is held by upper layers of earth's crust. If magma falls into the area of reduced pressures, then gases are expanded. If this is - crack in the earth's crust, then gases escape outside, being accelerated and carrying along in this case magma, which leads to the large stresses in the solid material of the earth's crust, which surround crack. The destruction of this material is possible. Then the motion of gas carries explosive character and is created ejection. Gas carries along after itself magma and solid material of upper layer, rejecting all this in the form of ashes, dust and stones. After ejection the magma under the action of internal pressure emerges outside through the formed opening in the earth's crust. The viscosity of magma is raised in proportion to congealing, its motion slows down, and then entirely ceases. If until this time in the magma, which is approaching the place of fracture in the earth's crust, gases have time to be saved, then ejection can be repeated. But if this does not occur, then volcano will be inactive to the following time, when as a result of moving of the earth's crust and earthquakes connected with this again appears the possibility of output outside for the gases, which were saved in the magma.

From point of view of ball lightning volcanic eruption is for us of interest as phenomenon, which is accompanied by electrical processes, and also by emitting processes in the atmosphere. Before passing to this phenomenon, let us pause based on some examples of volcanic eruption, which give representation both about the character of the manifestation of ejections and about the consequences, to which they can lead.

Let us recall known picture of K. P. Bryulov "Last day of Pompei". In it the artist communicated his representations about the eruption of Vesuvius, values, which were recently seeming firm, perish, everything will collapse, people in horror, attempt to leave this hell, but it is unclear, where to find path to rescue. It would seem, gods themselves attacked the people with their entire anger and from the incandescent sky they control the occurring tragedy .... The ejection of Vesuvius in 79 B. C led to the death of Roman cities of Pompei, Herculaneum, Stabii.

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Pompei was destroyed and covered with the thick layer of ashes. The excavations of this city, initiated in the XVIII century and which are continued up to the present time, make it possible to represent, what values were lost, to say nothing of human victims. The killed cities forever ceased to exist.

Most powerful ejection occurred 10 and 11 April, 1815, from volcano Tambora on island of Sumbava, which is located in probe archipelago in Indonesia. During the blast was displaced approximately 150 km^3 of rocks (if this material could be evenly distributed on entire terrestial globe, then would be obtained the layer with a thickness of 0.3 mm). The adjacent areas were covered with the thick layer of ashes; so, the house of the deputy of colony, which is found in 111 km from the volcano, under the gravity of ashes was destroyed. Volcanic eruption was accompanied by earthquakes, tidal waves and hurricanes. This led to the large destruction and to the death of approximately 80 thousand people.

One of that most memorable was volcanic eruption of Krakatoa in Sunda Strait between islands Java and Sumatra in Indonesia, which occurred on 27 August, 1883. As a result of this ejection into air was raised approximately 18 km^3 of the loose rock, which is eight times less than with the volcanic eruption of Tambora. However, material was strongly dispersed due to the incompactness and the layer of ashes was propagated to the large distance - to 1000 km. Small specks achieved the stratosphere and were located there in the course of many months that it influenced the optical properties of the atmosphere. Bright rises and sunsets were observed after the ejection of Krakatoa for a certain period of time as a result of the reflection of sunlight by stratospheric dust. A change in the optical properties of the atmosphere led also to a certain temperature drop on the planet in the months subsequent after ejection, since due to the reflection by particles on the surface of the Earth the smaller part of the solar radiation fell; this effect disappeared in proportion to precipitation of specks.

Extremely high explosive force was another special feature of volcanic eruption of Krakatoa. Blast was audible in Australia and on the island Rodriguez, that is found in Indian Ocean at a distance of almost 5000 km from the volcano. This blast caused the enormous tidal wave with a height of up to 40 m, which attacked the coasts of Indonesia islands.

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Large destruction and death of 36 thousand people were the result of its action. Tidal wave from the blast with the volcanic eruption of Krakatoa was recorded even in English Channel strait.

One of most tragic natural calamities of our century became volcanic eruption Mont-Pele on island Martinique (small Antilles Islands in Caribbean sea) on 8 May, 1902. This is how is described in the book of time of Rasta [99] this catastrophe, which eliminated city Saint-Pierre and 30 thousand inhabitants.

"In the morning on 8 May began sharp, almost terrible calm. Them it began to represent hell. With terrible crash cracked the mountain peak, and outside was pulled out the enormous burning cloud - igneous wall, with the inconceivable rate which dashed down along the slope. After several seconds it achieved city, and Saint-Pierre disappeared in its flame. The masses of people, which hurried to the harbor, by the pressure of the burning cloud were thrown in the sea, which began to boil. The ships, which stood to harbor, were inverted and burned. Only two their them, recently arrived "Roraima" and still stood under steam "Roddam", although it had many victims, who sustained large losses in people, with difficulty rescued them, after leaving into the high sea and after avoiding thus the entire force of the burning cloud ....

From inhabitants of Saint-Pierre only two - both negroes - remained living. One of them for the certain misdeed was placed into strong, overlapped by stone arch cell, whose grill window was shielded by wall from the impact front of the burning cloud; the second, shoemaker in the profession, survived catastrophe in its house, after hiding under the table, while several other persons, who were located in the same location, perished ....

Volcano Mont-Pele and after catastrophic ejection on 8 May, 1902, repeatedly emitted analogous burning beams, sometimes which were not inferior to first ejection and which completed destruction of Saint-Pierre, namely 20 and 26 May, 6 and 9 July, also, in particular on 30 August".

Complete absence of representation about danger was fundamental reason for described tragedy, as a result of which measures for rescue of inhabitants were not in advance accepted. For several days before the ejection, when volcano already developed its activity, for explaining the degree of risk governor assigned board.

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In its conclusions the board denied the objective danger of volcano for the city. Moreover, the day before the catastrophe the governor of Martinique with his wife arrived in Saint-Pierre in order to quiet population. Next day they perished as other inhabitants of city.

Thus, main reason for described catastrophe was incomprehension of degree of risk. The measures for the evacuation of inhabitants were not accepted for this reason. Entirely another relation occurred with the volcanic eruption on Kheymaey island near Vestmannaeyyar city in Iceland, that occurred on 23 January, 1973. Understanding danger, based on the contemporary knowledge about the behavior of volcano, and impulse, well organized actions on the evacuation of population made it possible this time to avoid victims. This is how is described this in book [99]:

"Although on Kheymaey island volcanic eruptions did not occur from immemorial times, Iceland as a whole is among the most active volcanic regions of the Earth and its inhabitants it is not possible to consider them unprepared to the incidents of this type. Specifically, therefore the evacuation of population, which was begun immediately, mainly with the aid of its own fishing fleet and partly with aircraft, occurred without the complications and was completed after nine hours. On the island remained only 300 people of auxiliary personnel ....

On 30 January at eastern part of city ashes rested already with layer to height of up to 4 m, filling up many houses and after making streets unpassable. Even in the center of city the height of layer reached 40 cm. The verdure of island was changed into the black deposit of ashes. Further overshoots of volcanic products and pressure head of lava increased the number of destroyed houses to 300.

Although precipitation of ashes in subsequent time began to weaken, further advance of lava created constantly increasing threat for city and port. At first they attempted to lead lava flow to the side with the aid of the rampart, installed from tephrite, but effect proved to be insignificant. The invited experts proposed to utilize sea water in order to cool the moving lava and accelerate its congealing.

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Through the city they lengthened 30 conduits from plastic, and strong flows of water with the aid of powerful pumps attacked the advancing lava. Improbable happened: the front of lava flow stopped".

Experiment shows that timely information on volcanic eruption and understanding of degree of risk makes it possible to high degree to avoid serious tragedies. On the contrary, the unexpected contingency of this event can lead to the large losses. An example to that is recent volcanic eruption Ruiz in Columbia, that occurred in the middle of November of 1985. Volcano Ruiz with the height of 5398 m is situated 150 km northwest of Bogota - capital city of Columbia. Last strong volcanic eruption occurred in 1595. The signs of processes within the volcano began to be noted on 11 September; however, this did not cause anxiety - the last 90 years volcano was considered extinct. Ejection began on 12 November and was accompanied by the overshoot of ashes. In the valley of the river, which leaks off from the volcano, 40 km from it was located Armero town with the population of 21 thousand people. In the surrounding settlements lived additional 24 thousand people. When next day strong volcanic eruption occurred, half of this population perished. Ejection was begun on 13 November at 21 hours. Several strong blasts first occurred, and then the rapid fusion of ice and snow at the apex of volcano led to the formation of flood flow, which after two hours achieved city and overwhelmed it. In Armero perished 15 thousand people, and the total number of those killed was about 23 thousand people. The material damage, caused by volcanic eruption, is estimated at 1 billion dollars.

This and other cases examined show that volcanos present objective danger to man. The correct understanding of volcanic activity and timely actions in the prevention of its consequences make it possible to avoid serious tragedies. Volcanic service in Japan is one of the positive examples of this relation. In Japan 77 active volcanos (only in Indonesia are there more) are located. On the slopes of these volcanos are seismographs and temperature sensors, which continuously transmit information to the special centers, where it is analyzed and processed with the aid of computer(s). Even with small changes in the activity of volcanos about this is communicated to the population of the adjacent areas on radio and television.

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Although this service cannot ensure the absolute safety of population, it proved to be very effective. From 1900 to 1965 in Japan volcanic eruptions involved 460 human victims, i.e., on the average of 7 people per annum. After 1965, when the service of early announcement about the volcanic eruption entered the system, in 20 years perished only 3 people.

From point of view of phenomenon of ball lightning volcanic activity and volcanic eruption interest us as physical phenomena, which are accompanied by electrical and optical processes. During the ejection the ejected dust can be charged as a result of natural processes - motion, fragmentation, etc. As a result of the precipitation of the charged particles can arise the regions of one charge, which will lead to the same phenomena, as with the usual thunderstorm. This is how Pliniy the Younger [100] describes the ejection of Vesuvius 79 B. C., as a result of which perished Pompei.

"We saw, as sea retired; earth was being shaken, seemingly repulsed it. Coast clearly advanced; many marine animals stuck in the dry sand. On the other hand - black terrible cloud, which broke through in the different places the crossing of igneous zigzags; it opened wide with the broad blazing bands, similar on the lightning, but larger".

Electrical phenomena were observed also during subsequent ejections of Vesuvius. These facts were assembled in the book of Arago [1].

"... in description of ejection of Vesuvius in 1182 we find that extremely dense fume continued from 12 to 22 August, and thunderstorm frequently was among that fume. Brachini, the eyewitness of the ejection of Vesuvius in 1631, tells that the column of fume, which was raised from the crater, was propagated in the atmosphere at a distance to 160 kilometers and that with the passage of this cloud of special kind from it frequently were thrown out the thunder, overturning several people and animals".

During the ejection of Vesuvius in 1707, Giovanni Valleta wrote from Naples to Richard Weller:

"On the third and fourth day volcano erupted through its mouth of the lightning, similar to those, which in known facts illuminate sky. They were bent, serpentine, and after their appearance were heard reelings of thunder ....

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Of lightning and thunder so frequent and strong, forced to assume the nearness of rain; but finally it was revealed that they were born in the dark cloud, which consisted not of the usual vapors, but singular from the ashes.

Peasants, who lived in base of Vesuvius, after ejection of 1767 told Sir William Hamilton that they were much more strongly frightened by continuous lightning and thunderstorm, which raged among them, than burning lava and other terrible phenomena, which always accompany volcanic eruption.

During terrible ejection of 1779 from mouth of Vesuvius together with burning lava emerged frequent smoke streams as black as possible to imagine. This fume according to Sir William Hamilton, it seemed, was intersected by serpentine lightning at the very moment of its coming out from the mouth. The ejection of Vesuvius in 1794, well described by the same observer, includes indications so positive.

On 16 June nothing burning emerged from mouth: from it were thrown out only black fume and ashes, that formed above mountain gigantic cloud. This cloud was slotted by lightning in the form of zigzags or broken lines, so known to meteorologists.

Volcanic lightning, seen by Hamilton in 1799, were not accompanied by any sensitive blast. Opposite that, in 1794 they were constantly accompanied by the crack, which were equal to the strongest thunder impacts. The thunderstorm, generated by one effect of volcano, was in every respect identical to usual thunderstorms. The thunder, from it flying, produced usual actions. During the investigation of the affected by thunder dwelling the Marquise of

Beriot in San-Gorgio occurred the special case to be convinced of the ideal resemblance of the actions of volcanic thunderstorms to the usual. The ashes, which composed the greatest part of the mass of cloud, was as fine as Spanish tobacco. The wind transferred this cloud to Tarenta city, which is located 400 kilometers from Vesuvius. Thunder of this cloud produced there large devastations in one house.

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I, until now, spoke only about ejections of Vesuvius. Although something to fear so that someone would decide to assign exceptional special feature to the clouds of ashes and fume, which rise from the mouth of this volcano, to give birth to thunderstorm, I will nevertheless give here still several references.

I borrow the first of them from Seneca. . In his "Natural questions" (book 11, S30) I find that thunder thundered during the large ejection of Aetna and thunderstorm burst among the clouds of the incandescent sand, ejected by volcano.

Second reference we will get from description of ejection of Aetna by abbot Francesco Ferrara: "In the beginning of 1755 from mouth of Aetna was raised enormous and very black column of fume, cut by frequent winding lightning".

When in 1811 islet Sabrina, that existed so short a time, rose from bottom of sea near Azore island Upper Mikhail, then according to captain Til'yar, the extremely black columns of dust and ashes, which were rising from the medium of the ocean, were continously slotted in darkest and most opaque their parts by unusually bright lightning.

Even small volcano, which arose during July 1831 between Sicily and Pantelarie, can find place in this chapter. In fact, John Davy says that on 5 August rose up every now and then from the mouth to the height from 900 to 1200 m columns of completely black dust, from which almost continously escaped in different directions of the lightning, accompanied by thunder".

All these examples, assembled 150 years ago of F. Arago, give representation about the fact that electrical processes can accompany volcanic eruptions. On the basis of the general considerations it is possible to arrive at the conclusion that the electrical processes can be developed not in any form of ejections, but only in such, where the fine dust is rejected. In this case is possible the charging of dust cloud similarly how this occurs in the clouds. Then in the dust clouds the thunderstorm phenomena, similar to usual thunderstorms, will appear. The finely dispersed charged dust, especially if in it are located the particles of organic eminations, with the electrical phenomena in the atmosphere can be the base of ball lightning.

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Therefore in certain cases volcanic phenomena can be accompanied by the onset of ball lightnings, similarly what is observed in the tornados. In this confirmation let us lead quotation from the same book of Arago [1].

"Light spheres are more frequent among volcanic than among usual thunderstorms. Thus, with ejections of Vesuvius in 1779 and 1794. Hamilton and other observers repeatedly saw very large fireballs, which, after being fixed from the dense cloud of dust, were disrupted in air similarly to bombs or crackers of our fireworks. The flame, erupted by these spheres in all directions at the moment of their blast, moved with broken lines".

§7.5. Aurorae polares.

In contrast to phenomena examined above aurora polaris can be called phenomenon, allied to ball lightning, very conditionally, since it is observed at relatively high altitudes of atmosphere and is caused by flow of fast particles, which fall into upper air. Nature of aurora polaris is well studied. Common in these phenomena only in the glow itself, which by its beauty and mysteriousness can cause in man equally strong emotional sensation.

Aurorae polares are distinguished by form of glow before sky, radiation spectrum, duration and character of its change in time [101-103]. But in all cases they have one and the same nature. Beginning to aurorae polares give the solar flares, as a result of which solar plasma is splashed out beyond the limits of the Sun. These bursts are created due to the instabilities of solar plasma in the convective region of motion and are observed as the evolution of sunspots. During the solar flare sharply grows the intensity of the solar wind - the flow of plasma, emitted by the Sun. This leads to a change in the character of interaction of the solar wind with the magnetic field of the Earth and in the final analysis causes the glow of the atmosphere. Let us examine the appearing processes more attentively [103-105].

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Interaction of stationary flow of solar plasma with magnetic field of Earth causes determinate structure in distribution of magnetic field and charged particles in space surrounding Earth (for example, see [106]). During interaction of the magnetic field of the Earth with the solar wind erect shock wave appears, since the directed rate of plasma exceeds thermal particle speed - speed of sound. In the intersection of shock wave front, i.e., disruptions, the charged particles of plasma are heated and lose their ordered motion.

Essential element of magnetosphere of Earth is magnetopause - surface, on which pressure of solar wind is compared with magnetic pressure of Earth. Magnetopause separates the region, where the magnetic field of the Earth, from the region, where is located plasma with the frozen-in into it magnetic field beyond the limits of magnetopause the magnetic field of the Earth does not operate, operates. On the other hand, the intersection of magnetopause with the charged particles of plasma with the frozen-in into them magnetic field hindered and therefore solar wind flows about the Earth at a certain distance from it. Characteristic distance from the center of the Earth to the magnetopause from the subsolar side under the normal conditions composes approximately 10 radii of the Earth.

Absence of magnetic field at its poles is important special feature of magnetosphere of Earth. The corresponding lines with the zero magnetic field are directed from the poles of the Earth in the direction, opposite to the Sun. Plasma, which is found in the vicinity of this line, can without difficulty reach the Earth's atmosphere. This "rash" of the charged particles in the atmosphere of the Earth causes airglow. Since it occurs near the poles, is observed in essence in the polar regions how is determined the name of this phenomenon.

Intense aurorae polares appear as consequence of solar flare. The plasma, emitted by solar flare, reaches the surface of the Earth in 1.5-2 days. The same sequence between solar flare and aurora polaris is observed. As a result of solar flare the intensity of the flow of the plasma of the solar wind considerably grows, and distance from the center of the Earth to the magnetopause decreases two - three times. Appear the new channels of the instabilities, as a result of which the plasma can penetrate in the region of weak magnetic field and thus achieve the Earth's atmosphere. The mechanisms of these instabilities are diverse and lead to the different forms of aurorae polares.

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Aurora polaris itself is secondary process of "rash" of fast charged particles, protons and electrons, in the atmosphere of Earth. These particles, which possess kiloelectronvolt energies, are braked at the heights of 100-400 km depending on their wave energy and part of their energy they lose to atom excitation and molecules of the atmosphere. The emitting transitions/junctions of excited atoms, molecules and ions of the atmosphere create the glow of the atmosphere, which is received as aurora polaris. In the visible region of the spectrum most intense are the transitions/junctions of atomic oxygen ${}^1D-{}^1S$ (wavelength 0.5577 μm, green line) and ${}^3P-{}^1D$ (wavelength 0.6300 μm, 0.6364 μm - yellow lines), and also the first positive band of the molecule of nitrogen $(B^3\Pi_g - A^3\Sigma_u^+)$ of red color, the second positive band system of the molecule of nitrogen $(C^3\Pi_u - B^3\Pi_g)$ of blue color and the band of Meinel of the molecular ion of nitrogen $(A^2\Pi_u - X^2\Sigma_g^+)$ of red color. In accordance with the intensity of separate emitting transitions/junctions, which depends on the condition of the penetration of particles in the atmosphere, can be observed the different coloration of aurorae polares, and the space and color distribution of luminous intensity before the sky is determined by the character of the instability, which causes the penetration of the fast charged particles in the atmosphere.

Comparing state of problem of ball lightning and level of investigation of other phenomena in the atmosphere of Earth, we find that for some of these phenomena (onset of atmospheric electricity, St. Elmo's fire, tornados), as in the case of ball lightning, we cannot give detailed description of their nature. Such description, which reliably isolated the totality of the processes, which compose the base of phenomenon, is intended. The representations about other phenomena examined appeared in the recent decades. All this gives to us the possibility to make the conclusion that the atmospheric phenomena, at base of which lies the totality of the processes of different nature, can be understood only with the use of a contemporary arsenal of science, and it makes it possible to hope that the junction/unit elements of the problem of ball lightning, as in the case of other phenomena of the atmosphere, will be permitted in the nearest time.

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CHAPTER 8.

SIMULATION OF BALL LIGHTNING.

§8.1. Experimental simulation.

Its reproduction under laboratory conditions is demonstration of understanding nature of ball lightning. Sizes and power engineering of ball lightning make this reproduction completely available. Therefore for the last hundred years were undertaken numerous attempts experimentally create ball lightning. The large part of these experiments is in detail presented in the book of Barry [12], here we briefly will pause at the fundamental approaches.

Different representations about nature of ball lightning were assumed as basis of laboratory experiments. But irrespectively of the basic ideas in all experiments the excitation of gas was realized with the aid of the gas discharge. Gas discharge proved to be the simplest and available method of the insertion of energy into the gas. Let us examine first that part of the investigations, where it was assumed that ball lightning - plasma. Since the formable plasma (hypothetical ball lightning) must not be connected with the walls, electrodeless high-frequency discharge is most adequate for this purpose. The first experiments on the creation of the glowing spheres it was carried out at the end of the past century by N. Tesla (see [12]). After creating powerful discharge device with a frequency of the discharge of 4.2 kHz, under some conditions Tesla observed the glowing spheres with the diameter of 2-6 cm. Since the results of these investigations were not published, it is now difficult to give to them estimate.

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Detailed investigations on obtaining of glowing formations of spherical form in sealed tank were carried out by G. I. Babat in 1942 (see [12]). Shf discharge with a frequency of 1-100 MHz was utilized for this purpose and the power introduced into the discharge was varied up to 100 kW. In the region of the pressures of gas of order 1000 Pa in the tank the fireball, which does not concern walls, appeared. The experiments of Babat many years were later continued and expanded by many authors.

Difficulties of designing of high-frequency discharge at atmospheric pressure were overcome by P. L. Kapitsa, as a result succeeded in creating several atmospheres [107] of shf discharge in helium at pressure of helium. The glowing discharge region was not connected with the walls and had a form of sphere. The addition of organic additives sharply amplified luminous intensity.

Work of Kapitsa are most consecutive in plan of simulation of ball lightning during plasma representation about its nature. Asserting that the plasma, which simulates ball lightning, must rapidly be decomposed, Kapitsa arrived at conclusion [108] that energy into the plasma must be conducted from without. Its experiments demonstrate possibility - the existence of the glowing plasma sphere with the external power supply. Thus, the idea of Kapitsa and his experiments are logically locked. It is another matter that the reality of this ball lightning, as the subsequent investigations showed, was scarcely probable.

Somewhat another method of designing of glowing sphere in shf discharge at atmospheric pressure is realized in work of Powell and Finkelstein [109]. Triggering at the atmospheric air pressure was conducted with the aid of the arc, and the shf discharge, whose frequency was 75 MHz, further was utilized, the power of generator - 30 kW. Discharge ignited in the glass open tube, moreover it would have been possible to change the sizes of region, occupied with discharge. After the disconnection of discharge the glowing region took the form of sphere and it decomposed for the fractions of a second, moreover in open air its decay occurred doubly faster than in the glass tube. In the work the detailed examination of the radiation spectrum of plasma is carried out. Although the lifetime of the observed glowing formations is substantially less than the lifetime of ball lightning, it considerably exceeds the typical time of decay of plasma at the atmospheric pressures. This anomaly the authors explain by the presence of a large quantity of metastable molecules.

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Represented experiments demonstrate possibility of designing of gas-discharge plasma in the form of glowing formation of spherical form, although in their properties such objects differ from actually observed ball lightning.

During setting of its experiments of Andrianov and Sinitzin [110] proceeded from the assumption that ball lightning appears as secondary effect of forked lightning from vaporized after its action material. For the simulation of this phenomenon the authors utilized the so-called erosion discharge - pulsed discharge, which creates plasma from the evaporating material. The stored energy under the conditions for experiment composed 5 kJ, potential differences 12 kV, capacitances of the discharged capacitor 80 μF. Discharge was directed to dielectric material, maximum discharge current was 12 kA. Discharge region was at first separated from the standard atmosphere by the thin membrane, which was disrupted upon the switching on of discharge, so that the erosional plasma vented to the atmosphere itself. The region moving glowingly took the spherical or toroidal form, moreover the visible radiation of plasma was observed in period on the order of 0.01 s, but generally plasma radiation was recorded not more than 0.4 s. These experiments once more show that the lifetime of plasma formations in atmospheric air is substantially less than the observed lifetime of ball lightning.

Among experiments, which simulate chemical nature of ball lightning, most interesting and consecutive is experiment bariums [12, 17, 111]. In the Plexiglas cabinet with the sizes 50×50×100 cm^3 is placed air at the atmospheric pressure with the admixture/impurity of propane, which is ignited by spark. Distance between the electrodes 0.5 cm, voltage 10 kV, the duration of discharge 10^{-3} s, output energy 250 J. The concentration of propane is 5% of inflammability limit, with this and higher concentrations the blast of mixture with the oxidation of propane occurs. Combustion ceases, when propane concentration falls to 4.8%. However, with the concentration of propane 1.4-1.8% following the spark discharge in the chamber is formed yellowish-green sphere with diameter of several centimeters. It completes rapid random movements along the chamber and in one-two seconds goes out.

Page 1[illegible]7.

This phenomenon according to its properties resembles ball lightning and, in any case, can be treated as its analog.

Supplementary investigations [112] showed that in conditions for experiment more complicated compounds are formed. Barry [12] gives other information, which confirms this possibility. Apparently, this process is critical for the observed glow. More complicated connections, including hydrocarbons, are condensed at a low temperature. In the conditions for experiment they form aerosols and in the final analysis are concentrated in the small region of space. Initial spark creates the necessary number of complicated connections, and the small region of concentrations of propane, in which it is possible to obtain the glowing spheres, testify about the competition of different chemical processes in the system in question. Described of processes in the system in question. The described experiments of Barry are the best laboratory simulation of ball lightning.

There are many reports about observation of glowing spheres from vapors of metals, which appear during short circuits, upon lightning strike to metallic objects, during some pulsed discharges, which are accompanied by evaporation of electrodes. Some of these reports are published (see [12]). As a result of evaporating metal is formed the glowing sphere, which more frequently falls to the earth or on the floor and there disorderly it moves, fading for the time of the order of second. This system can be represented as the ball of metallic filamentary aerosols, which cools in air. Unfortunately, the described observations carry random character, but experiments, as a rule, are not reproduced, which impedes analysis.

S8.2. Analogs of ball lightning.

Ball lightning - real phenomenon. Therefore the separate mechanisms of this phenomenon, even if they seem exctic, must be developed, also, in other physical systems or phenomena. In connection with this important to isolate and to analyze the physical systems, similar to ball lightning according to the fundamental properties. Such systems, which will serve as the analogs of ball lightning, simulate the separate sides of this phenomenon and can be used further for the reproduction of ball lightning under laboratory conditions.

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Fundamental value has two analogs of ball lightning. One of them, pyrotechnic illuminating composition, simulates the process of converting the chemical energy into the energy of glow in atmospheric air. Another - aerogel - is physical object with the same structure, as ball lightning. It has durable and light body and is characterized by very low specific gravity.

Pyrotechnic illuminating compositions are solid mixture of series of chemical compounds, into number of which enters fuel, oxidizer and glowing components. The arson of this mixture leads to the rapid burn-out of fuel with the participation of its own oxidizer, which creates in the combustion zone the high temperature, up to 3500 s. The located in the combustion zone macroscopic particles, and also the excited atoms and molecule create bright glow.

Illumination means can be divided into two groups. The first create light in the wide region of the spectrum, the second are intended to give the light of the specific coloration. Illumination means of the first group, which create white light, provide higher specific light output, since their emission answers the wide region of the spectrum. The emission of illumination means of the second group is caused by the transitions/junctions of the specific atoms or molecules, so that the radiation spectrum of such mixtures is concentrated in the not wide wavelength range. From the point of view of ball lightning to us are interesting the illumination means of the second group. Let us give as an example the parameters of the composition of the light of yellow.

Yellow of this illumination means is determined by emission of excited atoms of sodium. The composition of the chemical constituents of yellow light is the following [81]: KNO_3 - 37%, $Na_2C_2O_4$ - 30%, Mg - 30%, resin - 3%. Magnesium is fuel, saltpeter and dioxalate of sodium are oxidizer, and resin - binder. Sodium resultant during the heating provides the glow of hot mixture. The specific energy reserve of this composition of 6 $kJ \cdot g^{-1}$ several times lower than in carbon, combustion temperature is 2500-3200 K. The luminous efficiency of substances with this composition is equal to 8 $lm \cdot W^{-1}$, i.e., by an order exceeds the value, observed in ball lightning.

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The luminous flux for average/mean ball lightning of lightning can be provided with 0.3 g of this composition, and the energy reserve of average ball lightning - approximately with 3 g. Let us note that the mass of air, the blockaded volume of average ball lightning, is 15 g.

Essential feature of chemical process in illuminating composition is caused by fact that oxidizer is taken from composition itself, but it is not atmospheric oxygen. This is determined to temperatures and to the high luminous efficiency of the light source in question. However, a similar conclusion about the coincidence of the reacting components was made with respect to chemical process in ball lightning. In this case, besides ozone, the oxygen-containing components in atmospheric air can be the oxides of nitrogen and sulfur, and also salt of nitric and sulfuric acids.

Let us examine another analog of ball lightning - aerogel - macroscopic cluster, comprised of solid, rigidly connected single particles. The rigid body of aerogel occupies a small part of its space, almost entire space falls to the pores. The first part of the name "aero-" reflects the fact that the specific weight of aerogel is small. Even the first samples of aerogel, obtained are more than fifty years ago [114, 115], they had specific weight/gravity up to 0.02 $g \cdot cm^{-3}$. In a certain region of sizes (exceeding size of single particles) the aerogel, as ball lightning, has a structure of fractal cluster.

In aerogel durable bond between particles is realized and therefore a few connections can form this structure. Are at present obtained aerogels for ten oxides (and also for their mixture), in number of which are located by SiO_2 and Al_2O_3. However, the widest use received aerogels from silicon dioxide. The discussion predominantly further and will deal with them.

Aerogels are formed in solution with isolation of this component in solid phase [116]. In the solution are created such conditions that the macroparticle in proportion to its increase is charged, so that the connection to it of the new ions of connection, of which it consists, hinders. Thus it is possible to isolate this component in the solution in the form of macroscopic particles with the close sizes. At the following stage these particles are connected with each other, forming gel - macroscopic cluster with the rigid body.

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If this gel is dried, then aerogel will be obtained; however, to make this is complex - are too great the forces, which hold the molecules of the solution in the pores of the gel of small sizes. It found successful resolution of this problem in 1931. Kistler [114]. He placed gel into the autoclave and created supercritical conditions on the temperature and the pressure for the molecules, which are located in the pores. Thus it was possible to isolate aerogel, and its history is counted off from this time.

Technology of production of aerogel sufficiently bulky, complete cycle of its obtaining occupies several days. Furthermore, since the aerogel is formed in the solutions of spiritists, this technology is sufficiently dangerous. For this reason it was necessary to forego the large installation for its production - exploded. All this limits the accessibility of aerogel and raises its value. At present the base mass of the aerogel produced is utilized during the experiments in high-energy physics, where its cost is not main problem.

Aerogel is characterized by properties of fractal cluster in region of sizes

$$r_0 \ll r \ll R, \quad (8.1)$$

where r_0 - characteristic radius of particles, of which it is comprised, R - maximum size of pores. Taking this into account the average density of the piece of aerogel, limited by the sphere of radius r, according to formula S4.3 is equal to

$$\rho(r) = A\rho_0(r_0/r)^{3-D}, \quad (8.2)$$

where A - coefficient of the order of one, ρ_0 - substance density of the aerogel, when it is continuous mass, D - fractal dimensionality of cluster. Hence, in particular, it follows that the maximum size of pores in order of magnitude is equal to

$$R = r_0(\rho_0/\bar{\rho})^{\frac{1}{3-D}}, \quad (8.3)$$

where $\bar{\rho}$ - average density of substance in the aerogel.

Fractal dimensionality of gel of silicon dioxide was found in works [117, 118] at study of intensity of scattering X-radiation on gel at different wavelengths. Processing the results of measurements gives $D = 2{,}12 \pm 0{,}05$.

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Use of rougher results on scattering of X-rays on the aerogel of the dioxide of silicon [119], and also function of the distribution of pores according to sizes of [120] gives D=2.3. It is difficult to understand, with how is connected the disagreement between these data - with the different samples, or with errors of measurement.

Aerogel - porous substance with large internal surface. If we consider that its body is comprised of the identical spherical particles of radius r_0, which concern each other, then we have for the specific area of internal surface:

$$S = \frac{3}{r_0 \rho_0}, \qquad (8.4)$$

here ρ_0 - material density of aerogel, equal to 2.2 $g \cdot cm^{-3}$ for silicon dioxide. The majority of aerogels possesses to specific square of internal surface, which is located in interval of 500-800 $m^2 \cdot g^{-1}$ [116]. This corresponds to a radius of the components of its particles (2-3 nm). If these values are utilized in formula (8.3) for the aerogel with a density of 20 $g \cdot l^{-1}$, then in the case of the fractal dimensionality D=2.1 we will obtain the maximum size of pores R~0.5 μm, and in the case of D=2.3 the maximum size of pores will be R~2 μm.

Its strength and thermal resistance are important properties of aerogel. In particular, the aerogel of silicon dioxide retains its structure during the heating to 800 s, and heating above 1100 s leads to coarsening/consolidation of the particles of its body and sintering of aerogel. Fig. 8.1 depicts the dependence of Young's modulus of aerogel on his density.

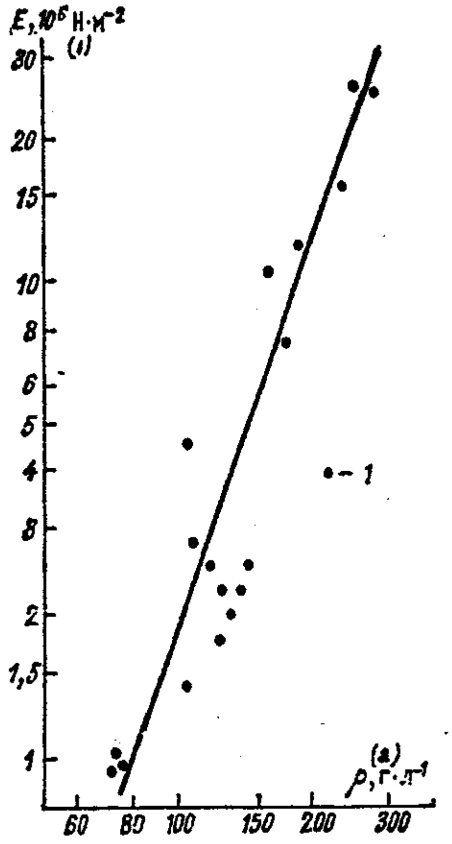

Fig. 8.1. Young's modulus E of aerogel of silicon dioxide: 1 - measurement [121]; unbroken curve - dependence $E = E_0(\rho/\rho_0)^\beta$ with parameters $E_0 = 4\cdot10^6$ $N\cdot m^{-2}$, ρ_0=130 $g\cdot l^{-1}$, β=2.8, ρ - density of aerogel.

Key: (1). $N\cdot m^{-2}$. (2). $g\cdot l^{-1}$.

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Let us continue these data into the region of lower densities and we will consider that the aerogel is broken down, if the pressure differentials on it are compared with Young's modulus. We will obtain that the density of aerogel 0.02 $g\cdot cm^{-3}$ corresponds to Young's modulus

0.2 atm., i.e., it is required for the production of this aerogel that the pressure differentials on it would not exceed this value. Aerogel with the specific weight/gravity, equal to the specific gravity of standard air, is characterized by Young's modulus of approximately 10 Pa, which corresponds to sound pressure 120 dB (hum of aircraft near it). Hence it follows that the aerogel with the specific weight/gravity of the order the specific gravity of air can exist. However, such aerogels will possess lower strength than created for commercial purposes, and they cannot be created on the basis of traditional technology.

S8.3. Special features of nature of ball lightning.

Carried out in book analysis, based on comparison of parameters of ball lightning, obtained from observational data, with contemporary information about processes and structures in nonequilibrium systems showed constructiveness of this approach. It was convenient methodological instrument for explaining the set of the elements, which compose the physical picture of ball lightning. In Table 8.1 the results of this analysis, which relate to the character of the processes, taking place in ball lightning are assembled. Let us comment table.

From analysis of observed properties of ball lightning it is possible to make series of conclusions relative to character of process of consumption of internal energy, which leads to glow of ball lightning. The main thing of them - the source of internal energy - chemical, moreover the reacting components must be combined from the very beginning. As far as the glow of ball lightning is concerned, is evident that effective temperature of the glowing zone is great (T>2000 K). When the radiating region is gas, we obtain that the radiating atoms or molecules are located in the thermodynamic equilibrium with atmospheric air. This makes it possible to isolate the type of atoms or molecules - candidates for the role of the radiating particles. Furthermore, for the effective transformation of chemical energy into the radiant energy it is necessary that the sizes of the radiating region would be not very small.

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Let us note that all these conclusions follow from the analysis of observational data; therefore they carry general character and must be assumed as the basis of any model of ball lightning.

At the same time interesting conclusions follow from assumption about filamentary or fractal structure of ball lightning. The analysis of the properties of ball lightning in this case gives the possibility to draw the conclusions, represented in Table 8.2. Results in fact given in this table are the development of idea about the filamentary structure of ball lightning, which was proposed by Aleksandrov, Golubyov and Podmoshenskiy [46].

Table 8.1. Special features of processes in ball lightning.

(1) Способ установления закономерности	(2) Выводы
(3) Сопоставление плотности энергии и времени жизни для гипотетической и наблюдаемой шаровых молний (см. гл. 2)	(4) Возможен только химический способ хранения энергии
(5) Сочетание большого удельного энерговыделения (интенсивный процесс) с большим временем протекания (медленный процесс) (см. § 3.3)	(6) Химический процесс сложный и может состоять из нескольких стадий
(7) Исследование конвекции в зоне химической реакции и тепловыделения (§ 3.1)	(8) Активное вещество шаровой молнии не может быть в виде газа или отдельных частиц (пыли или аэрозоля)
(9) Малое нагревание при диффузии газового окислителя к гетерогенному горючему (§ 3.2) (11) Высокая температура в области реакции — излучающей зоне (§ 6.1, 6.4)	(10) Окислитель и горючее с самого начала процесса совмещены
(12) Сравнение наблюдаемых параметров шаровой молнии с параметрами равновесного излучателя (§ 6.1)	(13) Эффективная температура излучающих частиц $T \geqslant 2000$ K
(14) Высокая эффективность тушения возбужденных атомов и молекул в атмосферном воздухе (§ 6.3, 6.4)	(15) Равновесные условия в зоне излучения, ограниченный набор сортов излучающих атомов или молекул
(16) Сравнение световой отдачи наблюдаемой шаровой молнии и горячей излучающей зоны (§ 6.4)	(17) Размеры элементарной излучающей горячей области не менее 0,1 мм

Key: (1). Method of the establishment of law. (2). Conclusions. (3). Comparison of energy density and lifetime for hypothetical and that observed ball lightnings (see Chapter 2). (4). Only chemical method of storing energy is feasible. (5). Combination of large specific energy release (intense process) with long time of course (slow process) (see S3.3). (6). Chemical process complicated and can consist of several stages. (7). Study of convection in zone of chemical reaction t of heat release (S3.1). (8). Active material of ball lightning cannot be in the form of gas or single particles (dust or aerosol). (9). Small heating during diffusion of gas oxidizer to heterogeneous fuel (S3.2). (10). Oxidizer and combustible from the very beginning of process are combined. (11). High temperature in scope of reaction - to radiating zone (S6.1, 6.4). (12). Comparison of observed parameters of ball lightning with parameters of equilibrium emitter (S6.1). (13). Effective temperature of radiating particles $T \geqslant 2000$ K. (14). High effectiveness of quenching of excited atoms and molecules in atmospheric air (S6.3, 6.4). (15). Equilibrium conditions in zone of emission, limited set of types of radiating atoms or molecules.* (16). Comparison of luminous efficiency of observed ball lightning and hot radiating zone (S6.4). (17). Sizes of elementary radiating hot region are not less than 0.1 mm.

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Conclusions, given in tables 8.1 and 8.2, make it possible to draw specific conclusions about separate characteristics of phenomenon (Table 8.3) in question. There are reliable conclusions, which can be made on the basis of the analysis of the observed data on ball lightning and their comparison with the existing information on the processes and the phenomena in excited air. The conclusions, given in table 8.3 can be considered as the system of the properties, by which ball lightning is characterized.

Data of table 8.3 composes base of phenomenological model of ball lightning. This model gives schematic representation about nature of ball lightning and separate sides of this phenomenon, without defining concretely the chemical composition of active material, the condition of onset and course of phenomenon. Thus, the results of the carried out analysis embed bed for the subsequent step in the study of ball lightning - the investigation of its properties under laboratory conditions.

Table 8.2. Properties, which follow from the structure of ball lightning.

(1) Свойства шаровой молнии	(2) Выводы
(3) Сферическая форма шаровой молнии и сохранение размеров в процессе эволюции (§ 3.1)	(4) Шаровая молния имеет структуру фрактального кластера или сгустка нитевидных аэрозолей
(5) Наличие электрического заряда шаровой молнии (§ 5.1)	(6) Создание поверхностного натяжения, обеспечивающего устойчивость кластера
(7) Взаимодействие нагретого каркаса шаровой молнии с окружающим воздухом (§ 3.4)	(8) Возникновение подъемной силы шаровой молнии. Нагревание прошедшего через каркас воздуха на 20÷200 К
(9) Ограниченное время образования кластера из твердых частиц (§ 4.3)	(10) Размеры частиц малы (не выше 1 мкм)
(11) Высокий электрический заряд и электрический потенциал шаровой молнии (§ 5.3)	(12) Разделение плазмы и заряженных твердых частиц на первой стадии их ассоциации в кластер, ограниченные размеры твердых частиц (не более 1 мкм)

Key: (1). Properties of ball lightning. (2). Conclusions. (3). Spherical form of ball lightning and maintaining sizes in process of evolution (§3.1). (4). Ball lightning has structure of fractal cluster or cluster of filamentary aerosols. (5). Presence of electric charge of ball lightning (§5.1). (6). Creation of surface tension, which ensures stability of cluster. (7). Interaction of heated body of ball lightning with surrounding air (§3.4). (8). Onset of lift of ball lightning. Heating passed through the body air on 20-200 K. (9). Limited time of formation of cluster from solid particles (§4.3). (10). Particle sizes are small (not above 1 μm).

(11). High electric charge and electric potential of ball lightning (§5.3). (12). Separation of plasma and charged solid particles during the first stage of their association into cluster, limited sizes of solid particles (not more than 1 μm).

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Table 8.3. Special features of physical nature of ball lightning.

(1) Характеристика	(2) Вывод
(3) Способ хранения внутренней энергии	(4) Только химический способ хранения энергии может обеспечить вытекающие из наблюдательных данных высокие удельные плотности энергии и большие времена ее расходования
(5) Особенности процесса тепловыделения	(6) Реагирующие компоненты — активное вещество шаровой молнии, находятся вместе до начала процесса; сам химический процесс сложный, т. е. имеет обратные связи, может включать в себя ряд последовательных стадий. Поэтому он одновременно — интенсивный и медленный
(7) Структура активного вещества в шаровой молнии	(8) Активное вещество шаровой молнии образует прочный каркас в виде фрактального кластера или нитевидных аэрозолей (комка). Одно из следствий такой структуры — возникновение подъемной силы при нагревании каркаса
(9) Электрические явления в шаровой молнии	(10) Каркас заряжен, что создает поверхностное натяжение и его устойчивость. Заряд каркаса создается при кластер-кластерной ассоциации отрицательно заряженных твердых частиц — такой заряд они имеют в слабоионизованной плазме воздуха. Чтобы ассоциация происходила быстро и каркас не разряжался в процессе роста, необходимы малый размер частиц (не более долей микрона), высокая плотность активного вещества (не менее долей грамма на 1 г воздуха) и разделение заряда частиц и положительного заряда плазмы на первой стадии процесса
(11) Свечение шаровой молнии	(12) Свечение шаровой молнии может создаваться как излучением нагретого каркаса или отдельных частиц, так и излучением возбужденных атомов и молекул. Во втором случае цвет излучения более определенно выражен. Эффективная температура излучающей области не менее 2000 К. Если излучение создается областью газа, то имеет место термодинамическое равновесие в этой области между возбужденными частицами и газом. Это означает, что излучающая способность области не зависит от способа

	создания возбужденных частиц и имеется ограниченное число сортов возбужденных атомов и молекул, ответственных за излучение шаровой молнии. Кроме того, размер элементарной излучающей газовой зоны составляет доли миллиметра, что значительно превышает размеры частиц

Key: (1). Characteristic. (2). Conclusion. (3). Method of storing internal energy. (4). Only chemical method of storing energy can ensure escaping/ensuing from observational data high specific energy densities and long times of its consumption. (5). Special features of process of heat release. (6). Reacting components - active material of ball lightning, are located together prior to beginning of process; chemical process itself complicated, i.e., it has feedback, it can include series of consecutive stages. Therefore it simultaneously - intense and slow. (7). Structure of active material in ball lightning. (8). Active material of ball lightning forms durable body in the form of fractal cluster or filamentary aerosols (lump). One of the consequences of this structure - onset of lift during heating of body. (9). Electrical phenomena in ball lightning. (10). Body is charged, which creates surface tension and its stability. The charge of body is created during a cluster-cluster association of the negatively charged solid particles - they have this charge in the weakly ionized plasma of air. So that the association would occur rapidly and body was not discharged in the process of growth, were necessary a small size of the particles (not more than fractions of micron), the high density of the active material (not less than fractions of gram by 1 g of air) and separation of the particle charge and positive charge plasma during the first stage of process. (11). Glow of ball lightning. (12). Glow of ball lightning can be created by both the emission of heated body or single particles and by emission of excited atoms and molecules. In the second case the color of emission is more definitely expressed. Effective temperature of the radiating region is not less than 2000 K. If emission is created by the region of gas, then thermodynamic equilibrium in this region between the excited particles and the gas occurs. This means that the radiating capacity of region does not depend on the method of designing of the excited particles and there is a limited number of types of excited atoms and molecules, critical for the emission of ball lightning. Furthermore, the size of the elementary radiating gas zone comprises fractions of millimeter, which considerably exceeds particle sizes.

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On the basis of available representations about physical nature of ball lightning let us attempt to answer question, why this phenomenon is observed relatively seldom. For this let us trace the character of the onset of ball lighting. The appearance of plasma, which is located under the high potential, is the first stage of the formation of ball lightning. The density of plasma can be small in comparison with its density in the glow and arc discharges, so that such conditions are sufficiently propagated in the prebreakdown and breakdown electrical phenomena, which take place in atmospheric air.

Following stage - inclusion of substance in the form of aerosol particles into the plasma. It is possible to visualize that as a result of electrical breakdown on the solid surface the evaporation of material occurred. Returning to the solid phas , this vaporized material in the air plasma became the solid aerosol particles, which took upon themselves the charge of plasma. When high electric fields appear on the evaporating solid surface, the vaporized material has electric charge, also, with the ejection into nonionized air.

Following relatively prolonged and calm phase is connected with formation of body of ball lightning during association of solid aerosols. It is necessary that gas dynamics of surrounding air would not lead to the structural failure. The body of ball lightning is formed after, it absorbs the active material, which can be ozone, in also some nitrogen and organic compounds in the atmosphere. Although a quantity of active material is relatively small and occupies a small part of the capacity of the body of ball lightning, we virtually do not have available specific information along this question.

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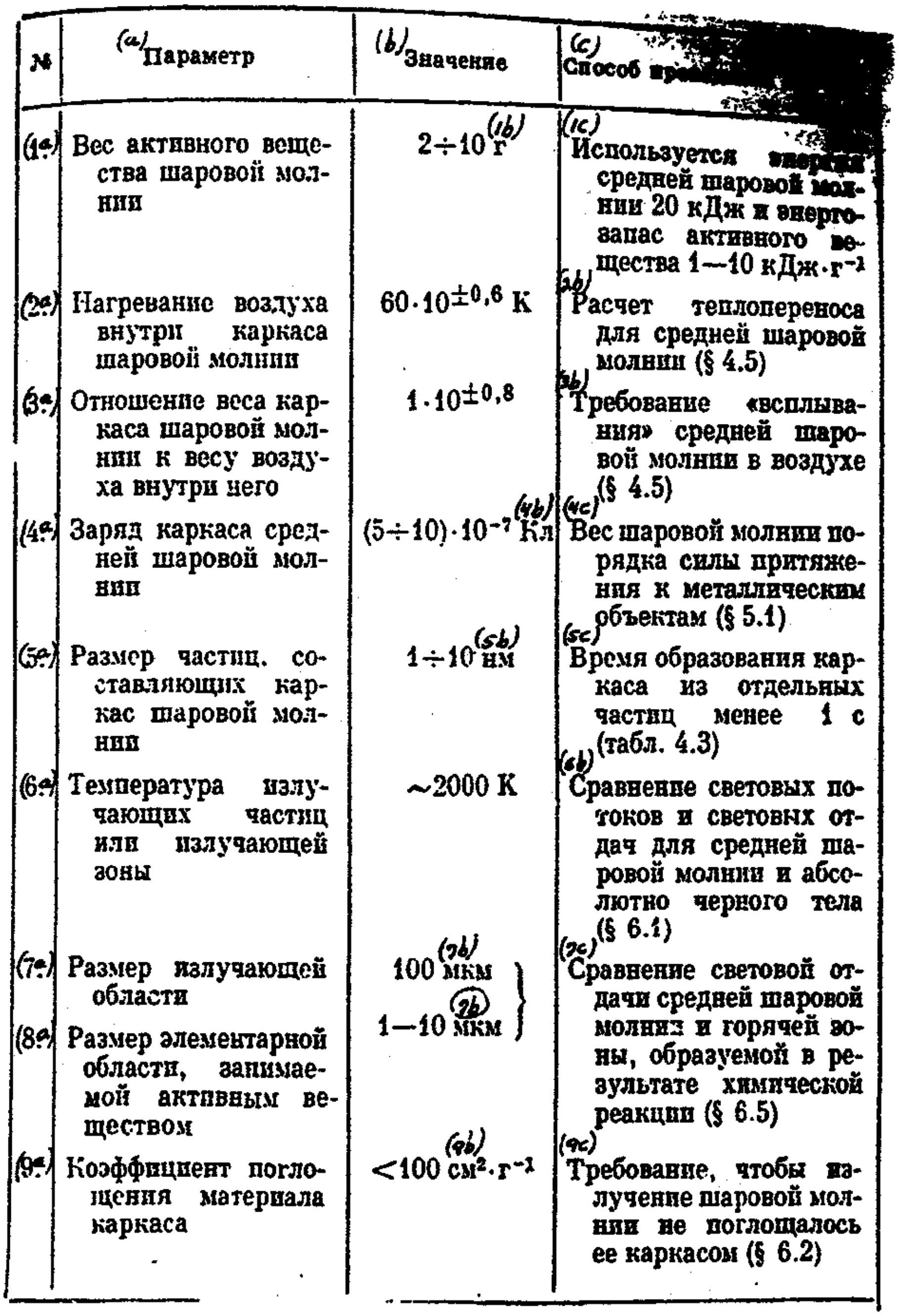
Table 8.4. Parameters of ave.age ball lightning.



№	(a) Параметр	(b) Значение	(c) Способ про[illegible]
(1a)	Вес активного вещества шаровой молнии	(1b) $2\div10$ г	(1c) Используется энергия средней шаровой молнии 20 кДж и энергозапас активного вещества 1—10 кДж·г$^{-1}$
(2a)	Нагревание воздуха внутри каркаса шаровой молнии	$60\cdot10^{\pm0.6}$ К	(2b) Расчет теплопереноса для средней шаровой молнии (§ 4.5)
(3a)	Отношение веса каркаса шаровой молнии к весу воздуха внутри него	$1\cdot10^{\pm0.8}$	(3b) Требование «всплывания» средней шаровой молнии в воздухе (§ 4.5)
(4a)	Заряд каркаса средней шаровой молнии	$(5\div10)\cdot10^{-7}$ (4b) Кл	(4c) Вес шаровой молнии порядка силы притяжения к металлическим объектам (§ 5.1)
(5a)	Размер частиц, составляющих каркас шаровой молнии	$1\div10$ (5b) нм	(5c) Время образования каркаса из отдельных частиц менее 1 с (табл. 4.3)
(6a)	Температура излучающих частиц или излучающей зоны	~2000 К	(6b) Сравнение световых потоков и световых отдач для средней шаровой молнии и абсолютно черного тела (§ 6.1)
(7a)	Размер излучающей области	100 (7b) мкм	(7c) Сравнение световой отдачи средней шаровой молнии и горячей зоны, образуемой в результате химической реакции (§ 6.5)
(8a)	Размер элементарной области, занимаемой активным веществом	1—10 (8b) мкм	
(9a)	Коэффициент поглощения материала каркаса	<100 (9b) см$^2\cdot$г$^{-1}$	(9c) Требование, чтобы излучение шаровой молнии не поглощалось ее каркасом (§ 6.2)

Key: (a). Parameter. (b). Value. (c). Method of conducting the estimate. (1a). Weight of the active material of ball lightning.

(1b). g. (1c). Is utilized energy of average ball lightning 20 kJ and energy reserve of active material 1-10 kJ·g^{-1}. (2a). Heating air within the body of ball lightning. (2b). Calculation of heat transfer for average/mean ball lightning (§4.5). (3a). Ratio of the weight of the body of ball lightning to the weight of air within it. (3b). Requirement of the "floating up" of average ball lightning in air (§4.5). (4a). Charge of the body of average ball lightning. (4b). C. (4c). Weight of ball lightning of the order of attracting force to the metallic objects (§5.1). (5a). Size of the particles, which compose the body of ball lightning. (5b). nm. (5c). The time of the formation of body of the single particles is less than 1 s (Table 4.3). (6a). Temperature of the radiating particles or radiating zone. (6b). Comparison of the luminous fluxes and the luminous efficiencies for average/mean ball lightning and blackbody (§6.1). (7a). Size of the radiating region. (7b). μm. (7c). Comparison of the luminous efficiency of average/mean ball lightning and hot zone, formed as a result of chemical reaction (§6.5). (8a). Size of the elementary region, occupied by active material. (9a). Coefficient of absorption of the material of body. (9b). cm^2·g^{-1}. (9c). Requirement so that the emission of ball lightning would not be absorbed by its body (§6.2).

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Therefore it is sufficiently difficult to estimate the probability of this event, when it is characterized by the parameters, necessary for the existence of ball lightning.

It follows from given diagram of formation of ball lightning that for its appearance is necessary existence of certain sequence of events, each of which is random. Hence it is possible to draw the conclusion that ball lightning - phenomenon rare.

Analysis of processes, which take place in average/mean ball lightning, taking into account observed characteristics of ball lightning made it possible to estimate some numerical parameters of ball lightning. The values of these parameters, assembled in Table 8.4, supplement information about ball lightning according to observational data (see Table 1.5) and they expand our representation about ball lightning.

§8.4. Phenomenological model of ball lightning.

Carried out analysis and obtained conclusions (see Table 8.3) make it possible to construct schematic model of ball lightning. Aerogel is its analog according to the structure, and using the method of the processing chemical energy into the radiant energy - pyrotechnic illuminating composition. Such fundamental four models are the following. Ball lightning has a body, similar to the rarefied aerogel with the specific weight/gravity of the order the specific weight/gravity of atmospheric air. This body is electrically charged, which creates its stability and rigidity. In the pores of body the small quantity of active material, which is the mixture of fuel and oxidizer is located. The weight of active material several times of less than the weight of body. Active material within the body has fractal structure and can be represented as the system of the large number of thin filaments.

Phenomenon in question consists of propagation of wave of chemical reaction and, consequently, also wave of glow along separate filaments of active material. The simultaneous glow of many filaments creates the impression of volumetric glow. The special features of the propagation of the wave of chemical reaction along the system of the intersecting filaments determine the transiency of the processes of heat release and glow. As a result the evolution of this system can lead to its blast, to the decay on the part or the slow extinction.

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Quantitative characteristics of process of propagation of wave of chemical reaction along separate filament were examined earlier. In the appropriate parameters of the filament of active material they can be coordinated with the observed parameters of ball lightning. One should emphasize in this case that the special features of chemical process were not utilized in these estimates. Chemical process can have complicated nature and include the stages of delay, feedback, multistage reactions. This depends both on the specific composition of active material and conditions of the course of process, and it is reflected in the character of its course. For this reason without the use of a specific composition of active material the model of ball lightning is schematic.

Together with common model of ball lightning can be used whole series of models, which make it possible to investigate only separate sides of this phenomenon. In particular, heating by the laser of the lump of thin metallic wire made possible to investigate the lift of ball lightning and gas dynamics of its surrounding air. Electric iron is the convenient model of ball lightning during the investigation of the sensation of heat near it. The isolated charged sphere simulates some of its electrical properties and it makes it possible to understand, for what time it is discharged in the actual air.

All these and similar models are convenient by their simplicity. They make it possible to in detail analyze the separate sides of phenomenon and thus to give clear information about the separate elements of the common physical picture of ball lightning.

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CONCLUSION.

Material represented in book makes it possible to total next stage of investigation of ball lightning. Specifically, after was carried out the detailed analysis of the observations of ball lightning with obtaining of quantitative characteristics the stage in question it made it possible to reveal physical nature of ball lightning with the explanation of the separate sides of the phenomenon being investigated. It is significant that in this case the contemporary physical representations about the phenomena close in nature were used, and also the existing quantitative information on the specific physical and physicochemical processes. As a result we have the physical picture of nature of ball lightning.

Understanding fundamental laws governing physical nature of ball lightning discloses path to following stage - laboratory investigation of ball lightning. This problem was carried out in the experiments of Kapitsa, Barry, Powell and Finkelstein and some other scientists, where was demonstrated the existence of the long-lived glowing formation of spherical form under the atmospheric conditions, which is not attached to the walls. Each of these experiments can be considered the reproduction of phenomenon, which reflects the fundamental observed properties of ball lightning. By laboratory investigation of ball lightning is understood the detailed laboratory study of the specific groups of processes and structures, which relate to ball lightning. Such investigations will help to more deeply understand nature of atmospheric phenomena and to be selected at qualitative laws governing the specific physical phenomena, objects. The study of the processes of the propagation of the waves of chemical reactions, combustion and glow in the substance, absorbed by the rarefied porous material, is one of such problems. The discharged aerogel as the porous medium and pyrotechnic connections as the chemically active substance is the adequate model for these investigations.

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APPENDIX.

FRACTAL STRUCTURES.

Target of this appendix consists in explaining of sense of fractal systems, giving general physical idea about them, and also describing character of investigations in this direction. Fractal structure refers to the structure of globular lightning and therefore it is of interest in the layout of this book. Fractal systems are interesting from the point of view of the achievements of the sciences of last time, which changed our representations about many objects and concepts. In some of these representations (for example, chaos, nonlinear waves, structure in the gas and the plasma) we now pack entirely another sense, than twenty - thirty years ago. In this respect many contemporary views on the objects and the phenomena previously had to seem exotic.

The same it is possible to speak also about ball lightning. The unusualness of this phenomenon made it necessary to think that the surprising effects compose its base. In spite of the incompleteness of contemporary concepts about ball lightning, from these positions we can confirm such guesses. Specifically, the fractal structure of ball lightning from the point of view of old representations about her physical nature must seem exotic. Actually, we became accustomed, that the solid state of substance can be amorphous or crystal. In the first case it can have pores, but usually the space, which falls to the pores, the same scale or less than the space, occupied by the material of substance. Despite the fact that in the technology there were very "perforated" porous substances - aerogels (see S8.3), whose space of pores considerably exceeded the space of material, such objects could be examined only as exception.

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Now our relation to such objects (we call them objects with fractal structure) significantly changed. They are observed in the different physical situations, which makes it possible to consider them as a certain class of physical objects. The conducted investigations made it possible to understand the laws of the formation of such units and to study their properties. In the process of these experiments the circle of objects relating here was widened. All this as a whole created new relation to the fractal systems as to the real objects, with the clear properties.

Fractal structure, according to one of properties, assumed as basis of its definition - this system with fractional dimensionality (fractional is converted from English as fractional). Such systems are familiar in mathematics; however, they drew the attention of physicists only in the last decade, after appeared the remarkable monograph of Mandelbrot [1]. The use of fractal representations in physics proved to be fruitful (for example, see surveys [2-8]). Let us begin the explanation of these concepts.

Properties of fractal system are simplest to understand based on example to continuous fractal line (Fig. P.1). Let us visualize that we want to measure the length of river. Let R - straight-line distance from the source of river to mouth. It is clear that the length of river in reality is more due to the brokenness of coast. However, we not can to unambiguously determine its value. Let us assume that we arranged marking poles on the bank of river at a distance of 1 km from each other.

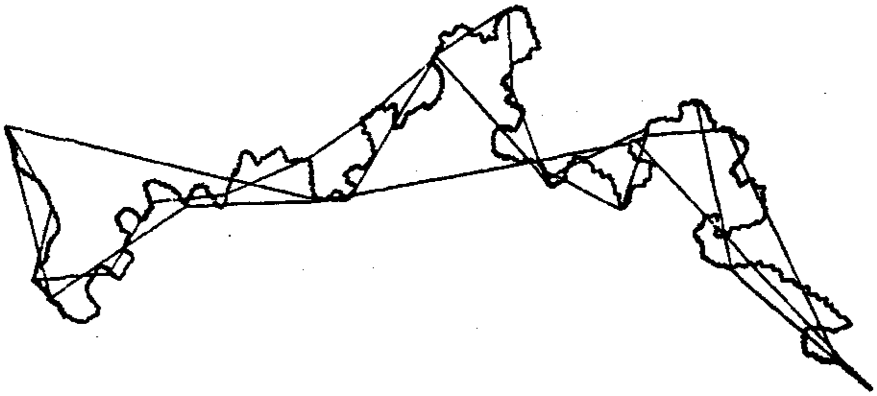

Fig. P.1. Curve with the fractal structure. The shore line of river, lake, sea takes this form. The method of measurement of the length of curve, which is based on the approximation with curved broken line with the identical length of segments, is shown. The fractal dimensionality of this curve is equal to 1.3±0.1.

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We will obtain a certain value of the length of river, which exceeds R. Let us further supply marking poles at a distance of 100 m from each other. The measured length will increase. Finally, if we measure the shore line of river by steps, an even larger value will be obtained. As is evident, the less lower range for the measurement we select, the greater the degree in which the brokenness of coast is reflected in the result. Thus, the length of river depends on the scale, with which we measure it (see Fig. P.1). This dependence is conveniently represented in the form

$$L = a\left(\frac{R}{a}\right)^D, \quad (\Pi.1)$$

where a - scale, R - distance from the mouth to the source on the straight line. Value D is called fractal dimensionality.

Fractal system convenient for analysis is so-called figure of Koch. For its obtaining the section of intended size is taken and converted according to the specific law. Further each of the sections of the obtained figure is converted according to the same law. This operation is conducted repeatedly.

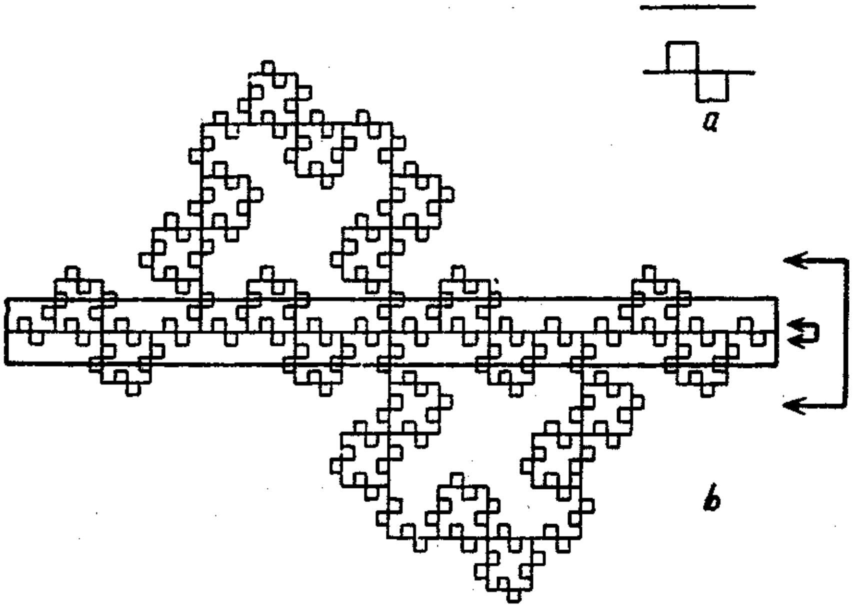

Fig. P.2. Koch's figure with the fractal dimensionality D=1.66. a) the translation algorithm of severing; b) cluster after triple transformation on this algorithm. By arrows is indicated the scale of the rectangles, which cut out the pieces of cluster for determining the fractal dimensionality D_β

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Fig. P.2 presents one of the figures of such type, obtained by the transformation of section on the algorithm, which is given in the upper right-hand corner of figure. This transformation for the figure, depicted in Fig. P.2b, is carried out three times. During each transformation the scale decreases four times, and the overall length of element increases 2.5 times. Hence according to formula (P.1) the fractal dimensionality of figure is equal to $D = \ln 10/\ln 4 = 1{,}661$.

Example to lines of type in question is trajectory of Brownian motion of particle. Let after each magician Brownian particle be displaced by distance of a, but direction of motion is random for each step. Then the square of particle displacement for the large number n of steps is equal.

$$R^2=\left(\sum_{i=1}^{n}\mathbf{r}_i\right)^2=\sum_{i=1}^{n}r_i^2+\sum_{i\neq k}\mathbf{r}_i\mathbf{r}_k=na^2+\sum_{\substack{i,k=1\\ i\neq k}}^{n}\mathbf{r}_i\mathbf{r}_k, \qquad (\Pi.2)$$

where $\mathbf{r}_i$ — radius-vector of the i displacement, and was used condition $r_i=a$. Since the direction of each displacement is by chance, the second term on the average is equal to zero. Hence we obtain the known formula of the Brownian motion: $R^2=na^2$. Introducing the total particle path length $L=na$, we will obtain from the formula (P.2) that

$$L=a\left(\frac{R}{a}\right)^2, \qquad (\Pi.3)$$

i.e. that the fractal dimensionality of the trajectory of Brownian motion is equal to two. Let us note that this result does not depend on the dimensionality of space.

In case in question, when continuous line contains large number of separate components/links, value of fractal dimensionality of line lie at interval 1<D<2. In this case value D=1 corresponds to straight line, and D=2 answers the identical scale of the separate components/links of line and their random arrangement. In other cases fractal dimensionality has the intermediate value (for example, see Fig. P.1).

Line, which has fractal structure and which does not have branchings - simplest example of fractal systems.

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It is possible to propose the set of two-dimensional and three-dimensional fractal structures (see [1]). As one of such examples let us examine porous body. Investigations show that according to the sizes of pores corresponds to fractal structure. In this case the fractal dimensionality, for example, of brown coal [10] comprises 2.56±0.03, fractal dimensionality it is sandstone [11] it is located in interval of 2.57-2.87 with relative volume of pores 5-30%. In the latter case the fractal properties of samples are observed in the wide region of sizes - from 0.1 to 100 μm.

Adsorptivity of substance is characterized by its specific surface area. At low temperatures entire internal surface of porous body is covered with molecules adsorbed by it. However, if in the porous substance are small pores with the sizes of the order of molecular dimensions, then determined thus the complete specific surface area of substance depends on the size of the adsorbed molecules. [12] Show investigations that in many instances the specific surface area of substance depending on the sizes of the adsorbed molecules can be represented as fractal system.

Another object with fractal structure, which has direct relation to thematics of this book - this is fractal cluster (see S4.3). It is the structure, comprised of the large number of macroparticles (see Fig. 4.3). Under some laws of the association of particles cluster obtained in this case possesses fractal properties and therefore it is called fractal.

Let us pause at fundamental properties of fractal structures. One of them - the property of self-similarity. If we around a certain point of fractal structure conduct the specific figure (for example, circle or sphere) and to repeat this operation, after selecting as the base the different points of fractal structure, then elements, which are found in each case within this figure, on the average will prove to be similar in the sense that on the average they contain the identical number of elements. For the symmetrical fractal structure (Koch's figure) this operation can isolate the identical combination of the structural elements.

Another property of fractal structures includes previous and considers correlation properties of structure.

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Let us break fractal system into N identical elements and will introduce the correlation function

$$C(r) = \frac{1}{N}\sum_{i}\rho(\mathbf{r}_i)\rho(\mathbf{r}_i + \mathbf{r}) = \frac{\langle\rho(\mathbf{r}_i)\rho(\mathbf{r}_i + \mathbf{r})\rangle}{\langle\rho(\mathbf{r}_i)\rangle}, \qquad (\Pi.4)$$

where $\mathbf{r}_i$ - coordinate of the i element; $\rho=1$ if at the particular point of space the element of this system is found, and $\rho=0$, if it at the particular point is absent. During this representation the space is divided with the aid of the grid into the cells and it is further customary to assume that the piece of fractal system either is located or it is not located in this cell. This diagram is convenient for the mathematical analysis of fractal structure. In the extreme case, when the size of cell vanishes, value $\rho(\mathbf{r}_i)$ is the space density of system.

Fundamental property of fractal systems is given by dependence

$$C(r)=\frac{\text{const}}{r^{d-D}}, \quad a \ll r \ll L. \quad (\Pi.5)$$

We analyze this property. Value C(r) in fact is the average density of system at a distance of r from the points of this system. This distance is small in comparison with the size of system L and it is great in comparison with the scale of the element of this system a. In the formula (P.5) value d is the dimensionality of space, D - fractal dimensionality of the system in question. For the continuous system d=D and the average density of the elements of system does not depend on r.

One of consequences of correlation property (P.5) is formula (4.17), according to which material density of fractal cluster, which is located in sphere of radius r with center in one of points of cluster, changes according to the law

$$\rho(r) = \rho_0 \left(\frac{a}{r}\right)^{d-D}, \quad (\Pi.6)$$

where a and ρ_0 - some constants. It follows from this formula that the average density of the material of cluster falls from an increase in the size of the chosen element of fractal system. This apparent contradiction is removed, if we consider the fact that in proportion to an increase in the space within it being isolated appear the pores ever of larger and large sizes.

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Therefore relative volume of pores within the chosen element increases with an increase in the space of this element.

In plan of study of ball lightning among fractal structures to us, in the first place, interests fractal cluster - system of connected macroparticles, which has fractal structure. Fractal clusters are formed under specific conditions for the association of macroparticles. Such conditions can be realized with the formation of gel in the solution, during the relaxation of vapors of metals, with the aggregation of particles in the time. Fractal clusters and conditions for their formation are examined in surveys [4-6] and are represented in collections [13-15]. As an example let us give the results of work [16], where the clusters were formed from the steam flame, obtained during the laser evaporation of metals (iron also titanium). During the first stage of the relaxation of the vaporized metal from the vapor are formed the particles with a mean radius of 20 nm. Further these particles are united into the cluster with size on the order of 1 μm. The fractal dimensionality of this cluster is close to 1.8.

It should be noted that investigation of relaxation of vapors of metals played special role both from point of view of understanding process of forming fractal clusters and in plan of understanding structure of ball lightning. Namely, contemporary concept about the structure of ball lightning arose from the analysis of the structures, which are formed during the relaxation of the vaporized metal (see §4.3). Further, the detailed analysis of the structure carried out in work [17], which appears during the relaxation of vapors of metal, demonstrated the fractal character of such systems. Understanding this fact led then to the creation of the models of the formation of fractal clusters and on their basis - to obtaining of contemporary representations and contemporary information about such systems.

During analysis of cluster, formed during relaxation of vapors of metals, authors of work [17] placed photograph of this cluster, obtained with the aid of electron microscope (see Fig. 4.3), to square grid. Then the projection of cluster was written on this grid in such a way that each cage of grid could be either empty or filled. The obtained picture was processed by the determination of correlation function (P.4) and on its base was defined the fractal dimensionality of cluster, designated as D_α.

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Another method of determining the fractal dimensionality of cluster consisted of the determination of the number of filled cages squared of the given size. In this case fractal dimensionality is determined on the basis of formula (P.6) and is designated D_β. An error in the obtained values of fractal dimensionality depends both on the collected statistics and on the degree of "fractalness" of object (for example, the degree of satisfaction of conditions (P.5)). Natural to expect the coincidence of values D_α and D_β. The described methods of the determination of the fractal dimensionality of cluster became subsequently universal (Fig. P.3).

Fundamental basis of physics of fractal clusters consists of set of models, which describe process of formation of fractal clusters with aggregation of macroscopic particles, and also of aggregate of the results, which ensue from analysis of these models. Experiment is developed considerably slower than the theory, which presents in essence computational experiment and simulation. Therefore experimental investigations determine, mainly, reliability and reality of the obtained representations, and they do not affect their character.

Some results, which relate to structure of fractal cluster, are represented in S4.3. Table 4.2 contains the values of the fractal dimensionality of the clusters, formed in the different modes of aggregation.

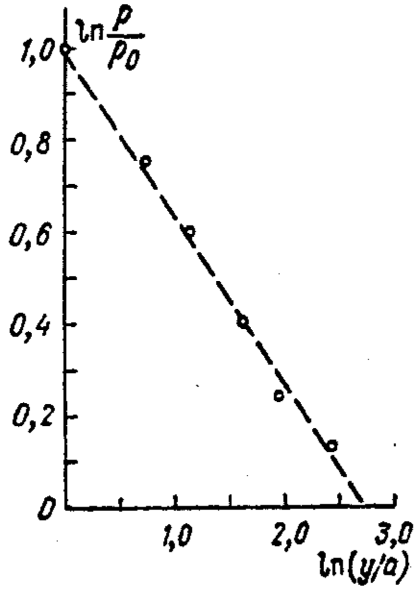

Fig. P.3. Dependence of the density of the piece of cluster (see Fig. P.2), which is cut out by rectangle, from the width of rectangle. The density of the piece of cluster ρ - the ratio of the overall length of cluster in the rectangle to the area of rectangle - is given in the arbitrary units, the width of rectangle y - in the units of minimum scale. Broken line corresponds to the fractal dimensionality of cluster 1.64; point - processing data of Fig. P.2.

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From the point of view of the fractal clusters, which are formed in the gas, the vapor and the solution, of greatest interest is a cluster-cluster association. In this case during the first stage of the process of relaxation the material, which is located in the gas or the solution in the form of separate atoms or molecules, is assembled during the solid phase in the form of the large number of macroparticles, which have small sizes. At the following stage of process these macroparticles are united into the clusters of small sizes, and those, in turn, are collected into large-size clusters.

It follows from Table 4.2 that structure of formable cluster depends on character of motion of associated particles. These results relate to the cases, when the probability of the adhesion of particles with their mutual contact - order of one. These data should be supplemented with one additional mode of the aggregation of the clusters, when the probability of the association of particles with their contact is small. This case is called the mode of the cluster aggregation, limited by reaction (reaction - limited cluster aggregation). In the mode of cluster aggregation the structure of the formable cluster does not depend on the character of particle motion. The fractal dimensionality of the cluster, which is assembled of the clusters of smaller sizes, in this case comprises 1.98±0.02 [18, 19], if its base compose monodisperse particles and 2.11±0.03 [19], if it is constructed from the polydisperse particles. These values are in accordance with the experimental data, given in S4.3.

Let us note that for extended system fractal properties can be observed in limited region of distances, determined by formulas (4.18) and (8.1). At the distances, which exceed a radius of correlation $\tilde{R}$, this system is uniform, while at the distances smaller than the radius of correlation, it possesses fractal properties.

Let us pause at one more special feature of fractal cluster, which is interesting from point of view of ball lightning. As it follows from the analysis carried out in the book, ball lightning has a body, which possesses fractal properties. This body as porous body adsorbs the active material, which occupies a small part of the space, occupied with pores. Question arises, in what form the active material is located - does it occupy separate connected regions or is it found within the body in the form of separate grains. If we rest on the results of experiment [20], then the second possibility is more preferable.

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In experiment [20] structure of dye/pigment (rhodamine B or malachite of green), absorbed by porous glass, was investigated. To the pores of glass fell 0.28 part of its total space, the mean diameter of pores was 4 nm, the specific internal surface of glass composed 200 $m^2 \cdot g^{-1}$. It turned out that the adsorbate formed fractal cluster with the fractal dimensionality 1.74±0.12.

Results, obtained for fractal clusters, are of interest, also, for other geometric figures with fractal properties. The investigations of other fractal systems in exactly the same manner expand our representations about the fractal clusters. Therefore further we will rapidly examine some geometric fractal systems. To them can be attributed dielectric breakdown [21-23], isolation of metal on the electrode during electrolysis [24, 25], an increase in the films from gas and vapor phase [26], an increase in the crystal films on amorphous base [27] and so forth. Let us pause briefly at the hydrodynamic fractal systems, whose convenience consists of the simple experimental simulation.

The first of hydrodynamic fractal systems in question answers so-called viscous dactylate [28-31]. If we attempt to push liquid with a small viscosity (for example, water) through the viscous fluid (for example, oil), then under specific conditions appears the "instability of viscous dactylate". As a result the nonviscous liquid takes the form of the branched finger, moreover with an increase in the pressure on the nonviscous liquid increasingly lower ranges on the branchings off of finger/pin appear. The obtained structure possesses fractal properties.

Similar method of designing of hydrodynamic fractal structure is realized in instrument of Healy Shaw [29, 31, 32]; although figure at first glance obtained in this case proves to be more symmetrical. Healy Shaw instrument consists of two parallel plates, between which is placed the viscous fluid. In the middle of upper plate is an opening, through which under the pressure injects itself the nonviscous liquid (water) or gas (air). The injected substance takes the form of the bubble, from which they will move away in the radial directions several elongated flange-fingers.

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These fingers/pins can have branched structure and each of them on the form it resembles the structure, formed during the extrusion of the nonviscous liquid through the viscous. As is evident, nature of formation of both hydrodynamic structures is identical.

Strongest multiplexing during creation of hydrodynamic structures occurs during use as viscous fluid of liquid crystal [33]. Some results of the simulation of this process of [34] are represented in Fig. P.4. It follows from the figure that in proportion to the decrease of surface tension (in the dimensionless units) and increase in the value of a radius of the ends of the cluster occurs the sharper division of scale during the development of system, which makes the fractal properties of system more clearly expressed.

Enumerated geometric fractal structures, in spite of different nature of origin, they have much in common. The resemblance of such systems is developed in their fractal nature, and sometimes and corresponding to these structures fractal dimensionalities prove to be close. Therefore impression is created, that the formation of such systems is described by close laws.

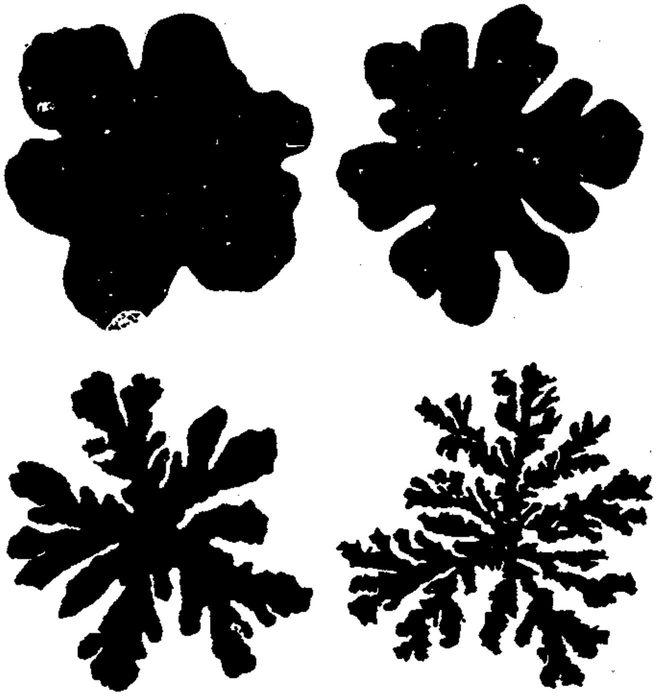

Fig. P.4. Hydrodynamic geometric figures, been simulated in theory [34] for the conditions of Healy Shaw instrument in the different parameters of system (rate of the injection of additive, the size of system, the viscosity of liquid, etc.).

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Actually, theoretical analysis is shown (for example, see [34-37]), that the evolution of such systems for many conditions for their development can be described by Laplace's equation for the function, which relates to the different values 1).

FOOTNOTE 1). These values are particle density in the description of an increase in the fractal cluster in the case of the diffusion motion of the associated particles, electric potential with the dielectric breakdown, pressure with the formation of viscous finger/pin, temperature in the case of crystallizing the film on the amorphous surface, etc. ENDFOOTNOTE.

This creates analogy for the distribution functions in the systems, which have different nature, if the boundary conditions, which describe the formation of data of systems, are close. In this case important value for the formation of fractal systems has a presence in system of large fluctuations.

It is significant that systems in question, which look like consisting of random set of elements, are determined systems. They are created in the parametric domain, the corresponding to stable development system. The factors, which lead to the large fluctuations in the system, play fundamental role in formation and evolution of such systems. Anisotropy is one of such factors [32, 38]. The presence of large fluctuations causes the fragmentation of scale with the formation of system, i.e., creates fractal system in the stable process. The relationship of different fractal systems helps their study. In particular, since the hydrodynamic fractal systems are simulated on the simple installations, this makes it possible to experimentally analyze the role of different factors in the formation of fractal systems.

From that outlined above it follows that fractal cluster is one of studied geometric fractal structures. There is a whole series of other fractal systems, each of which has their specific character, but all them unites single nature of the formation of systems. Combined analysis of such systems makes it possible to glance at them from unity of opinion and supplements our representations about the fractal clusters.

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