Ball lightning –
a bubble of molten glass

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Ball lightning – a bubble of molten glass. Mark B. Zhelezniak

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Abstract. The work proposes a model of ball lightning (BL). Ball lightning is considered as a thin-walled bubble of foamed molten glass filled with hot gas. The BL shell material is formed from molten soil components as a result of an electrical discharge in the soil caused by cloud-to-ground lightning strike. The bubble is inflated by gases released from the discharge channel. The shell thickness can range from tens to hundreds of micrometers, and the BL mass reaches several tens of grams for medium-sized BL (20–40 cm). The pressure of the hot gas filling the BL differs only slightly from the atmospheric pressure, which ensures the integrity of the BL shell. Ball lightning may not have internal energy sources, acquiring energy at birth. The initial temperature of long-lived ball lightning is about 2500 K, this value decreases due to the cooling of the BL. Ball lightning may or may not have an electric charge, this is not a decisive factor for its existence.

Micron-sized gas bubbles, which form the foamy structure of the shell, burst when approaching the surface of the BL. As a result, hot gas and nanodroplets are ejected into the surrounding air. An eyewitness perceives this as sparks and hears a buzzing or hissing sound. Nanodroplets cool in the air, turning into glass nanoparticles. The resulting cloud of nanoparticles scatters the light of BL forming a halo. In addition, the release of hot matter from the surface of BL creates a protective layer that prevents direct contact of ball lightning with the surrounding cold air, which reduces heat loss.

An explanation for the weak thermal radiation of BL is provided. At temperatures above 2000 K, the internal molecular structure of the melt—the network of unit cells—disintegrates. This leads to a significant reduction in infrared radiation due to the disappearance of the main source—the collective vibrations of the network. The processes that lead to the formation of ball lightning of various colors are also discussed.

A system of equations for describing the time evolution of ball lightning is proposed, and solutions are obtained for some special cases.

Keywords: ball lightning, ordinary lightning, fulgurite, foamed molten glass, thin-walled bubble, halo, visible and thermal radiation, energy characteristics, time evolution.

Contents

Preface - Conversation with artificial intelligence chatbot Microsoft Copilot about ball lightning

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1. *Please give a brief overview of the state of the art in ball lightning research.*

Ball lightning remains one of the most mysterious and elusive atmospheric phenomena, and modern research continues to explore it from multiple angles:

- **Observational studies** have documented thousands of eyewitness accounts, often during thunderstorms, but the rarity and unpredictability of ball lightning make it difficult to study in the wild.
- **Laboratory experiments** have attempted to recreate ball lightning or similar luminous plasma structures. These include long-lived luminous formations (LLFs) and artificial plasmoids, which help researchers understand the physical conditions that might give rise to the phenomenon.
- **Theoretical models** span a wide range—from chemical and plasma-based explanations to optical illusions. Some models propose spinning electric dipoles or magnetic knots to explain the stability and motion of ball lightning, while others suggest it could be a purely optical effect caused by internal light reflection.
- **Controversy and skepticism** still surround the topic. Some scientists question whether ball lightning is a distinct phenomenon at all, or simply a misinterpretation of other natural events.

Recent work, such as that by Vladimir Bychkov, has focused on comparing natural and artificial ball lightning, emphasizing the need for a unified framework that bridges observational data, experimental results, and theoretical insights.

2. *Could you give a brief definition of ball lightning?*

Certainly! Ball lightning is a rare and unexplained atmospheric phenomenon where a glowing, spherical object appears during thunderstorms. It can range from the size of a golf ball to several meters in diameter and usually lasts a few seconds before disappearing, sometimes with an explosion. Scientists speculate it may involve plasma, electromagnetic fields, or even chemical reactions, but its exact nature remains a mystery.

3. *Does ball lightning really exist or is it speculation based on very vague and unreliable eyewitness reports? In our time, when CCTV cameras are installed everywhere in cities and on highways, the registration of ball lightning would also become widespread. However, such data is practically absent on the Internet. Does this indicate that ball lightning is a fiction, an illusion perceived as a real object?*

That's a fair point—if ball lightning were common, we'd expect to see more footage from security cameras and dashcams. While sightings remain rare, there are videos claiming to capture ball lightning. However, many recordings are debated, with skeptics arguing they could be electrical discharges, reflections, or even hoaxes.

The lack of widespread, verified footage doesn't necessarily mean ball lightning is fictional—it could simply be extremely rare, difficult to capture, or misunderstood. Some scientists propose that ball lightning occurs under specific atmospheric and electromagnetic conditions, making it unpredictable and hard to document systematically.

4. *Can you give an example of an observation where you could say without a doubt that it was indeed ball lightning?*

One of the most scientifically significant observations of ball lightning occurred in China in 2012. Researchers studying ordinary lightning on the Qinghai Plateau accidentally recorded a high-speed video and optical spectrum of a ball lightning event. The glowing sphere appeared just after a cloud-to-ground lightning strike, lasting about 1.3 seconds before vanishing. The spectral analysis revealed elements from the soil, supporting a theory that ball lightning forms when lightning vaporizes minerals, creating glowing plasma.

This observation is one of the few cases where ball lightning was scientifically recorded and analyzed, making it a strong piece of evidence for its existence.

5. *There are dozens of models of ball lightning in literature based on various physical principles. Can you formulate criteria based on which the most preferable model can be selected?*

Great question! Since ball lightning is still a mysterious phenomenon, selecting the most **preferable** model requires evaluating several key criteria. Based on scientific literature, here are some factors that could help determine the most viable theory:

1. **Consistency with Observations** – The model should explain well-documented characteristics of ball lightning, such as its **size, movement, duration, and disappearance**.
2. **Energy Source Explanation** – Since ball lightning appears to sustain itself for seconds, the model must provide a **plausible mechanism** for storing and releasing energy.
3. **Reproducibility** – A strong model should allow for **experimental verification**, meaning scientists should be able to recreate ball lightning under controlled conditions.
4. **Mathematical and Physical Validity** – The theory must align with **known physics**, including electromagnetism, plasma physics, and quantum mechanics.
5. **Compatibility with Environmental Conditions** – The model should explain why ball lightning appears in **specific weather conditions**, such as thunderstorms.
6. **Predictive Power** – A good model should not only explain past observations but also **predict new phenomena** that can be tested.

Some researchers have proposed models based on **plasma physics, quantum effects, and chemical reactions**, but no single theory has been universally accepted

6. *Could you comment on ball lightning models that include dark matter, magnetic monopole, or ether inhomogeneities?*

Certainly! Ball lightning has intrigued scientists for centuries, and some **alternative models** propose explanations based on unconventional physics. Here's a brief overview of a few speculative theories:

1. **Dark Matter-Based Models** – Some researchers suggest that ball lightning could involve **dark matter interactions**, particularly in the form of exotic particles influencing electromagnetic fields. However, dark matter remains largely undetectable, making this hypothesis difficult to test.
2. **Magnetic Monopole Theory** – A 2024 study explored the idea that ball lightning might be linked to **magnetic monopoles**, hypothetical particles carrying a single magnetic charge. The theory suggests that monopoles could catalyze nuclear reactions, producing the glowing effect seen in ball lightning.
3. **Ether Heterogeneities** – Some older theories propose that variations in the **ether**, a once-hypothesized medium for electromagnetic waves, could create localized energy concentrations leading to ball lightning. However, modern physics has largely discarded the ether concept, making this explanation less viable.

While these models are intriguing, none have been **experimentally confirmed**, and mainstream physics tends to favor explanations based on **plasma physics, electromagnetic fields, and chemical reactions**.

7. *There is one more type of model missing from your list of ball lightning models. Now imagine that ball lightning is a thin-walled bubble of molten glass, i.e. the shell material is liquid. What properties does such ball lightning have?*

Ah, now we're entering the realm of molten elegance—ball lightning as a **liquid-glass bubble** is a bold and fascinating twist. If we imagine the shell as a thin layer of molten silica or similar material, enclosing hot gas, several unique properties emerge:

🌡️ Thermal and Optical Behavior

Incandescence: Molten glass glows brightly at high temperatures (above ~1000°C), so the bubble would naturally emit visible light—likely orange to white—without needing plasma or electrical excitation.

Transparency and Refraction: Depending on thickness and composition, the shell could be partially transparent, refracting internal light and creating shimmering or halo effects.

Thermal Insulation: Glass is a poor conductor of heat, so a molten shell could help trap heat inside, extending the bubble's lifetime.

🧪 Mechanical and Fluid Properties

Surface Tension: The liquid shell would naturally form a sphere due to surface tension, especially in microgravity or low-turbulence environments.

Fragility: Being molten, the shell would be delicate—prone to rupture from mechanical contact or rapid cooling.

Viscous Flow: The shell might slowly deform or oscillate, giving the ball lightning a "breathing" or pulsating appearance.

🌀 Motion and Interaction

Neutral Buoyancy: If the internal gas is hot and light enough, the bubble could hover or drift slowly, mimicking observed ball lightning motion.

No Electromagnetic Interaction: Like your earlier model, this version would be electrically neutral, so it wouldn't respond to magnetic or electric fields—unless the molten shell somehow acquired charge through triboelectric effects or ionization.

💥 Disappearance and Effects

Silent Dissipation or Sudden Shatter: Cooling could cause the shell to solidify and fall, or it might burst violently if internal pressure builds. This could explain both quiet vanishings and explosive endings in eyewitness reports.

Glass Residue: In theory, such a bubble might leave behind tiny glass beads or splinters—though no consistent physical remnants have been documented.

This model is elegant in its simplicity and could potentially explain the glowing, spherical appearance and short lifespan of ball lightning without invoking exotic physics. It also invites some wild experimental possibilities, imagine levitating a molten-glass droplet in a controlled chamber and watching it dance.
Would you like to explore how such a structure might form naturally—say, from a lightning strike on sandy soil—or how it could be simulated in a lab? This idea has real sparkle. ✨ 🫧 🔥

8. *Is there any reason to believe that there will be a breakthrough in understanding the nature of ball lightning in the near future?*

There is **ongoing research** into ball lightning, but a major breakthrough remains uncertain. Scientists continue to explore its nature through **high-speed imaging, atmospheric studies, and laboratory experiments**. Some recent studies suggest that ball lightning may involve **plasma vortices, chemical reactions, or electromagnetic fields**, but no single theory has been universally accepted2.

One promising approach involves **controlled experiments** that attempt to recreate ball lightning-like phenomena. Some researchers have successfully generated **luminous spheres** using microwave radiation or electrical discharges, providing insights into possible formation mechanisms. However, replicating the exact conditions of natural ball lightning remains a challenge.

9. *Thank you very much! Can I publish our conversation online?*

You're very welcome! I'm glad we had this deep dive into ball lightning—it's such a fascinating topic.

The answers of the AI chatbot to the questions posed are left unchanged. The author does not agree with some statements and conclusions of the artificial intelligence chatbot. This can be a subject of discussion, which, however, should be conducted on another platform.

The picture under the book title and the pictures in the titles of chapters 7 and 8 were made by ChatGPT.

Acknowledgment

I am deeply grateful to my sons, Ilya and Boris—without their unwavering support and help, this work would not exist.

2025, Mark Zhelezniak

List of Symbols

$B_{tot}(T)$ total emissive power of blackbody, W/m^2

$B_\lambda(T)$ spectral emissive power of blackbody radiation in vacuum, W/nm m^2

c_{melt} specific heat capacity of melt, J/g K

D_{BL} diameter of ball lightning, m

e_{BL} average BL energy density, J/cm^3

E_{BL} energy of BL, J

$E(\lambda)$ spectral emissive power, W/nm m^2

h average heat transfer coefficient, W/m^2 K

h_{melt} specific enthalpy of melt, J/g

k absorption coefficient, cm^{-1}

k_λ spectral absorption coefficient, cm^{-1}

k_P Planck-mean absorption coefficient, cm^{-1}

L_V photometric brightness (luminance), cd/m^2

L_{VBL} photometric brightness (luminance) of BL surface, cd/m^2

M mass, kg

M_V luminous emittance, lm/m^2

M_{Vb} luminous emittance of blackbody, lm/m^2

n refractive index of the shell material

P gas pressure, Pa

P_{BL} pressure of gas filling ball lightning, Pa

q_{BL} radiation power density, W/m^2

Q_λ spectral radiation power from the BL shell W/nm

Q_{rad} total radiation power from the BL shell, W

Q_{conv} heat losses due to convection from the BL shell, W

S_{BL} BL surface area, m^2

T temperature, K

T_{BL} temperature of BL, K

V volume, m^3

$V(\lambda)$ photopic relative luminous efficiency functions of the human eye

δ reduced thickness of the BL shell $\delta = \varphi\delta_{shell}$, μm

δ_{shell} actual thickness of the BL shell, μm

λ wavelength of radiation, mm, μm

ν wavenumber, cm^{-1}

ρ_{melt} density of the melt, g/cm^3

φ volume fraction of melt in structure of the foamy BL shell material

σ Stefan–Boltzmann constant, 5.67 10^{-8} $W/m^2\ K^4$

σ_{gm} surface tension on air-melt interfaces, N/m

Subscripts

b blackbody

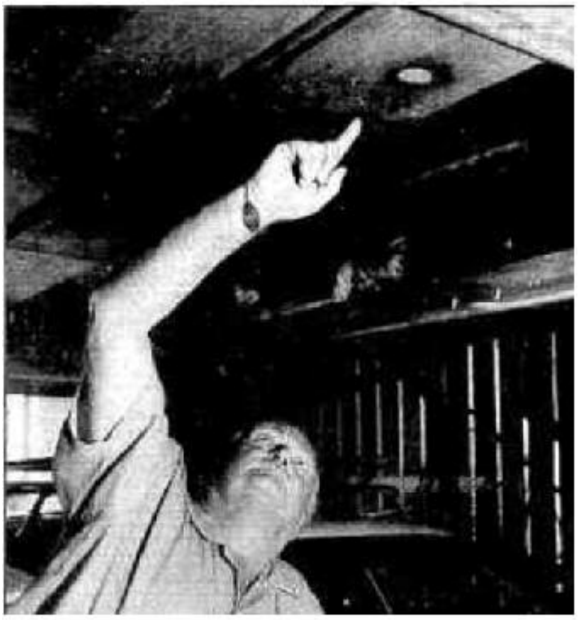
BL ball lightning

gas property of gas filling ball lightning

melt property of melt

shell BL shell parameter

λ wavelength of radiation



Mr. Joe Keunen shows the scorch mark left after the impact of ball lightning on wooden plank (from *The Canberra Times*, Feb. 11, 1993).

1. Introduction

Luminous natural phenomena, now commonly referred to as ball lightning (BL), have been observed since ancient times. However, systematic descriptions of such occurrences began only in the past century. By now, a vast number of eyewitness reports have been collected and analyzed. Nevertheless, direct study of ball lightning in nature or successful reproduction of it under laboratory conditions remains elusive. As a result, eyewitness evidence and rare traces left on surrounding objects remain the primary sources of information about the physical processes occurring within ball lightning. Summarized data on its properties can be found in several works: *Singer 1971*, *Stakhanov 1985, Smirnov 1992, Stenhoff 1993, Grigor'ev 2019, Shmatov et al. 2019, Keul 2021*, *Bychkov 2022*.

According to these sources, ball lightning is a rare phenomenon, observed primarily during thunderstorms, typically following an ordinary lightning strike. It usually appears as a glowing sphere 5 to 50 cm in diameter, can be any color, and generally lasts no more than 10 seconds—although in rare cases, it may persist for up to a minute. Ball lightning can disappear silently or with explosion. More detailed descriptions of its appearance and behavior are available in the referenced literature.

The analysis of eyewitness reports shows that the term “ball lightning” may in fact describe a variety of glowing objects with differing behaviors and structures (see discussion in *Stenhoff 1999*, *Rakov et al. 2003*). The conditions under which the phenomenon occurs significantly influence its properties. For example, if ball lightning is formed within the channel of ordinary lightning, it may be a plasma object. When ordinary lightning strikes the ground, the resulting ball lightning may include the soil components, forming a material shell that allows it to persist longer. There are documented cases of ball lightning forming after an ordinary lightning strikes electrical installations—in such cases, the ball lightning may include decomposition products of insulating materials or molten metal from wires.

Many experiments have been conducted to uncover the nature of ball lightning. The primary goal of these studies has been to create luminous spherical objects that float freely in the air and last for more than a second. However, until now no object has been convincingly identified as true ball lightning. In addition, no clear criteria have been developed for choosing a preferred theoretical model among the many proposed ones. The current situation on this issue can be found in *Bychkov 2022*.

Our research will focus on a specific type of ball lightning—the lightning that occurs when ordinary lightning strikes the ground. Accordingly, we will only consider studies directly related to this phenomenon.

While the association between thunderstorms and ball lightning has long been known, the realization that certain types of ball lightning originate specifically from lightning strikes into the earth came much later. Only in the mid-20th century, the hypothesis was proposed that fulgurites and ball lightning may be products of the same soil electrical discharge. This idea was likely first expressed in the work of *Andrianov et al. 1977*. They proposed that ball lightning forms from soil material vaporized by a lightning strike. In their experiments, the researchers obtained glowing objects whose lifetimes were less than a second—significantly shorter than the observed lifespan of actual ball lightning.

Numerous eyewitness reports indicate that ball lightning is a stable structure. According to *Smirnov 1990*, to maintain such stability, a spatial framework is needed. This framework must be extremely lightweight and composed of fine fibers. The volume of the framework is small compared to the total volume of the object, which results in a low overall mass of ball lightning. The temperature of BL is maintained by exothermic chemical reactions of the framework material with atmospheric oxygen. In estimates of ball lightning parameters, *Smirnov 1991* has considered silicon aerogels as a potential fiber material.

A similar idea was considered in the work of *Abrahamson and Dinniss 2000*, where it was proposed that nanoscopic particles of silicon or its compounds form within the soil electrical discharge channel. The particles are ejected into the air filamentary structures, oxidize and release heat, maintaining temperature up to 2000 K. Experimentally, such structures were obtained and existed for tens of seconds. However, in laboratory conditions, the filaments did not combine into spherical objects.

Attempts to reproduce ball lightning of such structure were also made in works of *Paiva et al. 2007*, *Stephan et al. 2008*, *Porter et al. 2014*, where ordinary lightning strike to the ground was modeled by an electrical discharge through a silicon layer. A more comprehensive investigation was conducted by *Hill et al. 2010*, where lightning was triggered from natural thunderclouds using the rocket-and-wire technique, and about 100 different material samples were exposed to the discharge. Despite the intense thermal action, no objects resembling ball lightning were obtained. To date, there is no convincing experimental evidence to support the purely fiber model of ball lightning.

Another way to maintain the integrity and shape of ball lightning is to use a shell made of liquid or solid material. This concept is the basis of “Chemical-thermal model” described in *Bychkov 2022*. According to this model, ball lightning is a unipolar electrically charged object consisting of a material spheric shell filled with hot gas—a gaseous core. Ball lightning is formed at the point where ordinary lightning strikes the ground. Therefore, the shell material is molten soil components, mainly silica (SiO_2), and vapors of these same substances and water vapor are the gas core. The key requirement for this model was an extremely high energy density of the BL—up to 10^{11} J/m^3. To meet this requirement, ball lightning must have a large shell mass and high gas pressure in the core. Depending on the size, the total BL mass can vary from a few hundred grams to several hundred kilograms, with the gas pressure in the core varying from 10^7 to 10^{11} Pa. The temperature of the BL is about 2000 K. Mechanical stability is believed to arise from electrostatic forces between the gaseous core and the shell.

There are some questions about the proposed model. The model does not discuss the thermodynamic stability of the filling gas. At the specified pressures and temperatures of the gas core, silica can only exist in liquid or solid form, *Melosh 2007*. Therefore, the pressure of gas core with a significant content of SiO_2 vapor will decrease rapidly due to condensation of the SiO_2 vapor, leading to the disintegration of ball lightning. In addition, this “heavy” model does not describe the BL observed characteristics, such as ability to pass through window glass, the absence of significant thermal radiation, a wide color spectrum, and peculiarity of motion. Therefore, even if such an object were to form, it would most likely not be recognized as typical ball lightning.

The idea that ball lightning has a material shell remains plausible. Based on the logic of the previous model and modifying several key assumptions, we also propose that ball lightning is a bubble of molten glass, which is formed at the point where ordinary lightning strikes the ground.

So, to be more specific, ball lightning is a thin-walled bubble of foamed molten glass. The pressure of the hot gas (mainly hot air) inside the bubble is only slightly different from atmospheric pressure, which allows the shell of molten glass to remain intact. The thickness of the shell can range from several tens to hundreds of micrometers, and the total mass reaches several tens of grams for medium-sized samples (20–30 cm in diameter). Initially, the temperature of ball lightning is about 2500 K, gradually decreasing as it cools. Ball lightning may not have an internal source of energy, acquiring the energy at formation. The presence or absence of an electric charge is not a critical factor for its existence. Unlike the above model, our approach does not rely on extremely high energy densities of BL, which we consider questionable.

Before discussing the details of our model, we will consider the general effects of a cloud-to-ground lightning strike. This event creates a high-temperature, high-pressure electrical discharge in the soil. After the discharge ceases, the molten components inside the discharge channel and the adjacent soil layers gradually cool. Under these conditions, the channel walls solidify, forming a glassy structure known as fulgurite, Figure 1.1.

Image from *Bindi et al. 2023*, CC BY 4.0.

Fig. 1.1. Glassy tubes that consist of a glassy melt surrounding an internal void, in turn surrounded by a crust consisting of cemented sand grains. The diameter of the fulgurite is 2 cm, and length is 7 cm.

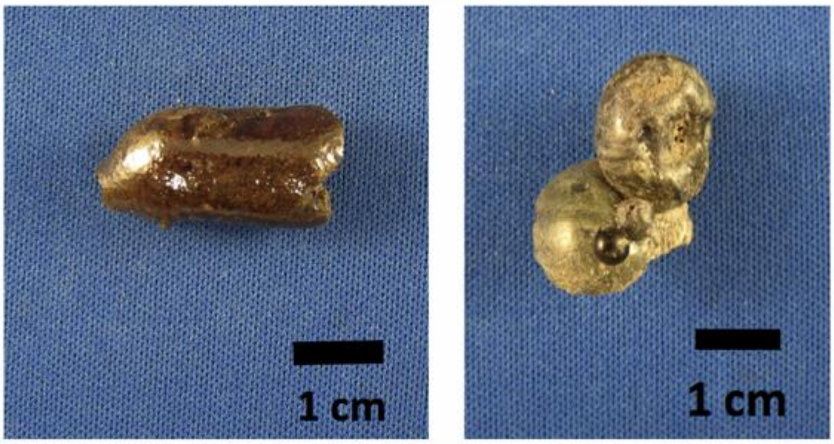


Image from *Block 2011,* CC BY 3.0.

Fig 1.2. Two melt droplet fulgurites, from York County, Pennsylvania (left) and Vernal, Utah (right).

The explosive development of the soil electrical discharge results in the ejection of molten clots into the atmosphere, where they take on a streamlined or nearly spherical shape. Moving in the air, and then, being on the surface of the earth, the drops cool down; the resulting solids are drop fulgurites (exogenic fulgurites or exofulgurites), Fig. 1.2. A detailed study of this type of fulgurites was carried out in the work by *Alte da Veiga et al. 2021*. Exofurites are small, no more than 2 cm, and are formed from the main components of the soil. A study of the material showed that it has an amorphous structure containing many gas bubbles. The presence of gas bubbles indicates rapid expansion of volatile components due to intense heating of the material during an electrical discharge in the ground caused by a lightning strike. A drop of melt moving in the air has the appearance of a spherical and luminous object, which makes it look like ball lightning. However, this comparison is misleading. There are no known cases of exofulgurites forming that are comparable in size to an average ball lightning (tens of centimeters). We believe that ball lightning is produced by a different process.

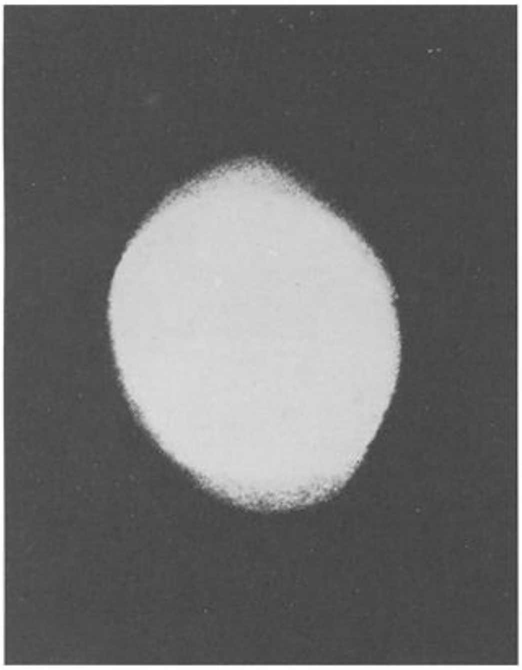


Fig. 1.3. Oval ball lightning. [H. Norinder, in Problems of Atmospheric and Space Electricity, Elsevier, Amsterdam, 1965. p 455; adopted from *Singer 1971*]

Eyewitnesses recorded the formation of another type of object associated with electrical discharges in the soil—glowing bubbles. The material for these bubbles is the molten components of the soil, and the bubbles are blown out by hot gases coming out of the discharge channel. Apparently, the formation of bubbles is a common phenomenon. But not all bubbles can break away from the outlet of the discharge channel and then live for a long time. The surviving bubbles, floating freely in the air, are ball lightning. A photograph of such an object is shown in Fig. 1.3. Obviously, the occurrence of a BL is possible if the electric charge introduced by ordinary lightning creates a sufficiently large channel of electric discharge in the ground, containing the required amount of molten glass. In addition, the outlet of the discharge channel must be open to the atmosphere. That is, not every strike of ordinary lightning is accompanied by the formation of a bubble.

Case 1. Now we will give an example of BL description from *Bychkov 2021*, p. 152, Case 21. Here we see all stages of the life cycle of ball lightning: the birth, life, and death.

Eyewitness: Gortunov I. E., software engineer. Interview 1997. The event happened in July 1952 at noon in the village Enishevo, Smolensk region, the eyewitness was 14 years old. We give only a summary of the description.

> During a thunderstorm, several teenagers were on an earthen dam blocking the river. They all observed ball lightning, and one of them (we will call him eyewitness) wrote a report about this event.
>
> Lightning struck the dam. Two things happened simultaneously: the eyewitness felt a strong electric shock in his bare feet, and 20 meters away from him, a blinding ball the size of an orange rose into the air, appearing at the place where the lightning struck. The ball was red and glowed brighter than a 200 W incandescent lamp. Its surface was clearly defined, and it made a hissing sound with a rare crackling sound. It got to a height of 3-4 m and then flew along a smooth trajectory 10 m at a speed of 1 m/s, descended to the ground, and exploded with a loud bang.
>
> After the thunderstorm, the boys examined the impact site. At the site of the ordinary lightning strike, they discovered a depression of approximately 7 cm in diameter and a narrow spiral-shaped channel. When they tried to probe it with a stick, they were unable to reach the bottom due to the channel's tortuosity. No fragments of ball lightning were found at the explosion site.

We believe that the observed ball lightning was a bubble of molten soil components filled with hot gas. Based on this statement we can infer several characteristics of the phenomenon.

A lightning strike induces an electric current in the soil. The resulting electrical discharge creates a high-temperature channel, heating the soil, causing it to melt and partially evaporate. Over time, the molten material within this channel cools and solidifies, forming a fulgurite—a thin-walled, tubular, glassy structure. Indeed, after the thunderstorm, the children discovered the discharge channel's outlet — "a depression of about 7 cm in diameter and a narrow, spiral-shaped channel." If they had carefully removed the soil around the channel, they might have discovered a fulgurite similar to the one shown in Figure 1.1.

A flow of hot gas from the electrical discharge channel blows out ball lightning. After ball lightning forms, this same gas flow propels it upward: "The ball rose to a height of 3-4 meters." The subsequent smooth movement of the ball lightning is like the motion of an air balloon. This movement is possible if vertical supporting forces act on the ball lightning. Such a force can be electrostatic interaction of the electric charge of the BL with the residual charge on the area of the ground where ordinary lightning has struck. Another force can arise because of the action of the ascending air flow on the ball lightning. The flow is caused by the contact of cold air with the ground surface, heated by solar radiation before a thunderstorm.

The eyewitness defined the color of the BL as red, which corresponds to the color of a black body radiation at temperature of about 1200 K. The eyewitness also estimates the ball lightning as a very bright object: "it was brighter than a 200 W lamp." The glow of a 200 W lamp is like the glow of a black body at 3000 K, which is perceived by the human eye as a warm, orange-red color. Such a significant difference in temperature when assessing color and brightness indicates the extremely subjective, approximate nature of the description of the phenomenon.

The ball lightning disappeared with the explosion. Since the shell of the ball lightning is formed by a thin film, it crumbled into small fragments. In addition, its composition corresponded to the local soil, and these fragments were difficult to detect. "No fragments of the ball lightning were found after the explosion."

Ball lightning exploded near or on the surface of the earth. However, the eyewitness reports no traces on the ground. This suggests that the energy of the ball lightning was small; most of it went into producing a loud bang or a weak shock wave that grew into a sound wave.

In addition, the eyewitness said that he felt an electric shock on his legs at the same time as the ordinary lightning strike. He stood barefoot on the ground at a short distance (20 m) from the point of the lightning strike and was affected by step-voltage. The step-voltage is a consequence of radial gradients of electric potential on the surface of the earth, which always occur when lightning strikes the ground (*Rakov et al. 2003*). This phenomenon is not in any way associated with ball lightning.

To get an idea of our model, we will give a set of questions on the BL characteristics from *Rakov* & *Uman 2003* and our answers.

> A successful ball lightning theory should at minimum account for the first four of the following eight characteristics or sets of characteristics:
>
> (i) *Ball lightning's association with thunderstorms or with cloud-to-ground lightning.*
>
> BL is caused by a cloud-to-ground lightning strike.
>
> (ii) *Its reported shape, diameter, and duration, and the fact that its size, luminosity, and appearance generally do not change much throughout its lifetime.*
>
> The perceived visible parameters of BL do not change much throughout its lifetime.
>
> (iii) *Its occurrence in both open air and in enclosed spaces such as buildings or aircraft.*
>
> BL appears in the open air, and it can penetrate enclosed spaces.
>
> (iv) *The fact that ball lightning motion is inconsistent with the convective behavior of a hot gas.*
>
> BL has a material shell, and its motion differs from convective behavior of hot gas.
>
> (v) *The fact that it may decay either silently or explosively.*
>
> BL may decay either silently or explosively.
>
> (vi) *The fact that ball lightning does not often cause damage.*
>
> Damage can be caused by direct contact or by explosive decay.
>
> (vii) *The fact that it appears to pass through small holes, through metal screens, and through glass windows*.

BL can pass through a small hole, and through glass window. It can cut a large hole in the windowpane.

(viii) *The fact that it is occasionally reported to produce acrid odours and/or to leave burn marks, is occasionally described as producing hissing, buzzing, or fluttering sounds, and is sometimes observed to rotate, roll, or bounce off the ground*

BL leaves burn marks when it touches organic matter. In many cases it produces hissing, buzzing, or fluttering sounds. It can bounce on hard surfaces.

The following points can be added to the characteristics listed above.

Since the shell material of ball lightning is liquid (has surface tension), ball lightning may disintegrate into several smaller ball lightnings.

Ball lightning can acquire an electric charge during its formation. We believe that this charge is not so large to affect the main physical and chemical processes in ball lightning. However, it interacts with external electric fields, which leads to a change in the trajectory of the BL.

This work examines a type of ball lightning that forms when ordinary lightning strikes the ground. The model we propose considers ball lightning as a thin-walled bubble of foamed molten glass filled with hot gas. Processes in the foam shell allow us to explain the appearance of threads on the surface of ball lightning, the formation of a halo, explosive disappearance, and some other observed features. An explanation is given for the weak thermal radiation of BL and the wide spectrum of observed colors. A system of equations is proposed to describe the time evolution of ball lightning, and solutions are obtained for some special cases.

However, it should be emphasized that due to the lack of complete and reliable data on the structure of ball lightning and the rate of physical and chemical processes occurring within it, we had to make several assumptions without sufficient grounds. For this reason, we do not consider this work to be entirely scientific. Despite these limitations, we believe that the ideas presented here may be useful in understanding the properties and behavior of ball lightning.

References

Abrahamson, J., & Dinniss, J. (2000). Ball lightning caused by oxidation of nanoparticle networks from normal lightning strikes on soil. *Nature*, *403*(6769), 519-521.

Alte da Veiga, N. M., Martín-Gil, F. J., Martín-Gil, J., Gomes, E. M. C., & Martín-Ramos, P. (2021). Physico-chemical study of an exogenic fulgurite from a thunderstorm on 10th August 2013 in Dallas, TX. *Physics and Chemistry of Minerals*, *48*(3), 12.

Andrianov, A. M., & Sinitsyn, V. I. (1977). Erosion-discharge model for ball lightning. *Sov. Phys. Tech. Phys*, *22*, 1342-1347.

Bindi, L., Feng, T., & Pasek, M. A. (2023). Routes to reduction of phosphate by high-energy events. *Communications Earth & Environment, 4(1), 70.*

Block, K. M. (2011). *Fulgurite classification, petrology, and implications for planetary processes*. The University of Arizona.

Bychkov, V. L. (2021*). Natural and Artificial Ball Lightning in the Earth's Atmosphere*. Moscow, «МАКС Пресс».

Bychkov, V. L. (2022). *Natural and Artificial Ball Lightning in the Earth's Atmosphere*. Cham: Springer.

Grigor'ev, A.I. & Shiryaeva S. O., . (2019). *Ball lightning through the eyes of eyewitnesses*. Григорьев, А. И., & Ширяева, С. О. *Шаровая молния глазами очевидцев*. ООО ДиректМедиа.

Hill, J. D., Uman, M. A., Stapleton, M., Jordan, D. M., Chebaro, A. M., & Biagi, C. J. (2010). Attempts to create ball lightning with triggered lightning. *Journal of atmospheric and solar-terrestrial physics*, *72*(13), 913-925.

Keul, A. G. (2021). A brief history of ball lightning observations by scientists and trained professionals. *History of Geo-and Space Sciences*, 12(1), 43-56.

Melosh, H. J. (2007). A hydrocode equation of state for SiO2. *Meteoritics & planetary science*, *42*(12), 2079-

Paiva, G. S., Pavao, A. C., De Vasconcelos, E. A., Mendes Jr, O., & da Silva Jr, E. F. (2007). Production of ball-lightning-like luminous balls by electrical discharges in silicon. *Physical review letters*, 98(4), 048501.

Porter, C. L., Miley, G. P., Griffiths, D. J., & Sánchez, E. (2014). Charge on luminous bodies resembling natural ball lightning produced via electrical arcs through lump silicon. *Physical Review E*, *90*(6), 063102.

Rakov, V. A., & Uman, M. A. (2003). *Lightning: physics and effects*. Cambridge university press.

Shmatov, M. L., & Stephan, K. D. (2019). Advances in ball lightning research. *Journal of Atmospheric and Solar-Terrestrial Physics*, *195*, 105115.

Singer, S., (1971). *The Nature of Ball Lightning*. Plenum, New York.

Smirnov, B. M. (1990). Physics of ball lightning. *Soviet Physics Uspekhi*, 33(4), 261.

Smirnov, B. M. (1991). A tangle of fractal fibers as a new state of matter*. Soviet Physics Uspekh*i, 34(8), 711.

Smirnov, B. M. (1992). Observational properties of ball lightning. *Soviet Physics Uspekhi*, *35*(8), 650.

Stakhanov, I. P., (1985). *The physical nature of ball lightning*. Стаханов И. П, *О физической природе шаровой молнии*. М. Энергоатомиздат

Stenhoff, M. (1999). *Ball lightning: An unsolved problem in atmospheric physics*. Boston, MA: Springer US.

Stephan, K. D., & Massey, N. (2008). Burning molten metallic spheres: One class of ball lightning? *Journal of atmospheric and solar-terrestrial physics*, *70*(11-12), 1589-1596.

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Cloud-to-ground lightning strike in Assen, Netherlands.

2. Origin of ball lightning and its features

2.1. Origin of ball lightning

2.1.1. Cloud-to-ground lightning discharge

This section discusses the lightning discharge (also called *flash*) generated by a thundercloud. We will not go into detail on this topic; the current state can be found in literature. Here we will give only a brief description of the phenomenon, which is necessary for understanding the material that follows. In this consideration, we will follow the book by *Rakov and Uman 2003*, from which the lightning parameters are taken.

Lightning discharges can be divided into two groups: cloud (intercloud or intracloud) and ground (cloud-to-ground, or CG). The frequency of CG discharges is half that of cloud discharges. Most CG discharges are downward negative discharges, that is, they originate in the cloud, propagate to the ground, and transfer negative electric charge from the cloud to the ground. Here we will consider this type of lightning in more detail. We will call these discharges *ordinary lightning* to distinguish them from *ball lightning*.

Stepped leader. The descending negative CG flash begins with an electrical breakdown inside the cloud. This process initiates the growth of a plasma channel called the *leader*. The leader departs from a negatively charged region of the cloud and moves toward the ground in a step-like manner; each step is about 50 m long. The leader channel has good electrical conductivity. Due to this, its potential is close to the potential of the cloud region from which the leader started, and the negative charge from this region spreads along the entire length of the leader. As the leader approaches the ground, the electric field near the ground under the leader head increases and reaches the breakdown level. This initiates streamer-type electrical discharges that move toward the leader head and bridge the gap between the leader and the ground.

Return stroke. Immediately after the formation of the plasma negatively charged channel between the cloud and the ground, a wave starts from the ground towards the cloud along this channel. The wave transports negative charge from the channel to the ground and leaves behind its front electrical neutral plasma. This wave is called the *return stroke*. Electric current of the return stroke heats the gas in the channel up to 30000 K that causes a bright flash of light. In addition, the gas pressure in the channel increases sharply, the channel expands, forming a shock wave, which at a large distance from the channel is perceived as a loud bang (thunder). Here we present several parameters that characterize the return stroke.

Speed	$(1\text{-}2)\cdot 10^8$ m/s
Channel radius	1-2 cm
Channel temperature	~30000 K
Charge transfer	1-20 C
Peak current	5-30 kA
Stroke duration	30-200 μs

Continuing current. The full duration of the return stroke current is tens of microseconds. After this time, the current may not fall to zero and remain at some low level for a long time. This long-term current is called the *continuing current,* it is an arc-type electrical discharge between the cloud and the ground. Some parameters of continuous current:

Current magnitude	100-200 A
Charge transfer	10-20 C
Current duration	~100 ms

It should be noted that, despite the relatively small magnitude of the continuing current, the charge carried by this current is large due to the long duration of action—up to several hundred milliseconds.

Finally, we note that there are also downward positive cloud-to-ground lightnings. Their features are similar to those of downward negative lightning with differences in some details. The frequency of positive lightning is low, but the energy and electric current can be significantly higher than those of negative lightnings, and their impact on the processes on the earth's surface is stronger.

2.1.2. Electrical discharge in soil

Cloud-to-ground lightning transfers a large electric charge to the surface of the earth, which must discharge, causing an electric current in the soil. The shape of the resulting electric discharge channel is determined by the properties of the soil, *Rakov 2009*. In dense clay soils, the discharge spreads along the surface and does not form underground plasma channels. In soils containing a significant amount of quartz sand, the electric discharge is most likely directed downwards and can have a single or branched form.

As previously noted, the discharge of ordinary lightning consists of several successive stages. We will discuss how each stage influences the development of electrical discharge in soil. The initial and most intense phase of soil discharge is associated with *return stroke*. Although it features high peak currents (up to 30 kA), this stage contributes relatively little to overall energy deposition in the soil due to its very short duration (less than 100 microseconds). Moreover, a significant portion of its energy is expended on hydrodynamic processes caused by the rapid pressure increase.
The next development of soil discharge is carried out by *continuing current*. This stage is less intense but longer-lasting: a relatively low currents (100-200 A) lasts for several hundred milliseconds. Under these conditions, the soil discharge can be considered as a steady-state, high pressure electrical arc. The plasma temperature in the core of this discharge may be 7000-10000 K, and the pressure is much higher than atmospheric levels. It should be noted that the decisive role of the continuing

current in the formation of soil high temperature channel is found in the work of *Çalışkanoğlu et al. 2023*, where fulgurites were successfully produced in a laboratory using electrical discharges simulating the shape of natural lightning pulse.

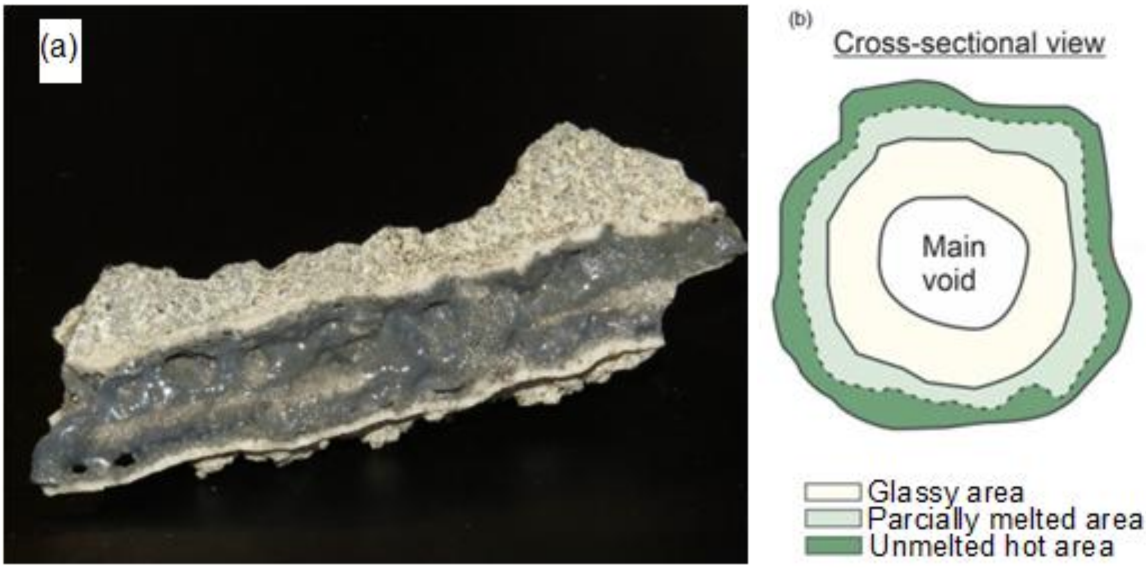


Fig. 2.1.1. (a) Longitudinal section of a tubular fulgurite (Sahara Desert). The glassy layer (lechatelierite) on inner wall of the canal is clearly visible (Image by *Ringwoodit*, via Wikimedia Commons, CC BY 4.0).
(b) A representative cross-sectional view of a fulgurite (adopted from *Çalışkanoğlu et al. 2023*, CC BY 4.0).

Direct measurements of the parameters of electrical discharges in soil are impossible. However, the study of fulgurites gives an idea of the shape and size of the channel, as well as the chemical composition of its wall material (*Pasek et al. 2012*, *Pasek et al. 2016*). The size of the channel depends on the soil structure and the energy transferred by lightning into the soil discharge. Channel lengths can range from several centimeters to several meters, while diameter may be up to several centimeters (*Rakov 1999*).

The soil components (grains of SiO_2 and other oxides) inside the electrical discharge channel are subjected to intense heating, which leads to their melting and partial evaporation. As mentioned, the vapor and associated gases at the discharge core may have a temperature up to 10000 K, while the wall of the discharge channel has a lower temperature (~2500 K). The wall is formed by partially molten sand grains, and the inner surface of the wall is covered with a layer of melt, Fig. 2.1.1.

The channel walls are not completely impermeable. Small vents in the walls allow hot gases from the discharge channel to escape into the surrounding medium. This creates an area of elevated temperature and pressure around the channel. In sandy soils, where the voids between grains are relatively large, this heated region can extend well beyond the channel diameter. The temperature at the outer wall of the channel likely does not exceed 1000 K and gradually decreases with distance. This temperature is insufficient to melt the primary soil components, so this surrounding area will be referred to as the *unmelted hot area* (see Fig. 2.1.1b). Among the gases that penetrate this area there are vapors of oxides that are soil components (SiO2, Al2O3, CaO, Na2O, etc.). These vapors condense (with heat release) and therefore the gas filling the voids between the sand grains consists mainly of hot air and water vapor. We believe that after the electrical discharge in the soil ends, it is these hot, high-pressure gases from the unmelted hot area that blow the bubble out of the molten glass.

2.1.3. Formation of bubbles from molten glass

We believe that the place where ball lightning is formed is electrical discharges in the soil. During the action of the electrical discharge, high gas pressure presses the melt of the soil components to the channel wall, which allows the gas to freely escape into the atmosphere. Under these extreme conditions, a bubble of molten glass cannot form. More favorable conditions arise after the electric current ceases. The evaporation of the soil component ceases, which leads to a sharp decrease in the gas pressure in the discharge channel, since it is connected to the atmosphere. As a result, the gas in the discharge channel will be replaced by gas from the *unmelted hot area* (mainly air and water vapor), where the gas pressure is higher. In the resulting gas flow, the speed and pressure are significantly lower than in the active electrical discharge. Under these conditions, the melt layer begins to flow by gravity along the wall and, due to the unevenness of the flow, can form liquid plugs. In addition, the discharge channel has a complex structure and some of its sections can be inclined. In these areas, the formation of a liquid plug is most likely. Then the plug, carried by the gas flow to the exit of the channel, turns into a bubble, Fig. 2.1.2. It should be noted that the existence of transverse bridges in fulgurite tubes (*Sponholz et al. 1993*) confirms the fact of the formation of melt plugs in the electric discharge channel, which turn into solid bridges after cooling.

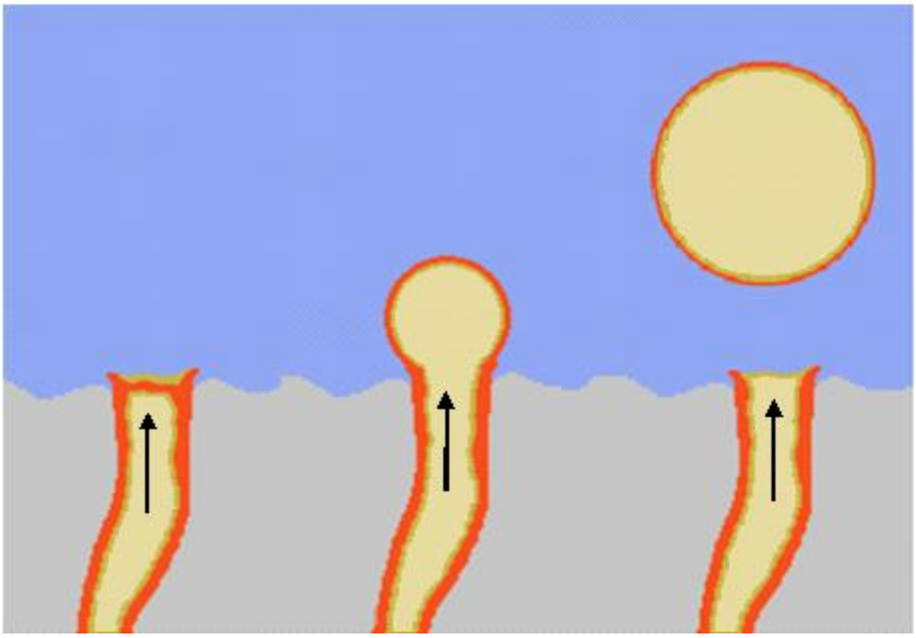


Fig. 2.1.2 Formation of a bubble from plug of molten glass.

The exact mechanism of bubble formation remains unclear, but it appears to be similar in many ways to glass blowing. Usually this does not require high gas pressure (static and dynamic), it is comparable to the pressure created by human lungs, Fig. 2.1.3. We also draw attention to the fact that a person can be near the bubble of melt without fear of being burned by thermal radiation. Weak thermal radiation is a characteristic feature of ball lightning (Section 4).

Fig. 2.1.3. Production of colored glass; glassblowing.

The resulting bubble is released from the channel outlet primarily by the dynamic action of the blowing gas flow, a process that is also observed in soap bubble formation (*Salkin et al. 2016*). Additional factors such as buoyancy and wind gusts also contribute to bubble detachment. After detachment, the hot gas jet from the discharge channel can lift the bubble to a considerable height.

These bubbles can also acquire an electric charge. After a soil electrical discharge, residual electric charges remain in localized areas of the soil. The electric field of these charges is insufficient to trigger electrical discharge in the poorly conductive soil. Such a charge may be present at the lightning strike site, i.e. at the discharge channel outlet. As the bubble separates, it may carry away some of this charge. We believe that this charge is small enough not to affect the processes inside ball lightning. However, it affects the BL trajectory due to interaction with external electric fields. It can also cause electric shock when a person comes into direct contact with the ball lightning.

Case 1. From *Stakhanov 1985*, p. 106, No 63. Eyewitness Grishchenko P.F. observed a ball lightning from 10 m.

> At the lightning strike site, a light-yellow ball, approximately 30-40 cm in diameter, suddenly erupted from the ground. It rose to a height of 6-8 meters and then began moving horizontally. The ball lightning pulsed, taking on the shape of a sphere and an ellipse. After traveling 50-70 meters for 1-1.5 minutes, it struck a pine tree and exploded.

2.2. General characteristics of ball lightning

2.2.1. Gas pressure inside ball lightning

So, ball lightning is a bubble of molten glass filled with hot gas. Since the BL shell is a thin film of melt, an imbalance of the transversal forces can break it. Therefore, the condition for the BL existence is the equality of the internal and external pressures acting on the film.

$$P_{BL} = P_{atm} + p_L \tag{2.1}$$

where P_{atm} is the atmospheric pressure and p_L is the Laplace excess pressure.

$$p_L = \frac{2(\sigma_{am}+\sigma_{gm})}{R_{BL}} \quad (2.2)$$

where R_{BL} is the BL radius, σ_{am} and σ_{gm} are surface tension on air-melt and internal gas-melt interfaces, respectively. Assuming $\sigma_{am} = \sigma_{gm}$ and taking these values 0.25 N/m (*Boyd et al. 2012*), we obtain, for example, p_L = 40 Pa for R_{BL}=0.05 m, that is, $p_L << P_{atm}$. It should be expected that this relation is always valid for ball lightning, and we will take further $P_{BL} = P_{atm}$ unless otherwise specified.

2.2.2. Material of the ball lightning shell

During the BL formation and at the subsequent cooling, the BL shell must respond to changing parameters of the filling gas and atmosphere. This is possible if the viscosity of the BL shell material is low.

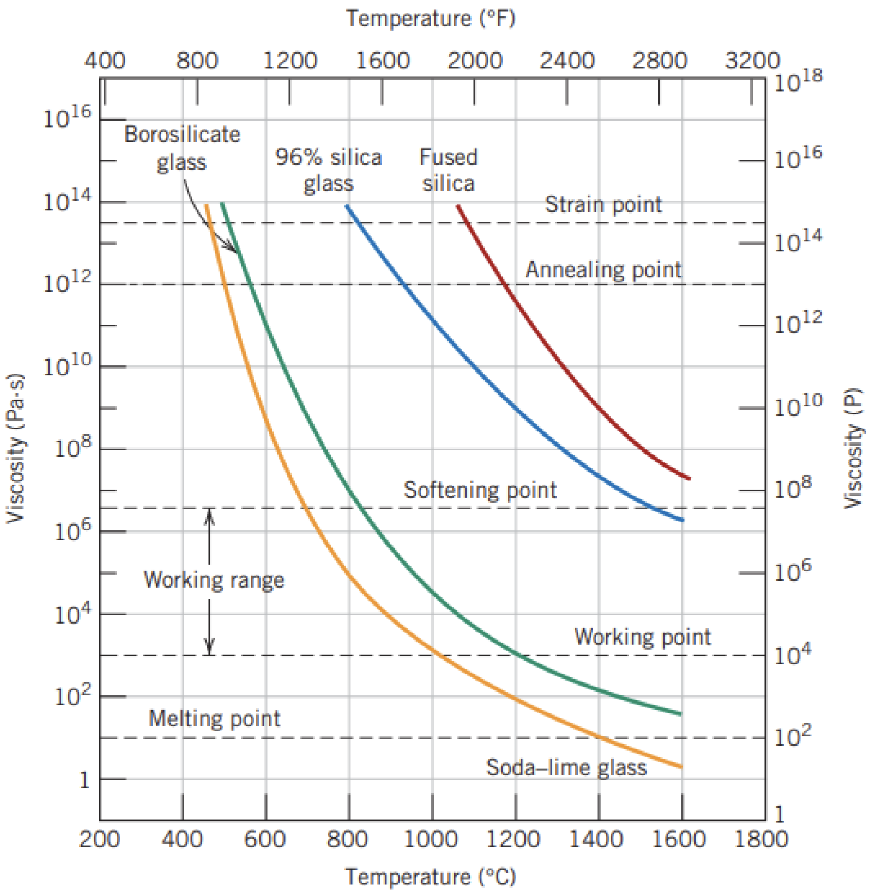


Fig. 2.2.1. Viscosity versus temperature for fused silica and three silicate glasses (from *Callister at al. 2018*, Fig. 13.14).

The viscosity of glass melts is a strong function of temperature. To describe general features of this function, reference points on the viscosity-temperature curve are marked. Some of them are shown in Fig. 2.2.1, where the temperature dependence of viscosity for fused silica and silicate glasses is given. We believe that at the birth of ball lightning the viscosity of the shell material is near the *melting point*, ~10 Pa s. In glass industry, the blowing process is carried out at viscosity range 10^3-$4 \cdot 10^6$ Pa s (*working range* in Fig. 2.3). Seemingly, the viscosity of the BL shell material during the cooling of ball lightning should at least be in this range.

The next question is what glass melts meet these requirements. The properties of the glass melt depend on its chemical composition. In the case of ball lightning, the composition of the shell material is determined by the components of the soil from which ball lightning arose. As seen from Fig. 2.2.1, the *softening point* of silica is near 1700 °C, while for ordinary glasses this value is 700-800 °C. Thus, when a bubble of molten silica cools, it quickly, even at high temperatures, loses the stability of its shell and collapses. Ball lightning most likely occurs in silica sandy soils with a significant content of alkali and alkaline earth metal oxides. In this case, the melt forming the BL shell will have properties close to those of ordinary glass melts.

2.2.3. Internal structure of the ball lightning shell

As already discussed, the basic structural element of ball lightning is the molten glass shell. So far, we have not considered its internal structure. Given the conditions of the electrical discharge in the soil, it is unlikely that the resulting melt will be homogeneous. The combination of high pressure and temperature, uneven flow in the discharge channel, and chemical interactions between the molten components contribute to the formation of numerous small gas bubbles within the melt. This is a common occurrence in glass melting processes. In the glass industry, the formation of small gas bubbles in molten glass is an adverse process. Special techniques are employed to remove them from the melt, *Pilo 2012*. The presence of gas bubbles in melted soil components is also confirmed by studies of fulgurites. In many cases, the inner glass layer of tubular fulgurites appears to be matte due to the trapped gas bubbles. And here we give a quote from *Sponholz et al. 1993*. “The fulgurite fragments prepared as thin sections represent a variety of fulgurite types: white/grey/brownish, transparent/ foamy/ translucent... As was already evident from the untreated samples, thin sections clearly show the glassy-foamy structure.” Thigh porosity (20-50 %) of the material of artificial fulgurites was noted in the work of *Çalışkanoğlu et al. 2023* cited above.

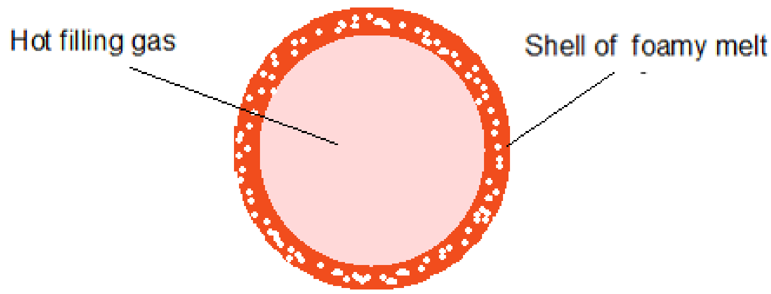


Fig. 2.2.2. Schematic representation of the ball lightning structure.

Based on this, we can conclude that the shell of ball lightning consists of a foamy material, and the structure of BL is like that shown in Fig. 2.2.2. At present, there is no data on the parameters of the ball lightning shell, and we will assume that the thickness of the foamed molten film that forms the shell does not exceed several hundred micrometers. Consequently, the gas bubbles inside this foamy structure will have micron and submicron sizes. We believe that such structure allows us to describe the features and behavior of ball lightning.

Liquid foam is a close packing of gas bubbles that are formed by liquid films. The properties of foam depend on its structural parameters. One of the key parameters is the volume fraction of the condensed phases. In our case, this is the fraction of glass melt, which we will denote as φ. Then the total volume of the BL shell V_{shell} and the melt volume V_{melt} are related as

$$V_{melt} = \varphi V_{shell} \tag{2.3}$$

The rates of many processes considered are determined not by the actual shell volume V_{shell}, but by the volume of melt V_{melt}. In this connection, instead of the actual thickness of the BL shell δ_{shell}, we will use the reduced value

$$\delta = \varphi \delta_{shell} \tag{2.4}$$

For brevity, we will refer to it as *shell thickness* unless otherwise stated.

The mechanical properties of foam are determined by the same parameters. At low liquid fractions (e.g., $\varphi < 0.15$, called "dry foam"), the foam consists of highly deformed bubbles. Foam deformation is difficult, since it requires relative displacement of the bubbles or a change in their size, which can lead to bubble rupture. In this state, the foam behaves like a rigid medium.

Fig. 2.2.3. Illustrative picture of the bubbly liquid foam— ball lightning shell material (high magnification).

As the liquid fraction φ increases, the foam rigidity decreases. The critical point is reached at $\varphi_c = 0.36$, where a transition occurs and the foam loses its rigidity (*Drenckhan et al. 2015*). Above this critical value ($\varphi > \varphi_c$), gas bubbles float freely in the liquid, and the foam exhibits rheological properties like those of a liquid (bubbly liquid foam, Fig. 2.2.3). Such a foamy medium is easily deformed and can flow through narrow openings under the influence of a pressure difference. We suggest that foamed molten glass with such characteristics can serve as a material for the formation of ball lightning.

In this foamy medium, the pressure inside the gas bubbles exceeds the external level at least by the Laplace pressure

$$p_L = \frac{2\sigma_{gm}}{r} \qquad (2.5)$$

where σ_{gm}= 0.25 N/m is surface tension on the gas-melt interfaces and r is bubble radius. For a bubble of r=0.5 μm, the pressure is $p_L = 5{\cdot}10^5$ Pa, which is significantly higher than atmospheric pressure.

The melt may also contain gas bubbles with internal pressures significantly exceeding the p_L value. These high-pressure bubbles can form during an electrical discharge in the soil, where the internal pressure significantly exceeds atmospheric pressure, sometimes by several orders of magnitude. At such extreme pressures, a significant amount of gas dissolves in the melt. When the melt exits the discharge channel and enters the atmosphere, supersaturated gases are released from the solution, forming high-pressure bubbles. Upon reaching the surface of the melt, these bubbles burst, releasing hot gas and nanoscale droplets of melt into the surrounding environment. These processes largely determine the behavior and appearance of ball lightning.

Bubbly liquid foam is an unstable structure. Processes occurring within the foam, as well as its interaction with the environment, alter the gas/liquid ratio and bubble sizes, which can ultimately lead to its disintegration (*Moradpour et al., 2024*). Furthermore, the foam is affected by gravity and the centrifugal force arising from the rotation of the ball lightning; the vectors of these forces do not generally coincide. Obtaining any information about the state of the foam shell of BL, considering the above-mentioned processes, is currently not possible. We can only make some general comments. Not all possible processes significantly alter the properties of the foam during the short lifetime of BL. The combined action of gravity and centrifugal force promotes liquid movement and mixing, resulting in greater foam homogeneity.

2.2.4. Filling gas

Above we considered ball lightning as a thin shell of molten glass surrounding a hot gas core consisting mainly of air and water vapor (Section 2.1.3). Importantly, this gas should contain only trace amounts of soil oxide vapors (e.g. SiO2, Al2O3, CaO). If such oxides were present in significant concentrations, they would begin to condense as soon as the temperature dropped below about 2000 K, causing the shell to collapse.

Moreover, water vapor at high temperatures is a powerful infrared emitter. Since the BL shell is transparent to IR radiation, a high concentration of water vapor in the filling gas will cause rapid radiative cooling of the gas, which will lead to a drop in its pressure. As a result, the shell will break down under the resulting pressure differential between the filling gas and the atmosphere. For ball lightning to remain stable over a long period, its core must be filled with hot gas that does not radiate much—essentially air with a small admixture of radiating components. We will use this assumption of non-radiating filling gas in all subsequent analyses.

In practice, the fill gas may also include trace amounts of other compounds, either extracted from the soil or formed by high-temperature chemistry. Although their concentrations are low, these species can result in particulate emissions or characteristic odors when the ball lightning dissipates.

2.3. Summary

Here, we have considered ball lightning as a hot thin-walled bubble of glass melt filled with hot gas. This type of ball lightning occurs when ordinary lightning strikes soil containing a significant amount of silica sand. As a result, a high temperature channel of electrical discharge is created in the soil, the walls of which are formed by partially melted sand grains, and the inner surface is covered with a layer of melt of the soil components. When the discharge ends and the channel begins to cool, conditions may arise that allow the escaping gas to inflate the bubble of molten glass, creating what we call ball lightning. Due to the heterogeneity and instability of gas and melt flows, as well as chemical reactions with gas release, the melt formed in the electrical discharge contains many micron-sized gas bubbles. That is, the BL shell material is a foamed molten glass. The properties of such objects will be discussed in the following sections.

References

Boyd, K., Ebendorff-Heidepriem, H., Monro, T. M., & Munch, J. (2012). Surface tension and viscosity measurement of optical glasses using a scanning CO2 laser. *Optical Materials Express*, *2*(8), 1101-1110.

Çalışkanoğlu, A. Z., Camara, A. S., Cimarelli, C., Dingwell, D. B., & Hess, K. U. (2023). Experimental generation of fulgurite under realistic lightning discharge conditions. *Scientific Reports*, *13*(1), 11685.

Callister Jr, W. D., & Rethwisch, D. G. (2018). *Materials science and engineering: an introduction*. John wiley & sons.

Drenckhan, W., & Hutzler, S. (2015). Structure and energy of liquid foams. *Advances in colloid and interface science*, *224*, 1-16.

Moradpour, N., Yang, J., & Tsai, P. A. (2024). Liquid foam: Fundamentals, rheology, and applications of foam displacement in porous structures. *Current Opinion in Colloid & Interface Science*, *74*, 101845.

Pasek, M. A., Block, K., & Pasek, V. (2012). Fulgurite morphology: a classification scheme and clues to formation. *Contributions to Mineralogy and Petrology*, 164(3), 477-492.

Pasek, M. A., & Hurst, M. (2016). A fossilized energy distribution of lightning. *Scientific reports*, 6(1), 30586.

Pilon, L. (2012). Foams in glass manufacturing. *Foam engineering: fundamentals and applications*, 355-409.

Rakov, V. A. (1999). Lightning makes glass. *J. Glass Art Soc*, 45.

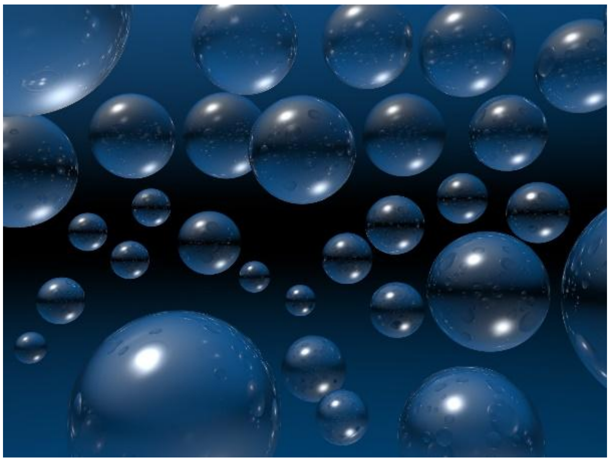
Rakov, V. A. (2009). Rocket-triggered lightning and new insights into lightning protection gained from triggered-lightning experiments. In *Lightning Protection* (pp. 97-164).

Rakov, V. A., & Uman, M. A. (2003). *Lightning: physics and effects*. Cambridge university press.

Salkin, L., Schmit, A., Panizza, P., & Courbin, L. (2016). Generating soap bubbles by blowing on soap films. *Physical review letters*, *116*(7), 077801.

Sponholz, B., Baumhauer, R., & Felix-Henningsen, P. (1993). Fulgurites in the southern Central Sahara, Republic of Niger and their palaeoenvironmental significance. *The Holocene*, *3*(2), 97-104.

Stakhanov, I. P. , (1985). *The physical nature of ball lightning*. Стаханов И. П, *О физической природе шаровой молнии*. М. Энергоатомиздат



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3. Shell of ball lightning—effect of micron-sized gas bubbles

hairs, noise, halo, heat loss protection, explosive decay

In the previous section, a model of ball lightning was proposed in which we assumed that the shell of ball lightning consists of foamed molten glass. According to this model, the volume fraction of the condensed phase (melt) in the foamy material should be greater than the critical value (φ_c = 0.36), and the gas phase is represented by micron-sized bubbles. In this section, we discuss the influence of the foamy structure of shell on the behavior and appearance of ball lightning. To get an idea of the subject of this discussion, we will start with brief reports in which eyewitnesses describe hairy ball lightning and ball lightning with active processes on the surface.

Case 1. From *Rakov et al. 2003*, p. 658 (fragment). The event took place in Australia on a dairy farm. The eyewitness was riding along a road, and men were leading a bull towards him. The eyewitness says the following.

> I can clearly recall that there was one of those periods of "quietness" that sometimes precedes a downpour. Just as I drew level with the bull there was one very loud bang or explosion and immediately down the white traffic line in the center of the road appeared the fireball. It seemed to be about 6 or 8 inches [15-20 cm] off the ground, was about the size of a basketball, like very

> golden butter in colour, and had the appearance of being "spun" or "fuzzy", like silk threads or wool, as distinct from a "molten" liquid look. It did not sparkle—just a ball of fuzz…
>
> The whole thing would have been over in probably two or three seconds, before the horse had time to be startled. The young men leading the bull cried out—in pure Australian—"What the bloody hell was that?" As there was another downpour shortly, we did not stop to discuss it. "

Case 2. From *Stakhanov 1985*, p. 29 No 9 (fragment). June 1955, noon, thunderstorm. Eyewitness Busik B. M.—electronics technician, five other people observed the event.

> The ball lightning entered the room through an open window, passed over the table around which the people were sitting, then it crossed the room and went out through the door into hallway. The ball lightning was silvery in color, with a diameter of 10-20 cm. It boiled, crackled, and blinked…

Eyewitness descriptions indicate active processes in ball lightning. It boils, crackles, blinks, and its surface can be covered with threads.

3.1. **Hairy ball lightning**

3.1.1. Glass filaments in industry and in nature

In our approach, ball lightning is blown out of molten glass by hot gas. Under these conditions, the appearance of "hairy" ball lightning is not uncommon. This phenomenon is reminiscent of the industrial process used to produce glass fibers (*Le Bourhis 2008*), where molten glass is stretched into filaments. Typically, this stretching is achieved using the centrifugal force of a high-speed centrifuge. The resulting molten fibers are then rapidly cooled by a stream of air, solidifying into thin glass filaments.

In nature, glass filaments are produced during volcanic eruptions (*Duffield at all. 1977*, *Sigurdsson 2000*, *Cicconi et al. 2019*). These filaments, known as *Pele's hair*, are named after the Hawaiian goddess of volcanoes. Pele's hair forms from volcanic magma and consists of oxides, primarily SiO_2 (approximately 50 wt%), Al_2O_3, CaO etc. They originate from gas-rich magma, such as Hawaiian tholeiitic basalt, which contains about 0.5–2% gas by weight.

Fig. 3.1. Greenish-gold strands of Pele’s hair form when bubbles in hot lava pop and throw droplets into the wind. The droplets can elongate into perfectly straight, glassy strands that are as thin as human hair.

The process of formation of volcanic filaments begins deep underground where gas is released from the magma, creating bubbles. These bubbles merge into high-pressure gas plugs. As these plugs ascend to the top of the magma column, they burst due to the drop in external pressure. This results in a violent gas jet that propels molten basalt drops into the air. If the magma has low viscosity (<100 Pa s at 1300-1500 K), numerous drops form in the jet. Some drops cool down and solidify forming small, irregular clumps known as *Pele's tears*. Others are stretched into long, thin strands by volcanic gases or wind—Pele’s hair.

These glass filaments are extremely delicate, ranging from 1 to 500 micrometers in diameter and up to 1 meter in length. Their structure often includes stretched gas vesicles, making them lightweight and easily transported by wind over long distances.

3.1.2. Glass filaments on the surface of ball lightning

The formation of glass filaments on the surface of ball lightning is similar in many ways to the formation of Pele's hair. The material forming the BL shell is molten soil components, created during an electrical discharge initiated by a cloud-to-ground lightning strike. Under conditions of extreme temperatures and pressures, chemical reactions between the melt components and flow instability, the molten material acquires a foamy texture (see section 2.2.3). The pressure inside its micron-sized bubbles significantly exceeds atmospheric level, and the condensed fraction of foam contains a large amount of dissolved gas.

When a piece of this foamy material enters a region of atmospheric pressure after the discharge ends, the gas bubbles near the melt boundary burst due to the pressure difference. As this piece of material begins to transform into the BL shell, its surface area increases dramatically, bringing more bubbles to the interface, where they also burst. The melt contains bubbles of different sizes, and larger bubbles are more likely to collapse. That can destabilize the forming shell, potentially preventing the formation of ball lightning altogether. As a result, the melt film that becomes the BL shell is filled with gas bubbles that are much smaller than the film thickness - they are micron sized.

Energy of small bubbles is stored in the high-pressure gas that fills it and in the surface energy of the bubble wall. When the bubble bursts, this energy is released, causing a micro-explosion that sends a fountain of nanodroplets into the surrounding environment. The evolution of these droplets depends largely on the melt's viscosity and the velocity at which the droplets are launched. Several outcomes are illustrated in Fig. 3.2.

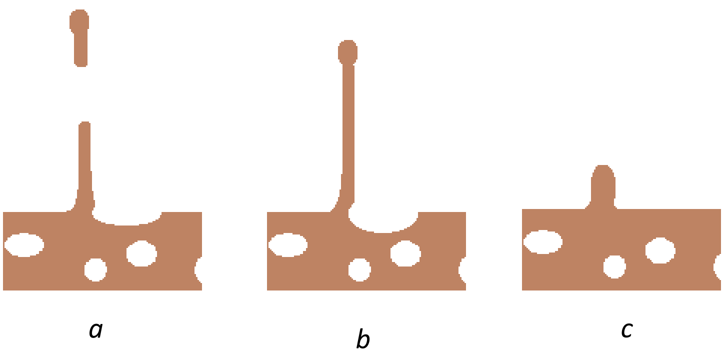


Fig. 3.2. Various scenarios of bubble explosion: detachment of a droplet, formation of a thread, extrusion of a tubercle.

When a droplet is ejected from a viscous melt, a thin bridge forms between it and the melt's surface. As the droplet moves away, this bridge elongates and thins. If the droplet's kinetic energy is sufficient, the bridge breaks, allowing the droplet—sometimes trailing a tail—to fly off (Fig. 3.2*a*). The remaining part of the bridge attached to the melt surface, or the unbroken bridge with droplet (Fig. 3.2b) may solidify in cold air, leaving threads attached to the surface. If the viscosity of melt is high or the pressure between the gas in the bubbles and the atmosphere is small, only a slight swelling of the surface may occur (Fig. 3.2c).

Bursting small bubbles on the surface of the BL disrupts its smoothness, as noted by eyewitnesses. “The ball lightning looked like a hedgehog, the needles sticked out of its surface, the ball seemed fluffy” (from *Bychkov 2021*, p. 104, Case 10). Another describes: “The surface of the ball was uneven, covered in tubercles that rose and fell” (from *Stakhanov 1985*, p. 124, case 102.).

The bursting of bubbles does not cease after the formation of ball lightning. It takes time for chemical and structural equilibrium to be reached in the melt. Throughout the life of the ball lightning, this relaxation process continues to release gas—and potentially energy—leading to further bubble formation. Supersaturated dissolved gases are also released, contributing to this bubble-forming activity.

However, the question arises here: how do bubbles from the internal regions of the melt get to the surface of the shell? We believe that this occurs because of the mixing of the melt under the action of two processes: the downward movement of the foamy melts under gravity inside film forming the BL shell and rotation of ball lightning around the axis as a whole object. Ball lightning can acquire a rotational motion, when a gas flow from an electrical discharge channel in the soil throws the ball lightning upward.

Above, we discussed how glass filaments form on the outer surface of the BL shell. Since the pressure of gas filling ball lightning differs only slightly from atmospheric pressure, similar filament-forming processes are likely to occur on the inner side of the shell as well. However, if the temperatures of both the shell and the filling gas are the same, the molten filaments will not solidify—they'll instead collapse into droplets under the action of surface tension.

Another situation arises if the gas filling the ball lightning cools faster than the shell. This creates a cooler gas environment inside the hot shell, allowing the molten filaments to solidify and persist. The result can be the formation of a framework of thin filaments inside the ball lightning, significantly changing its properties. This idea takes us back to *Smirnov 1991* fractal model of ball lightning; however, unlike Smirnov's version, this model has a shell enclosing the fractal structure. This situation can occur when the ball lightning is filled with a gas that radiates well in the infrared region, such as water vapor. Still, the question remains: how stable is ball lightning when the filling gas cools quickly?

3.2. Noise, formation of nitrogen oxides

Each bubble bursts with soft pop. When many bubbles burst, they make noise. Thus, eyewitnesses may see hot droplets flying out of the surface of the BL, which they identify as jets or sparks, and hear a slight buzzing or hissing sound. The sound emanating from ball lightning is noted by many observers. Here is an example of noisy ball lightning.

Case 3. From *BL Reports*, the report was posted on July 14, 2005. Champaign, IL, USA. The eyewitness: Linda Andersen. About 7PM, there was a thunderstorm. Linda's sister was in the kitchen.

> …On my way to the doorway, as I walked through the dining room, I began to hear this hissing noise, sort of like bacon frying. It was a noise I had never heard before. Although I wasn't really alarmed or afraid, I remember thinking ‘what is going on in there?’. As I arrived at the doorway to the kitchen, I looked above my sister's head to see a ball that glowed but had no colour. It was about 9" in diameter. It had sort of a transparency to it, I think. No sooner had I laid eyes on it there was a pop. All that was left was wisps of grey smoke. My sister and I both stood there speechless for a few seconds.

Ball lightning can carry an electric charge. The average electric field strength of this charge immediately behind the shell may be below the breakdown threshold of the surrounding medium (air). However, the breakdown electric field is achieved at micro protrusions formed by the explosion of small bubbles. These local electrical micro discharges also create sound. In addition, micro discharges can be a source of radicals that lead to chemical reactions in the air with the formation of ozone and nitrogen oxides. This explains the presence of nitrogen oxides in air samples taken by *Dmitriev* (*1969*) in the immediate vicinity of ball lightning.

3.3. Halo around ball lightning

Another consequence of bursting micron bubbles is the formation of a halo around the ball lightning. Under certain conditions (primarily, with low viscosity of the melt), many droplets are ejected into the surrounding air (Fig. 3.2a). The droplets solidify in the air, forming a cloud of glass particles around the ball lightning, on which the BL light is scattered. The type of scattering is determined by the size parameter

$$x = \frac{\pi d}{\lambda} \tag{3.1}$$

where *d* is characteristic diameter of particle, and *λ* is the wavelength of the light.

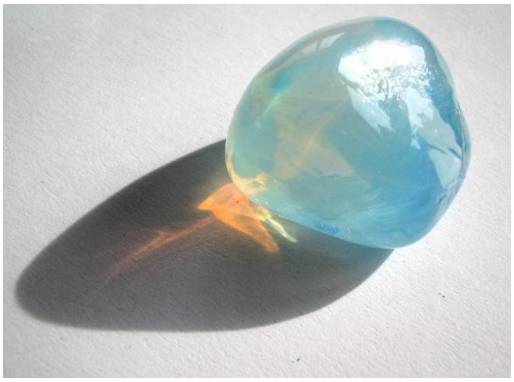


Image by *optick*, via Wikimedia Commons, CC BY 2.0.

Fig. 3.3. Rayleigh scattering in opalescent glass: the glass is orange in the direction of the external light beam, and bluish when viewed from other directions. The same processes are responsible for the formation of a halo around ball lightning.

In many cases eyewitnesses report a blue color of the halo, which corresponds to the Rayleigh type scattering (x<1). The Rayleigh scattering cross section depends on the parameter *x* as follows (*Howell et al. 2016*):

$$\sigma_{Ra} = cx^4 S \tag{3.2}$$

where $S=\pi d^2/4$ is cross-sectional area of particles, *c* is a constant that depends on the properties of the medium and scattering particles. Equation (3.2) implies that if a beam of light propagates through a medium with small particles, the short-wave portion of its spectrum will be scattered to a greater extent than the long-wave portion. That is, the scattered light becomes blue. When this situation occurs, the observer can see the light source and simultaneously the bluish light from the large scattering region. An example of Rayleigh scattering is shown in Fig. 3.3, where a piece of frosted glass acquires a bluish tint due to the scattering of an orange beam of light by internal inhomogeneities.

We believe that ball lightning emits light in a broad spectral range, including blue and violet regions. Assuming that the blue halo is due to Rayleigh scattering by glass particles, we can estimate their sizes. Taking the size parameter x <0.3 (*Howell et al. 2016*) and the average wavelength of scattered light λ=450 nm, we obtain from Eq. (3.1) the particle size d ≈40 nm. Thus, in the blue halo region there should be enough particles with a diameter less than 40 nm.

Case 4. Now we will give an eyewitness description of ball lightning with a halo. From *Bychkov 2021*, p. 105 Case 13. Eyewitness: Valery. Town Bratsk, Aug.14,1981, around 23.00. We give only a summary of this case.

> During a thunderstorm, the eyewitness was in his apartment on the ninth floor. He saw orange glare on the walls of the room and went to the window to find out the cause. An orange ball was slowly rising in the street, about half a meter from the window. Its diameter was about 15 cm. The ball had a smooth, shiny surface, the blue halo around the ball was about 10 cm thick. The ball hissed and pulsated; fountains of sparks were thrown from its surface. The ball continued to rise and soon disappeared.

The eyewitness' description indicates the conditions for the formation of the halo: the ball hissed, and fountains of sparks burst from its surface. We believe that this activity was caused by micro explosions of gas bubbles in the shell, forming a cloud of nanoparticles around the ball lightning that scatters the light of BL, Fig. 3.4.

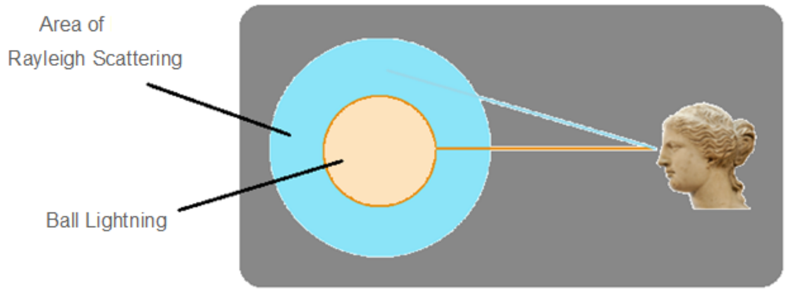


Fig. 3.4. Eyewitness sees ball lightning and a bluish halo around it; night thunderstorm creates a dark background.

Speaking of halos, we should note one more circumstance. When an eyewitness sees a luminous object, he cannot always determine the presence of a halo, even if he has direct contact with it. The following eyewitness report is such an example.

Case 5. From *Stakhanova 2005.* The event occurred in the village Mirny near Kazan, in summer 1967. Eyewitness: medic V. V. Varsonov'eff.

> Around 15-16 o'clock a thunderstorm with strong winds began. After a loud clap of thunder, a blue vaporous mass 30-40 cm in diameter flew into the open door and began to move quickly around the room. After traveling 10-15 m, it rolled under the stool on which the medic was sitting. Although the object was at his feet and his feet were partially immersed in it, the medic did not feel any heat. Then the ball lightning approached the radiator and disappeared with a sharp hiss, melting a 3-4 mm spot on the radiator.

We believe that the eyewitness observed ball lightning with a blue halo and had contact not with hot ball lightning, but with a cold halo. Based on this eyewitness description, it would be wrong to draw a conclusion about the temperature of the BL.

Previously, we discussed the formation of halos because of the interaction of ball lightning radiation with spherical particles whose sizes are much smaller than the wavelengths of the scattered radiation, as described by Eqs (3.1) and (3.2). However, the particles can have an irregular shape and size range. In this case, other types of scattering processes are possible, affecting the longer-wavelength part of the spectrum. The inclusion of a long-wavelength component makes the scattered light appear brighter and acquire a white tint.

And here, obviously, the question arises about the processes that control the concentration of nanoparticles in the halo area, i.e. about the rates of formation and removal of nanoparticles. At our level of understanding of the problem, we cannot give a satisfactory answer to this question.

In this regard we would like to mention a process that can largely influence the characteristics and behavior of ball lightning. We are talking about the possibility of the presence of an electric charge in droplets ejected from the surface of the BL due to micro explosions of gas bubbles. If ball lightning was initially electrically neutral, then to maintain the overall charge neutrality, ball lightning must acquire a charge opposite to the charge of the droplets. As a result, a system can be formed consisting of a charged ball lightning surrounded by a cloud of particles of the opposite sign (*space charge*). The distribution of charged particles in the space charge region is determined by two processes: the ejection of charged particles from the surface and their return under the action of electrostatic forces. We believe that this system quickly achieves a dynamic equilibrium. The resulting space charge is a fairly stable formation, and the cloud of particles can follow the ball lightning as it moves. We also note that the processes of formation of spatial charge cause cooling of the BL shell.

That such a system can only arise in high temperature ball lightning when the viscosity of the melt is low. Besides, the presence of an initial charge of the BL affects this structure and, if it is large, can prevent the formation of space charge.

Although there is no direct experimental evidence for the existence of oppositely charged melt surfaces and droplets in silicate systems, there are experiments that point to this possibility. For example, these processes are observed above the water surface: while microdroplets of water formed because of micro explosions of bubbles carry a negative electrical charge, the water surface acquires a positive charge (*Levin et al. 1971*, *Bhattacharyya et al. 2011*).

To conclude the section on halos, we will give one more example.

Case 6. In our opinion the paper *Stephan et al. 2016* also contains a description of a ball lightning with halo. The event took place in southern New York State on June 23, 2008, in the evening. An intense thunderstorm was in progress. The eyewitness was in the vehicle and could see the front entry to her house approximately 6 m away.

The entry consisted of an outer door of clear glass (storm door), behind which there was a solid door painted off-white; usually there is a gap of about 5 cm between them.

The eyewitness describes her experience as follows: “I just happened to glance over at my porch, and I was stunned. I mean, I saw that fiery ball, yellow-flame appearance in my front door… It was the center of the door, at least twice, two and a half times more area than you'd expect from that small cantaloupe-size blue object (14 cm in diameter) that I saw” (Fig. 3.5, anterior view).

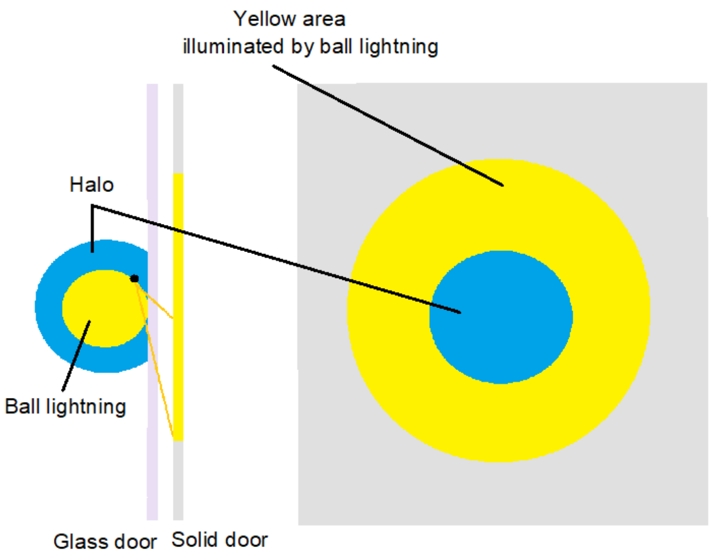


Fig. 3.5. Schematic representation of the event described in the paper of *Stefan et al. 2016*.

Yellow ball lightning with a blue halo is located close to the glass door (lateral cross-section). The radiation of ball lightning passes through the glass door and forms a large yellow spot on the solid door while the ball lightning is not visible because it is hidden by the halo (anterior view).

Here, a question arises. If we assume that the blue glow is a ball lightning, then what causes the yellow glow around it? The authors of the work *Stephan et al. 2016* suppose that the observed yellow glow is a fluorescent luminance of glass. They experimentally confirmed that the fluorescence of glass may occur under action of ultraviolet or x-ray radiation. Based on eyewitness observation and fluorometric analysis, the authors *Stephan et al.* concluded that ball lightning could be a source of high energy radiation.

We believe that there is another explanation for this phenomenon. A sketch of the event is shown on Fig. 3.5. A yellow ball lightning with a diameter of about 7 cm has a blue halo. The ball lightning is located close to the glass door and the thickness of the halo near the door is small. Thus, part of the BL light freely reaches the glass door, where it is partially reflected and partially passes through the glass. Since there is a gap of about 5 cm between the glass and the solid doors, the transmitted BL light spreads in this gap and forms a yellow luminous spot on the off-white solid door. The size of this spot is larger than the size of the ball lightning. For illustration, the figure schematically shows the solid angle in which the light from a small element of the thin BL shell spreads to the solid door.

We cannot evaluate the degree of transparency of the halo. Perhaps the observer saw not a pure blue glow, but a blue glow with a yellow tint from ball lightning. However, in any case, the halo area and the illuminated area on the door were clearly visible.

Another fact should be noted. The eyewitness does not mention any damage to the surface of the glass door, although the ball lightning was close to it or even touched it. A small part of the glass surface may have melted slightly. After the ball lightning moved away, this layer quickly hardened and became barely noticeable.

3.4. Effect of mass loss from the BL surface on heat transfer

The BL shell composed of foamed molten glass has a temperature of 1500-2500 K. This temperature is significantly higher than that of the ambient air, resulting in cooling of the ball lightning. Radiation losses will be considered in subsequent sections. Here we will briefly discuss other processes leading to heat loss of BL.

When a hot body is surrounded by still, cold air, the air near the surface heats up and rises due to buoyancy forces. This process forms a hydrodynamic boundary layer through which heat is transferred from the body's surface to the cooler air. Heat transfer from bodies of various shapes under such conditions is typically calculated using correlation-based methods, *Incropera et al. 2007.*

However, these standard correlations cease to apply when the boundary layer is disturbed by external factors. In the case of ball lightning, disturbance occurs due to the injection of hot gases and nanoparticles into the boundary layer, which is the result of bursting gas bubbles from the shell of foamed molten glass. In addition, the bursting bubbles disrupt the smoothness of the surface, and the appearance of glass threads on the surface of the BL further complicates the situation.

Estimating the rate of heat transfer under these complex conditions is a challenging problem that would require both experimental and computational investigation. As such studies are beyond the scope of this work, we will consider only two limiting scenarios. First, the BL behaves as a sphere with a smooth surface, and heat transfer is estimated using conventional formulas. Secondly, the mass ejection from the BL surface is substantial enough to create a hot layer that displaces the ambient cold air, significantly reducing convective heat transfer. In this case, only radiation losses need to be considered (see Section *7* for details).

It is worth noting that gas injection into a boundary layer as a method of thermal protection has long been utilized in aerospace applications, through systems such as transpiration and ablation cooling (*Rohsenow 1998*). These techniques are designed to shield vehicle structures from high-temperature gas flows. In the case of ball lightning, a similar mechanism appears to protect the hot BL body from cold air. In this case, the mass and total enthalpy of ball lightning decrease, while the specific enthalpy (and temperature) remains unchanged.

3.5. Explosive disappearance of ball lightning

The pressure in a soil electric discharge can be orders of magnitude higher than atmospheric pressure. At such high pressure, the amount of gas dissolved in the melt is also large. When a layer of this melt enters the atmosphere, supersaturated gases are released forming high-pressure bubbles inside the melt.

These high-pressure bubbles burst upon reaching the melt boundary. When many bubbles burst simultaneously, an explosive dissipation of the ball lightning shell occurs, that is, the shell breaks into many small fragments. The gas dissolved in the fragments is released. In addition, the fragments cool in the air, transferring their energy to it. This creates a localized region of elevated pressure and temperature. As this region decays, it generates a shock wave. This wave can cause damage in confined spaces, but in open air or large rooms, the shock wave quickly transitions into a sound wave, perceived by observers as a loud bang.

The phenomenon resembles the explosion of a champagne bottle, although there are important differences: the viscosity and surface tension of molten material are several orders of magnitude higher than those of water. Consequently, the time required to develop the necessary conditions for such an explosion is significantly longer in molten material than in water. This timescale may correspond to the lifetime of the ball lightning before its explosive disintegration. The process of explosive disintegration of ball lightning can also be caused by its interaction with external objects.

Case 7. From *Stakhanov 1985*, p. 90, No 42. Examples of BL explosion without causing damage.

> In many instances, the consequences of a ball lightning explosion are minimal—perhaps a broken window from a nearby explosion, a scorched patch on the wall, or a burned spot on the floor. Often, no significant damage is reported at all.
>
> For example, in one case, a ball of lightning 20-30 cm in diameter exploded less than five meters from a person. The only noticeable effect was a mild gust of air. In another case, lightning with a diameter of 15-20 cm exploded over a table, catching on a metal lamp hanger. There were four people sitting at the table, and the lightning was about half a meter away from them. There are no reports of casualties.

An example of a ball lightning explosion that caused significant damage is given in Section 6, *Case 8*: ball lightning exploded in a brick chimney and destroyed it.

It should be noted that explosive disintegration of ball lightning is possible only at high BL temperatures, when the viscosity of the melt is low. If the ball lightning cools down rapidly, the explosive conditions may not arise. In this case, other mechanisms of ball lightning disintegration are possible. For example, the same process of destruction of the shell of BL due to intensive release of gas dissolved in a melt can take place. However, under the higher viscosity, the characteristic times of all processes will increase, the release of gases and energy from the melt will occur more slowly, and the shock wave in the air will not be able to form. That is, the ball lightning will collapse without explosion.

3.6. Summary

We consider ball lightning as a thin-walled sphere filled with hot gas. The material from which ball lightning is formed (molten glass) contains many micron-sized bubbles; the same bubbles are also generated in the shell material during BL life. That is, the shell of BL is a foamy structure. The gas pressure in these small bubbles significantly exceeds atmospheric pressure, so when they approach the surface of the shell, they burst. The consequence of this process is the release of nanodroplets of melt into the surrounding air and the formation of threads on the BL surface. The resulting cloud of nanoparticles scatters the light of ball lightning, forming a halo around it. The micro explosions of gas bubbles are perceived by the observer as slight buzzing or hissing.

The release of droplets of melt and hot gas from the bursting bubbles creates a protective layer on the surface of BL, preventing direct contact of ball lightning with the surrounding cold air, which reduces or eliminates convective heat loss. The simultaneous bursting of many small bubbles leads to the explosive disintegration of ball lightning.

References

Bhattacharyya, I., Maze, J. T., Ewing, G. E., & Jarrold, M. F. (2011). Charge separation from the bursting of bubbles on water. *The Journal of Physical Chemistry A*, *115*(23), 5723-5728.

Bychkov, V. L. (2021). *Natural and artificial ball lightning in the Earth's atmosphere*. Moscow, «МАКС Пресс».

Cicconi, M. R., & Neuville, D. R. (2019). Natural glasses. In *Springer handbook of glass* (pp. 771-812). Cham: Springer International Publishing.

Dmitriev, M.T. (1969). Stability mechanism for ball lightning. Дмитриев, М. Т. О механизме устойчивости шаровой молнии. *ЖТФ.*, *39*(2), 387.

Duffield, W. A., Gibson, E. K., & Heiken, G. (1977). Some characteristics of Pele's hair. *J. Res. US Geol. Surv*, *5*(1), 93-101.

Howell, J. R., Mengüç, M. P., Daun, K., & Siegel, R. (2016). *Thermal radiation heat transfer.* CRC press.

Incropera, F. P., DeWitt, D. P., Bergman, T. L., & Lavine, A. S. (2007). *Fundamentals of heat and mass transfer,* 6th Ed. New York: Wiley.

Le Bourhis E. (2008). *Glass*. WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.

Levin, Z., & Hobbs, P. V. (1971). Splashing of water drops on solid and wetted surfaces: hydrodynamics and charge separation. *Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences*, *269*(1200), 555-585.

Rakov, V. A., & Uman, M. A. (2003). *Lightning: physics and effects*. Cambridge university press.

Rohsenow, W. M., Hartnett, J. P., & Cho, Y. I. (1998). *Handbook of heat transfer* (3d Ed.). New York: Mcgraw-hill.

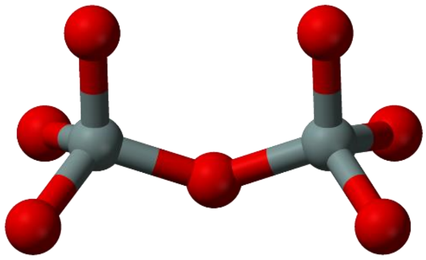
Sigurdsson H, Editor. *Encyclopaedia of volcanoes*. Academic Press (2000).

Smirnov, B. M. (1991). A tangle of fractal fibers as a new state of matter*. Soviet Physics Uspekh*i, 34(8), 711.

Stakhanov, I. P., (1985). *The physical nature of ball lightning*. Стаханов И. П, *О физической природе шаровой молнии*. М. Энергоатомиздат

Stakhanova, I. G., (2005). Ball lightning remains a mystery. Стаханова, И. Г. Шаровая молния остается загадкой. *Прикладная физика*, (1), 47-57.

Stephan, K. D., Krajcik, R., & Martin, R. J. (2016). Fluorescence caused by ionizing radiation from ball lightning: Observation and quantitative analysis. *Journal of Atmospheric and Solar-Terrestrial Physics*, *148*, 32-38.



Connection of unit cells via bridging oxygen atoms in silicate materials.

4. Thermal radiation of ball lightning

In this chapter we will use the following characteristics of radiation: wavelength λ and wavenumber v. These quantities are related by the relation v = 104/λ where v in cm-1 and λ in µm.

We assume that the emitting and absorbing energy levels are in thermal equilibrium at a given temperature. In this case, the spectral absorptivity and emissivity are equal, and henceforth we will use these terms assuming their identity.

4.1. Introduction

The traces that ball lightning leaves when interacting with various objects indicate that it is a high-temperature formation. Based on general considerations, ball lightning should emit in a wide range of wavelengths. However, as follows from eyewitness descriptions, this is not always the case.

Case 1. From *Stakhanov 1985*, p. 21, No 4. Eyewitness, engineer Ja. B. Berezovsky, was serving in the military in Germany in the spring of 1945. We give only a summary of the description.

> At night, the eyewitness slept in a room with open windows. His weapon (a carbine) was standing near the window. The eyewitness woke up from a crack near his head. He saw a white ball that smoothly slid along the walls parallel to the floor. After some time, the ball flew out the window. In the morning, when examining the weapon, the eyewitness discovered that the upper part of the steel ramrod (about 3 mm) had melted. But he did not find any traces of

> melted metal, as if the metal had evaporated. The eyewitness also did not feel any heat when the ball flew at a distance of 0.5 m from his face.

The melted part of the ramrod indicates an effect like the exposure of the metal to an oxy-fuel torch flame. This means that the BL temperature exceeded 2000 K.

Case 2. From *Stakhanov 1985*, p. 72, No 21. Eyewitness: V. N. Arkhipov, Bugulma, Russia.

> In the summer of 1955, during a thunderstorm, he and his two brothers wanted to take shelter under the veranda of the house. Bending down to crawl into a 50 cm wide hole, he looked back at the scream of his younger brother and saw a ball lightning about 10 cm in diameter, which, throwing sparks, was approaching the hole. Although the lightning passed less than 0.5 m from the observer and the sparks almost touched his face, he did not feel any heat. Having travelled 1.5 m from the hole to the foundation of the house in about 2 seconds, the lightning struck the foundation and exploded with a loud sound. However, this did not cause any destruction. There was no blast wave. As it turned out later, the antenna in the house melted.

Stakhanov notes an unusual characteristic of ball lightning: when it passes near exposed parts of the human body, observers rarely feel any heat. Of 294 eyewitnesses who saw ball lightning from a distance of less than 1 meter, only 25 reported feeling heat. As Stakhanov notes, "What is surprising about ball lightning is not the emission of light, but the fact that while emitting light, it emits almost no heat."

This suggests that ball lightning exhibits two seemingly contradictory properties: although it appears to be at a high temperature, it emits very little infrared radiation. To our knowledge, no existing research has satisfactorily explained this phenomenon. Here, we also do not aim to create a comprehensive description of this phenomenon. We will only try to give a qualitative explanation for this fact within the framework of our BL model and obtain some estimated values.

We assume that in a ball lightning of average diameter (D_{BL}≈10-40 cm) the energy is mainly concentrated in its shell of molten glass. In this case, the infrared radiation of the shell is one of the main sources of energy loss by the BL. Energy estimates will be made in Section 7.2, and here we focus on the IR optical properties of the shell material.

4.2. Optical properties of silicates

4.2.1. General characteristics of the spectra of silicates

As discussed earlier, the BL shell material is believed to be a molten glass composed primarily of soil oxides, with silica as the major component. Before delving into the optical properties of this shell, it is important to review the general characteristics of silicate-based glasses. Glasses and their molten states have similar features in their absorption spectra, as shown schematically in Figure 4.1 (*Griscom 1991*, *Tropf et al. 1995*). First, we see a wide transparency window in the spectral range $\lambda_{UV} < \lambda < \lambda_{IR}$, which includes visible and infrared parts of the spectrum. The short-wavelength edge λ_{UV}, typically between 0.3 and 0.5 μm, arises from electronic transitions within the material's network-forming elements.

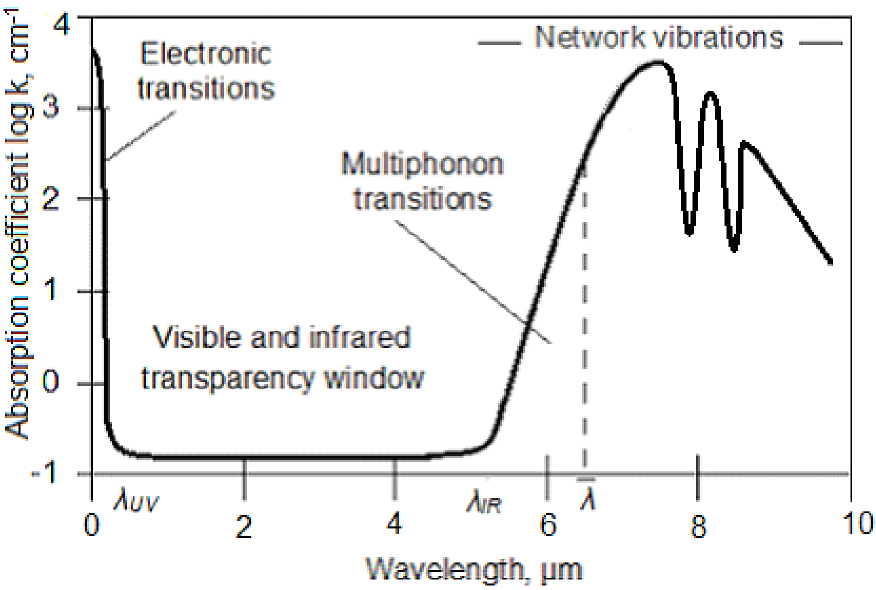


Fig. 4.1. Schematic representation of the absorption spectrum of oxide glasses.

The longwave edge λ_{IR} is determined by the phonon absorption. We'll discuss this process in a little more detail. Oxide molecules usually possess an electric dipole moment, enabling them to interact with electromagnetic radiation. When a photon is absorbed, its energy is transferred to the material's network in the form of collective atomic vibrations—one photon produces one optical phonon. In the harmonic approximation, the infrared absorption spectrum must consist only of bands corresponding to the fundamental frequencies of the network vibrations. Due to the disordered internal structure of the glass and the anharmonicity of the vibrations, the absorption bands are blurred. This spectral region has a high absorption coefficient and is generally opaque. In Fig. 4.1, this region is indicated to the right of the vertical dotted line, $\lambda > \bar{\lambda}$, where $\bar{\lambda}$ typically ranges from 5 to 10 μm for oxide materials.

In addition to one-phonon absorption, there is multiphonon absorption, when two or more phonons are simultaneously excited by one photon; these may be combinations and overtones of the fundamental vibrations (*Sova et al. 1992*, *Shelby 2020*). The probability of these processes is small, and at the region of fundamental bands, $\lambda > \bar{\lambda}$, their contribution to the total absorption is insignificant. However, at wavelengths $\lambda < \bar{\lambda}$, multiphonon processes become the dominant absorption mechanism. As we move away from the region of the fundamental bands towards shorter wavelengths, the intensity of multiphonon processes rapidly decay, defining the infrared absorption edge of the transparency region (λ_{IR}, in Fig. 4.1).

In pure form, glasses exhibit a transparency window that includes the visible and near-infrared regions. This property was fundamental to the pioneering work of *Kao and Hockham 1966*, who demonstrated the feasibility of optical fibers with extremely low signal attenuation—an innovation that earned C. K. Kao the 2009 Nobel Prize in Physics. In the years that followed, significant efforts were made to extend the transparency range of glasses. These advances led to the development of non-oxide glass materials with broader infrared transparency. Depending on their composition, the infrared edge λ_{IR} shifts progressively from pure silica (around 4 μm) to fluorides (6 μm), sulfides (11 μm), and selenides (up to 16 μm) (*Shearer et al. 2023*).

4.2.2. Network structure and absorption spectra of silicates

Currently, there is an understanding that different silicate materials are built up from the same unit cells - SiO4 tetrahedra (*Mysen et al. 2018*). These tetrahedra connect via corner-sharing oxygen atoms, known as bridging oxygens, to form different structures such as crystals, glasses, or melts. Crystals exhibit long-range translational order, while glasses and melts lack this but still maintain short-range order. Within these locally ordered regions, arrangements of SiO_4 tetrahedra resemble those found in crystalline structures. This structural similarity is reflected in their optical spectra. Experimental studies have shown that the primary absorption bands of silicate glasses closely match those of the corresponding crystals. However, due to the inherent disorder in glass structures, these bands appear broadened.

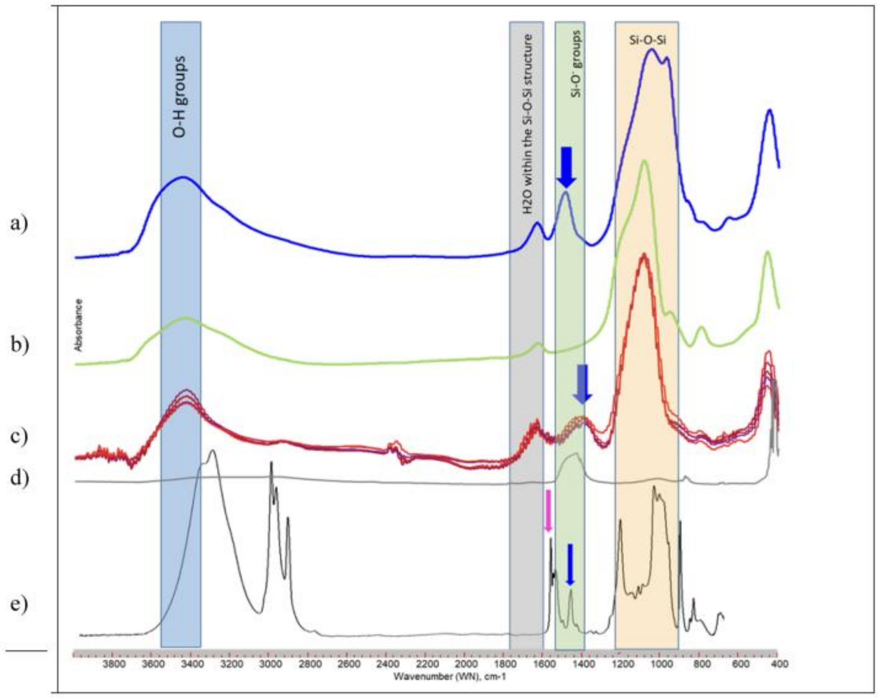


Fig. 4.2. FTIR absorption spectra of (a) precipitated calcium silicate (ZEOfree), (b) bulk precipitated silica (Sipernat 50s), (c) water soluble Sipernat 50s fraction, (d) sodium orthosilicate Na4SiO4, and (e) a dimeric organo-silica.

Absorption bands of silicate-based materials are in the interval 1200-130 cm^{-1} (about 8.5-75 μm). As an illustration, Fig. 4.2 (from *Ellerbrock et al. 2022*) shows the FTIR (Fourier Transform IR) spectra of two amorphous silicates: precipitated calcium silicate (ZEOfree) and precipitated silica (Sipernat 50s). Despite the difference in the chemical compositions of the substances, their spectra are very similar. This is a consequence of the fact that in both cases the 3D-network is formed mainly by identical unit cells - SiO4 tetrahedra. The presence of calcium oxides causes some destruction of the network, resulting in a decrease in the concentration of bridging oxygen atoms. However, this does not lead to a significant change in the spectrum. The strongest bands of silicates are due to the vibrational modes of the Si-O-SI group containing a bridging oxygen atom. These vibrational modes and the corresponding absorption bands are asymmetric stretching (~1070-1120 cm^{-1}), symmetric stretching (~800 cm^{-1}), and bending (~480 cm^{-1}), *Liu et al. 2022*.

The anharmonicity of the vibrational modes leads to the appearance of multiphonon absorption in the region of about 1200-2500 cm^{-1}. However, this region cannot be represented in Fig. 4.2 due to the use of arbitrary units. The multiphonon region is shown most fully in Fig. 4.3, where the normal spectral emissivity ($\bar{\varepsilon_\nu}$) of a silica sample at different temperatures is presented, *Rozenbaum et al. 1999*.

$$\bar{\varepsilon_\nu} = 1 - \exp(-k_\nu l)$$

where k_v is spectral absorption coefficient for wavenumber ν and l is thickness of the sample. For thin samples (here, l =162 μm) a good spectral resolution, as in Fig. 4.3, can be obtained. Note that at thermal equilibrium between absorbing and emitting levels, the spectral emissivity and absorptivity are equal (Kirchhoff's law), which allows us to compare Fig. 4.3 with absorptivity data.

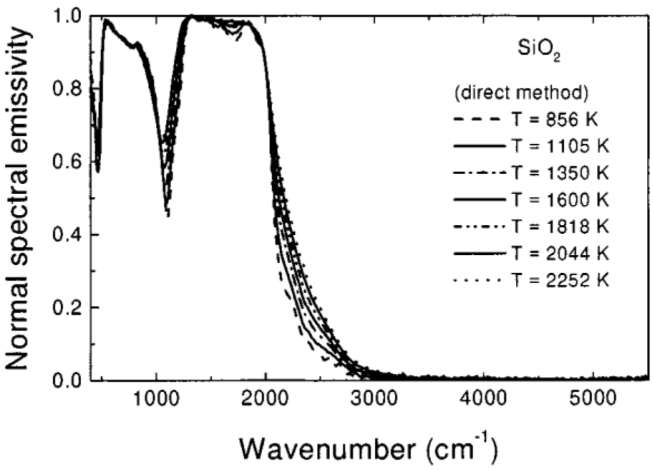
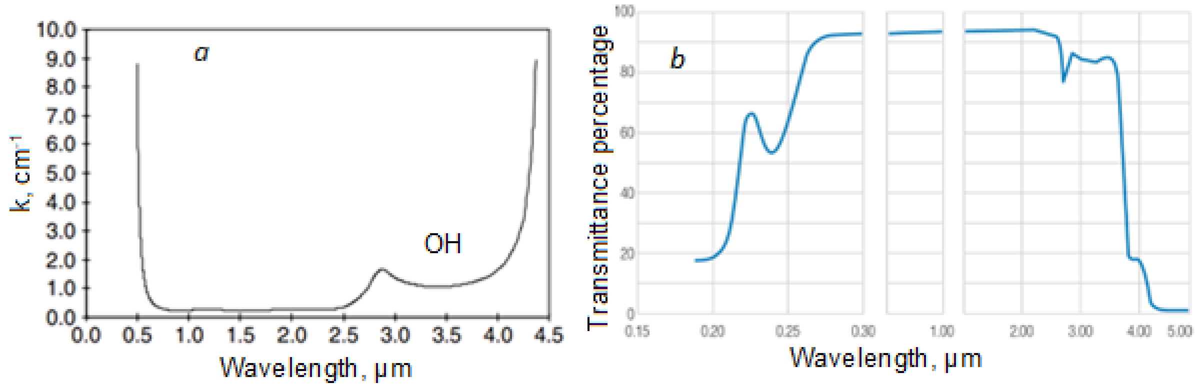


Fig. 4.3. Temperature dependence of the normal spectral emissivity of high-quality grade; sample ~162 μm thick and 10 mm in diameter (from *Rozenbaum et al. 1999*).

In Fig. 4.3, we see two peaks around 1200 and 500 cm^{-1} associated with vibrations of the group Si-O-Si. These peaks are slightly shifted towards higher wavenumbers relative to the peaks in Fig. 4.2 because of the different structures of the materials studied. In Fig.4.2, the spectra for porous materials are given while samples for Fig. 4.3 were solid. The emissivity (absorptivity) at wave numbers greater than 1250 cm^{-1} is due to the multiphonon processes.

Fig. 4.4*a* shows the spectral absorption coefficient of molten soda-lime glass (obtained by *Coenen 1968,* adopted from *Choudhary et al. 2005*). In the absence of impurities (H2O and radical OH), the spectrum has a transparency region of approximately from 0.5 to 4 µm. The IR edge $\lambda_{IR} \approx 4$ µm is consistent with the onset of the notable multiphonon absorption at ~2500 cm^{-1}, shown in Fig. 4.3 for the thin silica sample.



From *Choudhary et al. 2005*.   From Cryostat windows

Fig. 4.4. Optical spectra of silicate samples.
a - Absorption coefficient of soda-lime glass melt at 1400°C, *b* - Transmittance of a bulk sample of fused silica IR grade at room temperature.

Bulk samples of silicate materials are opaque in the multiphonon absorption region. An example of this is the transmittance of fused silica IR grade at room temperature shown in Fig. 4.4*b*. As can be seen, the sample is completely opaque at wavelengths longer than 4 µm.

A broad region of the silicate absorption spectra is associated with vibrations of the bridging oxygen in the Si-O-Si group. Changes in the abundance of bridging oxygen directly influence the intensity of these absorption bands. This abundance is primarily governed by the chemical composition of the material. In silicate materials, the presence of alkali and alkaline earth oxides promotes reactions with bridging oxygen, resulting in depolymerization—where bonds between neighboring structural units are broken—and the formation of non-bridging oxygen.

For instance, in binary mixtures of SiO2 and alkali oxides, increasing the alkali oxide content up to 50% reduces the number of bridging oxygen atoms by half (*Mysen 2021*; *Henderson 2005*). In extreme cases, silicates may contain no bridging oxygen at all. A notable example is sodium orthosilicate (Na4SiO4), which is composed of isolated $SiO4^{4-}$ tetrahedra whose outer oxygen atoms are coordinated with Na^{+} ions.

FTIR spectra in Fig. 4.2*d* show weak absorption of pure Na4SiO4 in wide infrared regions (at frequencies greater than 500 cm^{-1}). The weak band at 1450 cm^{-1} and strong bands ~500 cm^{-1} are apparently due to Si-O vibrations.

These spectral features generally persist up to ~1500 K in many silicate systems, though the precise temperature threshold may vary with composition. Beyond this temperature, spectral changes become more significant. The increased vibrational energy at higher temperatures leads to the breaking of inter-unit bonds, reducing the concentration of absorbing and emitting states. These effects will be examined in more detail in the following sections.

4.3. Optical properties of ball lightning shell material

As before, we assume that the source of ball lightning radiation is primarily its shell of molten silicate glass. Since the shell of ball lightning is a thin film, its spectral and total emissivity are far from those of a blackbody and depend on the spectral properties determined by the conditions under which ball lightning forms in a soil electrical discharge.

If the melt temperature is relatively low (e.g., below 1500 K), a network of long chains of unit cells forms within the melt. This network contains bridging oxygen atoms, the vibrations of which create intense emission (absorption) bands in the spectrum (Section 4.2.2). If the melt also contains impurities of water and the OH radical, the ball lightning shell formed from this material is an intense emitter in the infrared range. Such ball lightning will have high radiation losses.

However, numerous eyewitnesses report that ball lightning has weak thermal radiation. This is confirmed by the rather long lifetime of ball lightning (about 10 s), which is possible with low energy losses due to radiation. At the same time, traces left by ball lightning when it impacts surrounding objects indicate that the BL temperature is high (for example, melting of the surface of metal objects, Section 4.1). A significant weakening of the thermal radiation of silicate glass melts can be caused by a weakening of the intensity or complete disappearance of the main vibrational bands associated with bridging oxygen. In other words, the weak infrared radiation intensity of the silicate glass melt is due to the depolymerization of its internal structure.

We are not aware of any direct evidence for this fact. However, information can be obtained from the works on numerical modelling of the atomic-scale structures of silicates under conditions corresponding to Earth's magma. In work *de Koker et al. 2008*, first principles molecular dynamics (MD) modelling of liquid forsterite (Mg2SiO4) was carried out. A snapshot of the simulated structure at atmospheric pressure and at 3000 K, is shown in Fig. 4.5, right panel. For comparison, the forsterite crystal structure under ambient conditions but is given on the left panel of the figure.

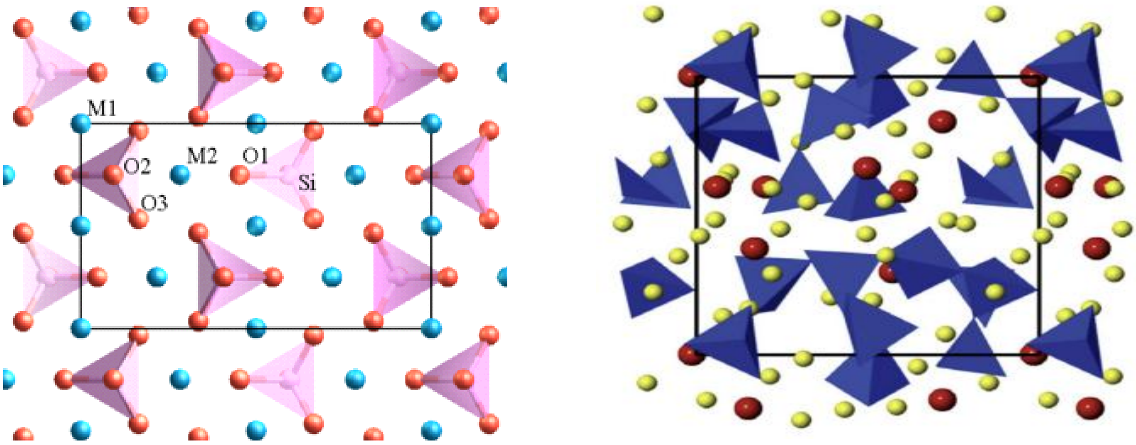


Fig. 4.5. The atomic-scale structure of forsterite (Mg2SiO4).

Left panel: the crystal structure at ambient temperature and pressure. Oxygen is shown in red, silicon in pink, and Mg in blue. A projection of the unit cell is shown by the black rectangle. (From Wikipedia, Forsterite).

Right panel: snapshots of the MD simulated liquid at 3000 K and ambient pressure. The structure is very open, with Si almost entirely fourfold coordinated. Tetrahedra are mostly free-floating, with dimers and a four-membered chain also visible. Free oxygen is shown in red, SiO_N in blue, and Mg in yellow. (from *de Koker et al. 2008)*.

We see that at high temperatures the network was destroyed. Authors *de Koker et al.* describe the structure of the melt as follows. The Si atoms are almost entirely tetracoordinated. The main elements of the structure are isolated tetrahedra that are mostly free-floating. Dimers and four-membered chains are also present in small quantities. Overall, the melt contains 70% non-bridging oxygen atoms, and 15% of O atoms are not bound to Si and are 'free oxygens' (red spheres in Fig. 4.5, right panel). The remaining 15% of O atoms are bridging oxygen, they are present in dimers and larger chains.

Similar calculations were carried out in the work of *Solomatova et al. 2019*, where the structure and properties of pyrolite (NaCa2Fe4Mg30Al3Si24O89) were studied using molecular dynamics methods. Baric and temperature conditions corresponding to the Earth's magma were considered. At low pressure (e.g. atmospheric) and temperatures above 2000 K, the melt contains only a small number of dimers or longer chains of SiO4 tetrahedra, their lifetime is short, on average several hundred femtoseconds, *Caracas et all. 2021* (1 fs = 10^{-15} s). The lifetime of components of the melt is also short. The longest-living species were SiO4 tetrahedra with an average about 3 picoseconds while AlO4 tetrahedra exist for an average of 0.3 picoseconds. The lifetime of the polyhedra of the cations that modify the network, i.e. Fe, Mg, Ca and Na, is several tens of femtoseconds.

Thus, in conditions of complete destruction of the network forming the structure of the melt, we could assume that the spectral bands associated with collective vibrations of the melt network are absent. This means that at high temperatures, a wide spectral region of 0.5-25 μm has virtually no radiation in the absence of emitting impurities. Note that sodium orthosilicate Na4SiO4, which has no bridging oxygen at all, has a very similar absorption spectrum under ambient conditions (Fig. 4.2*d*).

One can hardly expect a complete absence of radiation processes in the IR region; here we will use the absorption coefficient $k_\lambda \approx 0.2$ cm^{-1}(or 20 m^{-1}). This value corresponds to the absorption of the soda-lime glass melt in the region of 0.5-2.5 μm, Fig. 4.4a (see also *Faber 2002*). In addition, at wavelengths longer than 25 μm, there are intense bands associated with intra-tetrahedra vibrations. However, in the temperature range under consideration (1500-2500 K), this spectral region, as well as region < 0.5 μm, does not make a large contribution to the total emissivity. Therefore, to simplify the calculations, we will use a constant absorption coefficient in the entire spectral region unless otherwise specified.

Discussion

In summary, we can say the following. We believe that there are three temperature ranges in which the physical properties of silicate glass melts differ significantly. At relatively low temperatures (below 1500 K), the internal structure of the melt is a disordered network consisting mainly of SiO4 tetrahedra. This structure contains many bridging oxygen atoms, the vibrations of which cause high-intensity IR radiation.

At higher temperatures (say, 1500-2500 K), the tetrahedral network is destroyed. In this case, the radiation transitions that produce radiation in the IR region disappear and the intensity of thermal radiation of the melt decreases sharply.

With a subsequent increase in temperature, changes in the composition and structure of the melt occur. The role of electron transitions in atoms and ions increases and free electrons appear. Free electrons initiate free-free radiative transitions. All this leads to an increase in the intensity of radiation in the infrared region.

Apparently, the ball lightnings usually observed by eyewitnesses have temperature in the range of 1500-2500 K; ball lightnings with temperatures outside this range will quickly disintegrate.

It should be noted that the temperature range boundaries given here are very suppositive, they depend cardinally on the chemical composition of the melt. For pure silica, changes in structure and emissivity occur at higher temperatures, whereas the presence of alkali and alkaline earth metal oxides in the melt lowers these limits.

4.4. Effect of additives

The radiation characteristics of silicate glass melts that do not contain significant amounts of radiating impurities were considered above. However, the addition of the fourth period transition metal oxides Fe2O3, MnO, CoO, V2O3, etc., which are commonly found in soil, leads to the appearance of absorption bands in the visible and near infrared regions. In the glass and melt, these oxides decompose, forming ions Fe^{2+} and Fe^{3+}, Mn^{2+} and Mn^{3+}, Co^{2+}, $V4^{+}$, etc. The ions have a degenerate ground state and being free, do not have any radiative transitions in visible and infrared regions. In the network of silicate materials, the ions form a coordination complex with the surrounding anions. In the resulting non-uniform field, the degeneracy of the ground state is removed and new transitions between split energy levels arise, *Tilley 2020.*

Absorption coefficients associated with transition metal ions are given for limited temperature and concentration ranges in *Choudhary et al. 2005*, *Calas et al. 2021*.

We believe that using them to estimate the radiation fluxes of transition metal ions in silicate glass melts at high temperatures (>2000 K) would lead to an overestimation of these values. The reason for this is the following circumstances. Radiation of transition metal ions occurs only when they are in a coordination complex with cations. As noted above, the lifetime of large complexes is short, about 10 fs. In the near infrared range of 1-10 μm, the oscillation periods of electromagnetic waves are approximately 3-30 fs. As can be seen, the lifetime of radiating compounds can be less than the period of electromagnetic oscillations. In this case the radiating compound decays before the electromagnetic wave can be formed. Taking into account all these factors, it can be assumed that the IR radiation of transition metal ions in silicate glass melts at high temperatures is small, despite the significant presence of oxides of these metals in the soil (especially Fe2O3 and MnO). These bands will not be considered in our calculations. At the same time, the radiation of these ions in the visible region of the spectrum forms the color of the BL shell (Section 5).

Water and OH radical are the most common impurities in melts and glasses, Fig. 4.2 and 4.4*a*. When heated, water molecules are destroyed, but OH is a stable formation and apparently persists up to very high temperatures. The OH absorption bands are located approximately at 2700 cm^{-1} and are a strong source of radiation at temperatures above 1000 K. If the BL shell material contains an admixture OH, such ball lightning quickly cools and collapses. Perhaps this type of ball lightning was identified by eyewitnesses as short-lived.

4.5. Thermal radiation of ball lightning

Here we will estimate the radiation power of ball lightning depending on its size and temperature. As is accepted in Section 4.3.2, we will use the constant absorption coefficient $k \approx 0.2$ cm^{-1} (or 20 m^{-1}) throughout entire spectrum for the shell material of the BL. Another simplification is related to the small thickness of the ball lightning shell δ<100 μm. As can be seen, the product $k\delta$ <<1, and the optically thin layer approximation can be used to calculate the radiation processes. We also assume that under these conditions scattering by inhomogeneities of the foamy structure can be neglected. In this regard, we recall that the value δ used here represents the reduced thickness of the BL shell, that is, the thickness of the melt layer without gas bubbles. Finally, we will assume that ball lightning is filled with non-radiating gas (hot air) and therefore the shell is the main radiation source.

Using the optically thin layer approximation and assuming that the emitting and absorbing energy levels are in equilibrium with each other at temperature T_{BL}, the radiative power (W) from the BL shell can be written as (*Howell et al. 2017*; for more details see also Section 5.2.2)

$$Q_{rad} = 4n^2 k\sigma T_{BL}^4 V_{melt} \tag{4.1}$$

where k is absorption coefficient (m^{-1}) of the melt, σ=5.67 10^{-8} W/m^2 K^4 is the Stefan–Boltzmann constant and n=1.19 is refractive index of the foamy shell material. The radiating volume is the volume of the melt in the BL shell $V_{melt} \approx \delta S_{BL}$. Substituting this relation into Eq. (4.1) gives

$$Q_{rad} = q_{rad} S_{BL} \tag{4.2}$$

where q_{BL} is radiation power density, W/m^2.

$$q_{rad} = 4n^2 k\delta\sigma T_{BL}^4 \tag{4.3}$$

Note that within the framework of our approach, the q_{rad} value does not depend on the BL diameter but is a linear function of the product $k\delta$.

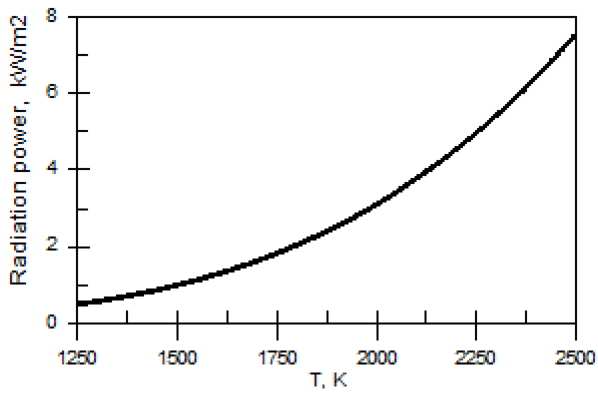


Fig. 4.6. Radiation power per unit area of the BL surface depending on temperature, shell thickness of δ = 30 μm and k=20 m^{-1}.

As an example, Fig. 4.6 shows the radiation power density from the BL surface depending on temperature. The values were obtained for the BL shell thickness of δ = 30 μm and the constant absorption coefficient k=20 m^{-1}.

Knowing the q_{rad} value, we can estimate the irradiance of objects surrounding the ball lightning. The irradiance G, W/m^2, is the radiation power received from the ball lightning upon a unit area of the surface of interest. If the surface element is at a distance L from the center of the ball lightning, Fig. 4.7, then the value G is

$$G(L) = q_{rad}\left(\frac{R_{BL}}{L}\right)^2. \quad (4.4)$$

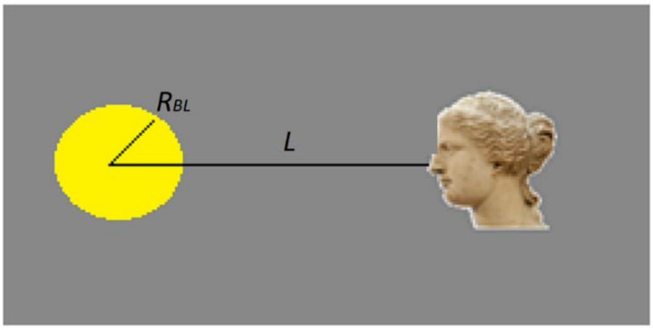


Fig. 4.7. A drawing showing the location of ball lightning and eyewitnesses; R_{BL} is the BL radius, and L is the distance from the center of the ball lightning to the eyewitness.

Now we can estimate heat sensation caused by the BL radiation. As an example, let's consider *Case 2* of Section 4.1. It follows from the eyewitness description that R_{BL}=0.05 m and L=0.5m. Taking the thickness of the BL shell to be δ= 30 μm, and its temperature to be 1750 K, from Fig. 4.6 we get q_{BL}≈2000 w/m^2, and G=20 w/m^2, respectively. This value is obtained for conditions when the melt does not contain any radiating impurities. If they are present, the irradiation will increase. For example, if the k = 100 m^{-1} then the irradiance will be five times greater, G=100 W/m^2.

To understand the degree of thermal impact on humans, we compare the irradiance of objects by ball lightning (G-value) with the solar irradiance of the Earth's surface in Athens, Greece (*Koudouris et al. 2017*). The irradiance of 20-100 W/m^2 exists for an hour after sunrise, when the angle of incidence of the sun's rays is close to 90°. We believe that in *Case 2*, eyewitness could only feel a very weak thermal impact from the ball lightning (see also Fig. 2.1.3 and its discussion in Section 2.1).

4.6. Summary

In silicate glasses and melts emission and absorption in the infrared are associated with collective vibrations of the network. The main elements that form the network are unit cells of SiO4 tetrahedra. The connection of the tetrahedra is achieved through bridging oxygen atoms common to adjacent tetrahedra. In this structure, Si-O-Si groups characteristic of silicates arise. Vibrations of the O atoms in these groups form the strongest fundamental spectral bands and a wide range of multiphonon transitions. In melts, these processes cause intense radiation at wavelengths $\lambda > 4$ μm. The network responsible for the radiation is formed and maintained if the temperature of the shell does not exceed ~1500 K.

At higher temperatures, the melt network is destroyed due to the rupture of the bonds between the unit cells. This result is a sharp decrease in the concentration of radiating atomic groups Si-O-Si. Another factor that influences the properties of these groups at high temperature is their short lifetime, about 10^{-13} s. Under these conditions the spectral bands associated with collective vibrations of the melt network are absent. This means that even at high temperatures, a wide spectral region of 0.5-25 μm has no radiation in the absence of emitting impurities. It can be expected that this situation will persist as ball lightning cools from its appearance at a temperature of 2500-3000 K to approximately 1500 K. This explains the low thermal radiation of ball lightning and the long duration of its existence because of low energy losses due to radiation.

Weak thermal radiation of thin layers of molten glass is known. When producing thin-walled glass products, workers often do not use special heat-protective clothing.

References

Calas, G., Galoisy, L., & Cormier, L. (2021). The color of glass. *Encyclopedia of Glass Science, Technology, History, and Culture*, *1*, 677-691.

Caracas, R., Kobsch, A., Solomatova, N. V., Li, Z., Soubiran, F., & Hernandez, J. A. (2021). Analyzing melts and fluids from ab initio molecular dynamics simulations with the UMD package. *arXiv preprint arXiv:2109.02916*.

Choudhary, M. K., & Potter, R. M. (2005). Heat transfer in glass-forming melts. *Properties of glass-forming melts*, Chapt. 9.

Coenen, M. (1968). Durchstrahlung des Glasbades bei Farbgläsern. *Glastechn. Ber, 41(1), 1-10.*

de Koker, N. P., Stixrude, L., & Karki, B. B. (2008). Thermodynamics, structure, dynamics, and freezing of Mg2SiO4 liquid at high pressure. *Geochimica et Cosmochimica Acta*, *72*(5), 1427-1441.

Ellerbrock, R., Stein, M., & Schaller, J. (2022). Comparing amorphous silica, short-range-ordered silicates and silicic acid species by FTIR. *Scientific Reports*, *12*(1), 11708.

Faber, A. J. (2002). Optical properties and redox state of silicate glass melts. *Comptes Rendus Chimie*, 5(11), 705-712.

Griscom, D. L. (1991). Optical properties and structure of defects in silica glass. *Journal of the Ceramic Society of Japan*, *99*(1154), 923-942.

Henderson, G. S. (2005). The structure of silicate melts: a glass perspective. *The Canadian Mineralogist,* 43(6), 1921-1958.

Howell, J. R., Mengüç, M. P., Daun, K., & Siegel, R. (2017). *Thermal radiation heat transfer.* CRC press.

Kao, K. C., & Hockham, G. A. (1966, July). Dielectric-fibre surface waveguides for optical frequencies. In *Proceedings of the Institution of Electrical Engineers* (Vol. 113, No. 7, pp. 1151-1158). IEE.

Koudouris, G., Dimitriadis, P., Iliopoulou, T., Mamassis, N., & Koutsoyiannis, D. (2017). Investigation on the stochastic nature of the solar radiation process. *Energy Procedia*, 125, 398-404.

Liu, H., Kaya, H., Lin, Y. T., Ogrinc, A., & Kim, S. H. (2022). Vibrational spectroscopy analysis of silica and silicate glass networks. *Journal of the American Ceramic Society*, *105*(4), 2355-2384.

Mysen, B. (2021). Structure of aluminosilicate melts. *ISIJ international*, *61*(12), 2866-2881.

Mysen, B., & Richet, P. (2018). Silicate glasses and melts. *Elsevier*.

Rozenbaum, O., Meneses, D. D. S., Auger, Y., Chermanne, S., & Echegut, P. (1999). A spectroscopic method to measure the spectral emissivity of semi-transparent materials up to high temperature. *Review of scientific instruments*, *70*(10), 4020-4025.

Shelby, J. E. (2020). *Introduction to glass science and technology*. Royal society of chemistry.

Shearer, A., Hauke, B., Montazerian, M., & Mauro, J. C. (2023). A critical review of infrared transparent oxide glasses. *Optical Materials: X*, *20*, 100258.

Solomatova, N. V., & Caracas, R. (2019). Pressure-induced coordination changes in a pyrolitic silicate melt from ab initio molecular dynamics simulations. *Journal of Geophysical Research: Solid Earth*, *124*(11), 11232-11250..

Sova, R. M., Linevsky, M. J., Thomas, M. E., & Mark, F. F. (1992). High-temperature optical properties of oxide ceramics. *Johns Hopkins APL Technical Digest;(United States)*, *13*(3).

Stakhanov, I. P., (1985). *The physical nature of ball lightning*. Стаханов И. П, *О физической природе шаровой молнии*. М. Энергоатомиздат

Tilley, R. J. (2020). *Colour and the optical properties of materials*. John Wiley & Sons.

Tropf, W. J., Thomas, M. E., & Harris, T. J. (1995). *Properties of crystals and glasses*. Chap. 33 in Handbook of optics. New York: McGraw-Hill.

Beer bottles. Glass colors in transmitted light, from left to right: brown, yellow-green, green, blue.

Iron oxide can be added to glass, resulting in a bluish-green glass often used in beer bottles. When combined with chromium, it produces a richer green used for wine bottles. Manganese gives glass an amethyst color. It is one of the oldest glass additives, and purple manganese glass has been used since early Egyptian history. Adding titanium produces yellowish-brown glass. Titanium, rarely used on its own, is more often employed to intensify and brighten other colorizing additives. (Wikipedia).

5. Photometric and chromatic characteristics of ball lightning

To understand the phenomenon of ball lightning, scientists rely on eyewitness reports describing the appearance and behavior of these glowing balls. Color and brightness are almost always present in the reports. The statistical analysis of these data has shown that the ball lightning may have any color. However, the probabilities of emerging different colors are different (*Smirnov 1992, Bychkov 2012, Piccoli et al. 2014, Grigor'ev et al. 2019*). The most common colors are red, orange, or yellow, and their brightness does not blind the eyes. White is also found and has greater brightness. Blue and violet colors are observed much less often, and green is extremely rare. Here, we will try to explain the nature of the color of ball lightning by considering ball lightning as a thin-walled bubble of molten glass filled with hot gas, assuming that this gas is transparent in the visible spectrum.

Now we give examples of eyewitness reports about ball lightnings. Only fragments are presented, the full text can be found at the links.

Case 1. From Wikipedia Talk: Ball lightning/Archive1. Event in Zilina, Slovakia, 1984. The eyewitness: Eltwarg, scientist,10 August 2007.
https://en.wikipedia.org/wiki/Talk:Ball_lightning/Archive_1

> About 15 children with the teacher were on the field. There was a storm before, and it was also raining just a few minutes before. Some child noticed the ball about 5m above the field and pointed at it. It was moving relatively slowly from above near the group and slowed down, almost stopped about 2m above the field. The movement was unstable, however. The ball was a sphere with about 15-20 cm of diameter and looked as 'made from fire' (I mean classical campfire) … The ball lightning disappeared without a sound. The observation time was about 5 s.

Case 2. Keul AG, „Der Kugelblitz – ein interdisziplinärer Zankapfel“. Referat vor der Österreichischen Gesellschaft für Parapsychologie und Grenzgebiete der Wissenschaft, 18. März 2013.
http://www.parapsychologie.ac.at/programm/ss2013/keul/keul.pdf

> In mid-July 2011, the eyewitness was standing in front of her house in Alland in the Vienna Woods next to her car when she heard a loud bang and a full-moon-sized, round, yellowish object flew west over her. It disappeared in about two seconds. The object had blurred contours; its brightness was not blinding. It flew along a curved trajectory and made a hissing noise. Her daughter also saw it from the window. A neighbor found later in his garden a singed spot where the ordinary lightning apparently struck.

We pay attention to the BL color: “looked as 'made from fire' (I mean classical campfire)” and “round, yellowish object, its brightness was not blinding.”

5.1. General information about human vision

5.1.1. Introduction

Color is the subjective perception of light by a person. There are two sides in this process: a light source and the human vision system. In our case, the source is a ball lightning, this subject will be discussed below. The human visual system is widely discussed in literature. Here we will look at some aspects of this problem, which are needed to understand the subsequent discussion; the necessary information was taken from *Gevers et al. 2012*, *Cao 2012*, *Rogers 2011*, *Tilley 2020*.

The term "light" denotes the electromagnetic radiation in the wavelength range of 350–750 nanometers (nm), this spectral region is perceived by the human eye. The term "visible light" is also used, and it is fully equivalent to the term "light". Definitions, charts, and quantities recommended to use by the International Commission on Illumination—also known as CIE (the abbreviation of "Commission Internationale de l´Eclairage")—will be referred to as CIE documents.

The human vision system receives light, processes it, and forms the image. Eyes are the outer part of this system. The eye optics directs the light to photoreceptor cells located in the retina. The cells respond to light and produce electrical pulses that are transported to neurons. There are two classes of the cells: cones and rods. Retina of the human eye contains about 7 million cones and from 75 to 150 million rods. In the central region of the retina, only cones are located. With distance from the center, the concentration of cones decreases, and the concentration of rods increases, and the efficiency of light perception also changes. The same object will be projected differently on the retina depending on the distance to this object (or on the vision angle). This means that the perception of the color and brightness of an object depends on the vision angle. To take this into account, all the main photometric and chromatic quantities are given for a standard observer with visual angles of 2 and 10 degrees. In this paper, we will use only the data for 2 degrees.

5.1.2. Brightness perception by human eye

The reaction of the human eye depends largely on the intensity of the perceived light. In this regard, three intervals of brightness are distinguished, in which the perception of color is carried out by different processes.

Photopic vision. In bright light (luminance level from 10 to 10^9 cd/m^2), rods are in saturation and do not generate signals, while the cones are active. At this level of illumination, a person with normal vision can distinguish many shades of color. These conditions are realized in daylight or in good artificial light.

Scotopic vision. In very low light (luminance level from 10^{-6} to 10^{-2} cd/m^2), visual perception is mediated by rods. Rods are extremely sensitive to light but the threshold for light detection depends on the time spent in the dark (dark adaptation). In extremely low illumination there is no actual color vision, image is formed by graded variation of light and dark areas. However, there is some color perception near the upper limit of luminance.

Mesopic vision. Between the photopic and scotopic vision there is an intermediate interval (luminance level from 10^{-2} to 10 cd/m^2) where cones and rods are simultaneously involved in the process of color perception. In this case, the color appearance is different from the photopic conditions. Rods enhance the brightness and contrast of the image and improve color discrimination at long-wavelengths. The mesopic light level corresponds to the illumination in the moonlight, twilight, and most night-time street lighting.

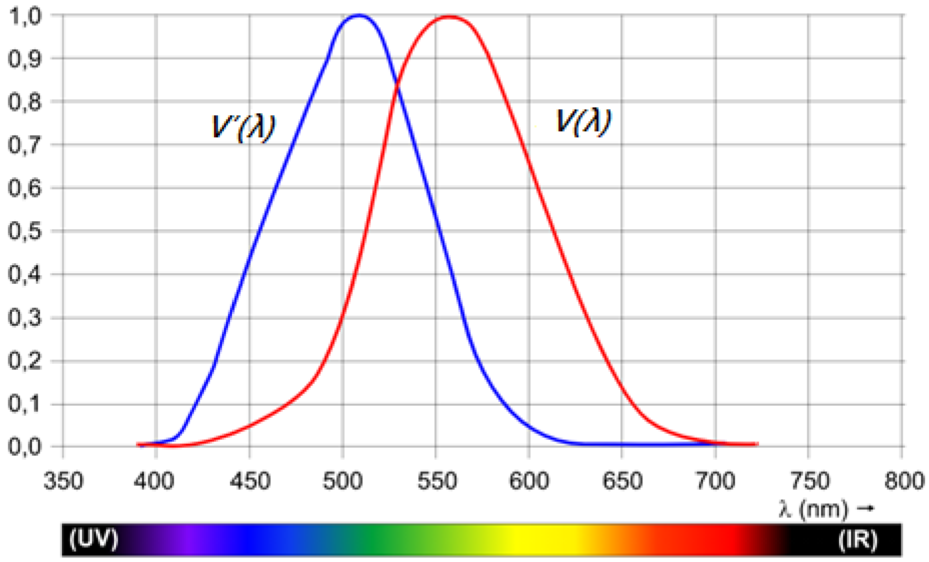


Fig. 5.1.1. The relative luminous efficiency functions of the human eye, *V'(λ)* - scotopic (night) vision, *V(λ)* - photopic (day) vision. The peaks of these functions are at 507 and 555 nm, respectively.

In vision and photometry science, a quantity of the spectral luminous efficiency is used. This quantity determines the fraction of radiation energy of a wavelength *λ*, which is perceived by the eye as light. The normalized functions of the spectral luminous efficiency for photopic *V(λ)* and scotopic *V'(λ)* vision are presented in Fig. 5.1.1. These functions are used to calculate the luminous flux, luminous emittance, luminance, and other photometry quantities if the corresponding spectral radiative characteristics of light source are known.

The luminosity of ball lightning, according to the description of eyewitnesses, is large enough to be considered as a photopic light source. Therefore, when calculating the BL brightness, we will use only the photopic function *V(λ)*.

The luminous emittance M_V, lm/m^2 of a light source with the known spectral emissive power *E(λ)* is

$$M_V = C \int V(\lambda)E(\lambda)d\lambda \tag{5.1.1}$$

where *E(λ)* has units of W/nm m^2, and *C*=683 lm/W. The numeric values of the function *V(λ)* are available at *CVRL Database*. Using some assumptions regarding the light source characteristics, we can derive other photometric quantities. For diffusely emitting surface, photometric brightness (luminance), cd/m^2, is

$$L_V = \frac{M_V}{\pi} \tag{5.1.2}$$

5.1.3. Color perception by human eye

As mentioned above, the most complete representation of color can be obtained under photopic luminance level when only the cones are active. Numerous studies have shown that there are three types of cone cells that are active at long-, middle-, and short-wavelengths (L, M, and S, respectively). This is the basis of trichromatic color model. When light with a spectral power distribution *E*(*λ*) enters the eye, it activates the cones. The number of activated cones, say L-cones, depends on the spectral distribution *E*(*λ*) and spectral sensitivity of the L-cones. This number is the only result of the interaction of light with the L-cones that is transmitted to the brain; information about the wavelengths is lost. The same light source *E*(*λ*) causes the responses of the M- and L-cones in the form of two other numbers. Thus, the color of a light is determined by a unique combination of three numbers corresponding to the responses of three types of cones.

The basis of the color image is the XYZ color space, where three numbers represent the response of a standard observer to a light source E(λ).

$$X = \int E(\lambda)\,\bar{x}(\lambda)d\lambda,\;\; Y = \int E(\lambda)\,\bar{y}(\lambda)d\lambda,\;\; Z = \int E(\lambda)\,\bar{z}(\lambda)d\lambda \qquad (5.1.3)$$

where $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ are the CIE color matching functions, Fig. 5,1.2.

Each combination of the (X,Y,Z) numbers carries information not only about color, but also about color luminance.

However, for our purposes it is more convenient to use the xyY color space where the color (chromaticity coordinates xy) is cleanly separated from the relative luminance Y (*Kerr 2010*). The chromaticity coordinates are defined through the XYZ numbers this way:

$$x = \frac{X}{X+Y+Z} \qquad y = \frac{Y}{X+Y+Z} \qquad (5.1.4)$$

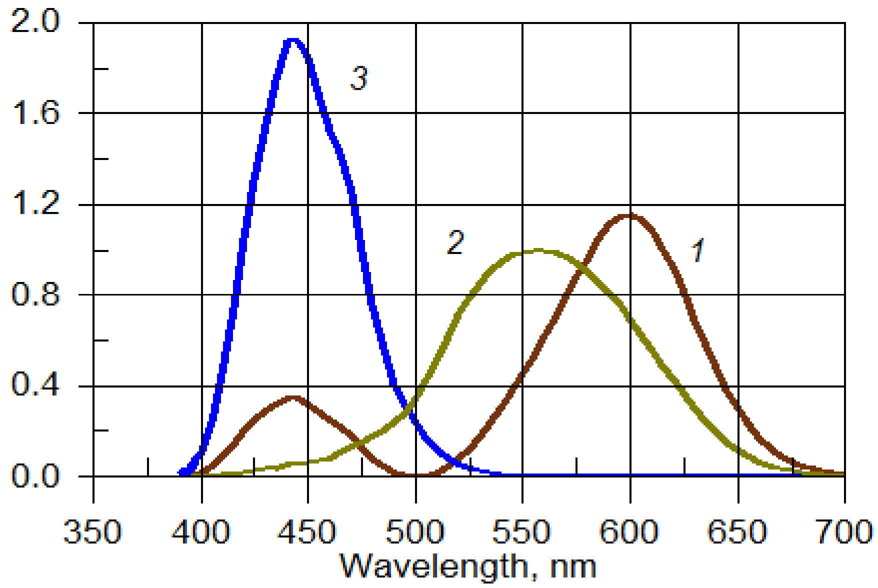


Fig. 5.1.2. Color matching functions from CIE 2006 for 2-deg standard observer (*CVRL Database*), $1-\bar{x}, 2-\bar{y}, 3-\bar{z}$.

Since the pair of numbers x and y define the chromaticity of a color, we can create a chart with x and y axes, where each point indicates a chromaticity. This CIE x-y chromaticity diagram is shown in Fig. 5.1.3. The absolute values of luminance L_V in units of cd/m^2 will be calculated using the method described in the previous section, Eqs (5.1.1 and 5.1.2).

As follows from Eqs (5.1.3 and 5.1.4), the spectral power distribution *E*(*λ)* uniquely determines a color (chromaticity coordinates (*x,y*)). However, the inverse problem does not have a univocal solution. If the coordinates (*x,y*) are known, we cannot confidently identify the distribution $E(\lambda)$ that gave rise to this color. Identical colors formed by sources with different spectral distributions are called metamers.

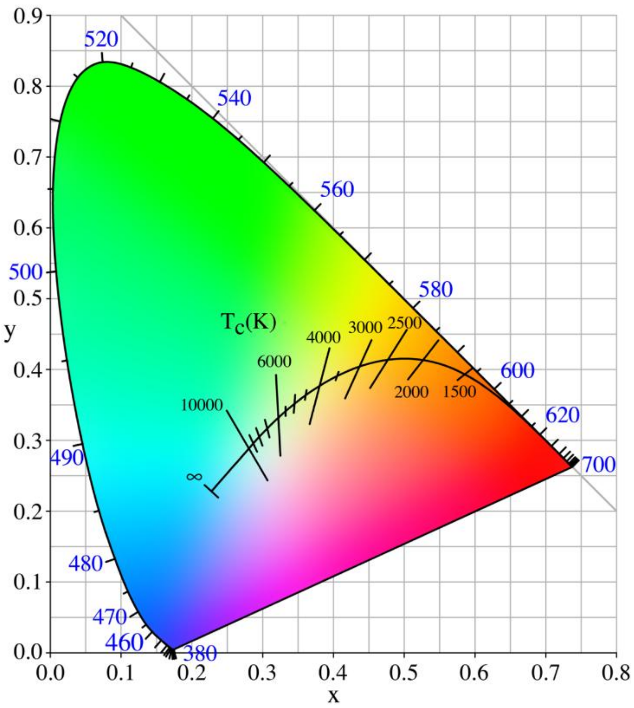


Image by *en:User:PA*, via Wikimedia Commons.

Fig. 5.1.3. CIE 1931 chromaticity diagram including the Planckian locus. The Planckian locus indicates the color of blackbody radiation as a function of temperature in K. Monochromatic wavelengths are shown in blue in units of nanometers.

Example

We will determine the photometric and chromatic characteristics of a blackbody radiator at the temperature of freezing platinum melt, T_{fr} =2041.4 K. The system was used in the middle of the last century as a standard of the luminance,
Page et al, 1974.

> The candela is the luminous intensity, in the perpendicular direction, of a surface of 1 / 600 000 square metre of a blackbody at the temperature of freezing platinum under a pressure of 101 325 newtons per square metre.

In other words, the luminance of blackbody at 2041.4 K is 6.0E+05 cd/m^2.

The spectral emissive power of blackbody radiation in air (vacuum) is

$$B_\lambda(T) = \frac{C_1}{\lambda^5[\exp(C_2/\lambda T)-1]} \quad (5.1.5)$$

where C_1= 3.742E+08 W μm^4/m^2 and C_2=1.439E+04 μm K. The total emissive power of blackbody is

$$B_{tot}(T) = \sigma T^4 \quad (5.1.6)$$

where σ=5.67E-08 W/m^2 K^4 is the Stefan–Boltzmann constant.

We'll start by calculating the spectral distribution of visible light power $\xi(\lambda)$ in units of "light-watt"/nm m^2.

$$\xi(\lambda) = V(\lambda)B_\lambda(T_s) \quad (5.1.7)$$

The photopic relative luminous efficiency function $V(\lambda)$ for 2-deg standard observer was taken from *CVRL Database*. The function $\xi(\lambda)$ in and the spectral emissive power of the blackbody $B_\lambda(T_{fr})$ are shown in Fig. 5.1.4.

The total power of perceived light is determined by the integral

$$F = \int \xi(\lambda)d\lambda \quad (5.1.8)$$

The ratio $\psi = F/B_{tot}(T_s)$ is the fraction of the emitted energy, which is perceived by the eye as visible light. For the conditions under consideration, F= 2.90E+03 W/m^2, $B_{tot}(T_{fr})$=9.85E+05 W/m^2, and hence ψ=2.94E-03. This value is small, but it increases rapidly with temperature; peaks at ~ 6000 K and then decreases.

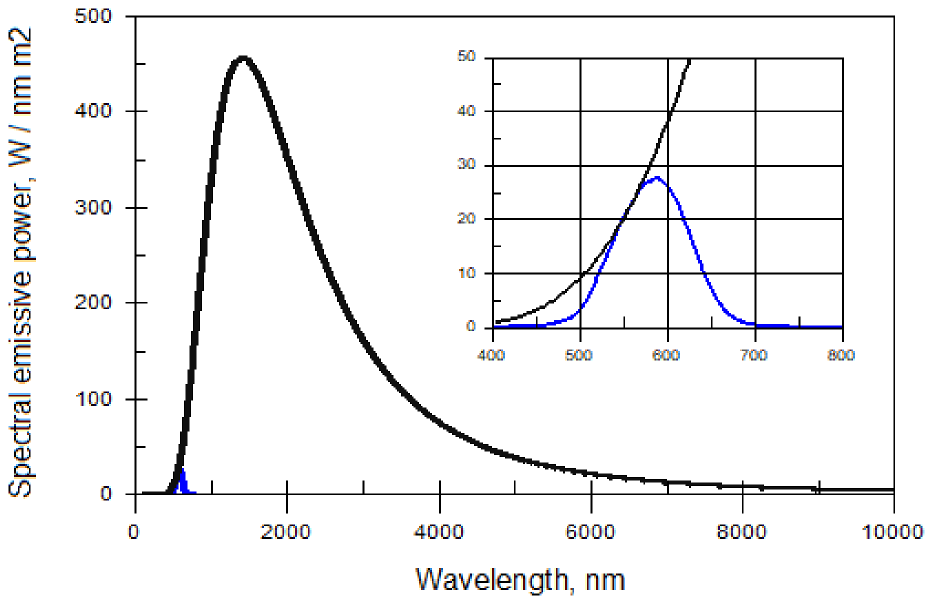


Fig. 5.1.4. Spectral emissive power of blackbody $B_\lambda(T)$ at 2041.4 K (black line) and corresponding spectral light power that can be perceived by eye, $\xi(\lambda)$ (blue line).

In Eqs (5.1.7 and 5.1.8), the light quantities have the energy units. To convert these values to the usual units employed in photometry, viz. the lumen, they must be multiplied by the factor C=683 lm/W, Eq. (5.1.1). The luminous flux emitted from a unit of surface (luminous emittance) is $M_V=C \cdot F$=1.98E+06 lm/m^2. Since the blackbody emits diffusely, the calculation of the luminance according to Eq. (5.1.2) gives $L_V = M_V/\pi$=6.3E+05 cd/m^2. We see that the reference value of luminance 6.0E+05 cd/m^2 is slightly less than the value 6.3E+05 cd/m^2 obtained here. This discrepancy is due to the use of different photopic functions *V(λ)*: the CIE 1931 standard data and the data from CVRL Database.

The procedure for calculating chromatic characteristics is described in Section 5.1.3. The integration in Eq. (5.1.3) was carried out using the distribution of spectral blackbody emissive power $B_\lambda(T_{fr})$ and the color matching functions from Fig. 5.1.2. The obtained XYZ values are substituted into Eq. (1.4), and we get the chromaticity coordinates x=0.527 and y=0.415. The corresponding color can be found in the chromaticity diagram in Fig. 5.1.3; it is

Table 5.1.1 shows the luminance of some light sources; it will be useful to compare these data with those obtained below for ball lightnings.

Table 5.1.1. Luminance of some light sources.

Source	cd/m^2	Source	cd/m^2
cloudy night sky	10^{-6}-10^{-4}	sun disk at noon	1.6 10^9
starry night sky	10^{-3}	blackbody at 2041.4 K	6.3 10^5
night sky with a full moon	0.1	LCD display, black	0.15-0.80
full moon disk*	2000	LCD display, white	150-500
medium overcast sky	2000	LED outdoor videowall	5000-7500
medium clear sky	8000	T8 fluorescent tube, white	11000

Data from Leuchtdichte, Wikipedia.
* Moon luminance at Earth's surface, *Yeraliyev et al. 2014*.

5.1.4. Discussion

The methods discussed above for calculating the luminance and color of a light (both emitted and reflected) are based on the CIE recommendations obtained experimentally in the study of human perception. The relative luminous efficiency functions, Fig. 5.1.1, and color matching functions, Fig. 5.1.2, were obtained under conditions when the environment is neutral and do not affect perception. In this case, the luminance and chromaticity are unambiguous functions of the spectral emissive power $E(\lambda)$. However, in everyday life, the process of perception is much more complex. Color appearance depends not only on the chromatic properties of the object of interest but also on the spatial, temporal, and spectral characteristics of the neighboring objects. For instance, the color appearance may both shift toward the nearby color (chromatic assimilation) and move away from it (chromatic contrast). Moreover, all other things being equal, different spectra can form identical color impressions (metamerism). A person's assessment of the brightness of an object also depends on the environment. The greater the contrast between the object and the background, the brighter (or darker) the object appears. In addition, the perception of light parameters depends on the psychological state of a person. An emotional evaluation of the situation caused by fear or unexpected action may also affect the perception. Therefore, information obtained from eyewitness descriptions of ball lightning should be considered only as very approximate.

5.2. Color and brightness of ball lightning

5.2.1. General description and assumptions

In this section, we explain the diversity of BL colors within our model using the above methods for calculating the color characteristics of emitting objects. As before, we consider ball lightning as a thin-walled bubble, the shell of which is formed from foamed molten glass. We assume that the gas filling the ball lightning is transparent to light (hot air, water vapor, or a mixture of them). In addition, we assume that the gas of the micron-sized bubbles in the foamed melt does not affect radiation processes. Then the only source of visible radiation is the melt forming the BL shell. For this reason, in calculations we will use a reduced thickness of the BL shell δ, which is related to the actual thickness δ_{shell} as $\delta = \varphi\delta_{shell}$ where φ is volume fraction of the glass melt, Section 2.2.3.

The optical properties of the BL shell material over a wide range of wavelengths are discussed in Section 4. Here we focus on the optical properties in the visible region, $350 < \lambda < 750$ nm. Obviously, detailed data about the spectra of shell material are unknown. However, based on the available information on melts and glasses, the following can be assumed.

- In the absence of impurity, glass melt has a weak absorption with a constant absorption coefficient $k \approx 0.2$ cm^{-1} (Section 4.2.2, Fig, 4.4).
- The variety of BL colors is due to the presence of small concentrations of fourth period metal ions in the melt; the absorption coefficient k_λ will depend on the radiation wavelength.

To the simplifications outlined above, we will add the following.

- The thickness of the film forming the BL shell is much less than the BL diameter, $\delta_{shell} << D_{BL}$.
- The absorption coefficient in the visible region satisfies the condition $k_\lambda \delta <<1$, that is, we can use the approximation of optically thin medium.
- The emitting and absorbing energy levels are in equilibrium with each other at the temperature T_{BL}.

The last assumption allows us to write the spectral emissive power per unit volume (W/ μm m^3) as

$$u_\lambda = 4k_\lambda \bar{B}_\lambda(T_{BL}) \qquad (5.2.1)$$

Here, $\overline{B_\lambda}(T_{BL})$ is the spectral emissive power of blackbody (W/μm m^2) inside the BL shell material.

As noted, the BL shell material is foamed molten glass. In this medium, in addition to the emission and absorption of light, the scattering also occurs. However, since the BL shell is thin, the number of scattering events is small, and the emitted light leaves the volume of the BL shell without a perceptible change in the spectral distribution. Thus, we will not consider light scattering on the inhomogeneities of the shell material.

5.2.2. Photometric and chromatic characteristics, optically thin medium.

Now, using the assumptions and simplifications proposed above, we can begin to calculate the photometric and chromatic characteristics of ball lightning, Eqs (5.1.1, 5.1.3 and 5.1.4).

Assuming that the radiation from the BL shell is freely escaping (approximation of optically thin medium) and using Eq. (5.2.1), we can write the spectral emission power from the entire BL shell Q_λ, W/nm.

$$Q_\lambda = 4n^2 k_\lambda B_\lambda(T_{BL}) V_{melt} \quad (5.2.2)$$

where $B_\lambda(T_{BL})$ is the spectral emissive power of blackbody radiation in vacuum, V_{melt} is the total glass melt volume, and n is the refractive index of the shell material.

When electromagnetic wave propagates in a condensed medium, where the refractive index n>1, its speed and wavelength decrease by n times compared to vacuum. This fact must be considered if we want to express the radiation parameters of the condensed medium through the Planck function for a vacuum. The consequence of this is the appearance of factor n^2 in Eq. (5.2.2), *Howell et al. 2016*.

Since the BL shell material is a two-phase medium, then effective parameters are introduced. The common approach is to use the known properties of the mixture components to form a joint property. In our case, to determine the effective refractive index, we use the simplest formula (zero-order approximation)

$$n = \varphi n_{melt} + (1-\varphi) n_{gas} \quad (5.2.3)$$

where φ is the melt volume fraction, n_{melt}=1.53 is the refractive index of the melt, and n_{gas}=1 is the refractive index of the gas filling the foam bubbles. We believe that for the longest-lived ball lightnings, the fraction of melt in the shell material is above the critical value φ_c=0.36 (Section 2.2.3). Substituting this value into Eq. (5.2.3) gives n=1.19; the value will be used further in the work.

Since we assume that the gas inside the ball lightning is transparent, then all the light emitted by the shell exits only through the outer surface of the ball lightning S_{BL}, and then the surface spectral emissive power is

$$E_{BL}(\lambda) = \frac{Q_\lambda}{S_{BL}} \quad (5.2.4)$$

Considering that $\delta \ll D_{BL}$, the volume of melt in the BL shell is

$$V_{melt} = \delta S_{BL} \quad (5.2.5)$$

Using Eqs (5.2.3 and 5.2.5) we can rewrite Eq. (5.2.4) in the form

$$E_{BL}(\lambda) = 4n^2 k_\lambda \delta B_\lambda(T_{BL}) \quad (5.2.6)$$

Substituting the function $E_{BL}(\lambda)$ in Eq (5.1.1) gives the BL luminous emittance M_{VBL}, lm/m^2.

$$M_{VBL} = 4Cn^2 \int k_\lambda \delta V(\lambda) B_\lambda(T_{BL}) d\lambda \qquad (5.2.7)$$

where C=683 lm/W. In the optically thin layer approximation, we take that the luminance does not depend on the direction and then

$$L_{VBL} = \frac{M_{VBL}}{2\pi} \qquad (5.2.8)$$

The function (5.2.6) of the surface spectral emissive power $E_{BL}(\lambda)$ is used to calculate the tristimulus quantities XYZ, Eq. (5.1.3). The obtained values M_{BL} and XYZ will allow us to find the luminance and the chromaticity of ball lightning, Eqs (5.1.2 and 5.1.4).

The condition of applicability of the optically thin layer approximation for the problem under consideration is $k_\lambda \delta << 1$. There may be spectral intervale where this condition is not met, usually near absorption coefficient peaks. In these intervals, we will use $k_\lambda \delta = 1$. This means that here the medium radiates as a black body.

5.2.3. Approximation of constant absorption coefficient - orange red ball lightning

We will start the consideration from a simplest case - a constant absorption coefficient k of the BL shell material. We believe that the value k and the thickness of the BL shell δ are known. Then the expression for spectral emissive power of the BL surface (Eq. 5.2.6) can be written as

$$E_{BL}(\lambda) = \alpha B_\lambda(T_{BL}) \qquad (5.2.9)$$

where the constant α (It does not depend on the wavelength of the radiation) is

$$\alpha = 4n^2 k\delta. \qquad (5.2.10)$$

The Eq. (5.2.7) for the BL luminous emittance will take the form

$$M_{BL} = \alpha M_{Vb} \qquad (5.2.11)$$

where M_{Vb} is luminous emittance of blackbody at the temperature T_{BL}

$$M_{Vb} = C \int V(\lambda) B_\lambda(T_{BL}) d\lambda \qquad (5.2.12)$$

Recall that the constant C=683 lm/W, Eq. (5.1.1). The luminance L_{BL} will be calculated using Eq. (5.2.8). Since $\alpha \ll 1$, the BL luminance is much less than the luminance of black body at the temperature T_{BL}.

The luminous flux Φ_{BL} emitted from the BL surface S_{BL} is

$$\Phi_{BL} = M_{BL} S_{BL} \tag{5.2.13}$$

The tristimulus values *XYZ* that define the BL chromaticity are computed by Eq. (5,1.3) using the spectral emissive power of the BL surface, Eq. (5.2.8)

$$X = \alpha X_b,\ \ Y = \alpha Y_b,\ \ Z = \alpha Z_b \tag{5.2.14}$$

where X_b, Y_b and Z_b are tristimulus values for a blackbody radiation at T_{BL}

$$X_b = \int E_b(\lambda, T_{BL})\, \bar{x}(\lambda) d\lambda,\ \ Y_b = \int E_b(\lambda, T_{BL})\, \bar{y}(\lambda) d\lambda,\ \ Z_b = \int E_b(\lambda, T_{BL})\, \bar{z}(\lambda) d\lambda.$$

And finally, chromaticity coordinates of the BL surface, Eq. (5.1.4), are

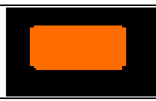
$$x = \frac{X_b}{X_b + Y_b + Z_b},\ \ \ y = \frac{Y_b}{X_b + Y_b + Z_b} \tag{5.2.15}$$

As follows from the equations (5.2.14) and (5.2.15), within the framework of the BL model based on the optically thin shell and constant absorption coefficient, the BL chromaticity is just a blackbody chromaticity at the temperature T_{BL}. In other words, the BL color temperature is the BL thermodynamic temperature.

Example.

Here we will obtain the light characteristics of ball lightning, the shell of which has a thickness δ=30 μm, and the absorption coefficient of the shell material is k=0.2 cm^{-1}, (Section 4, Fig. 4.4*a*). Accordingly, the parameter α=3.4E-03. The results for luminance L_{BL}, luminous flux Φ_{BL}, and chromaticity for different BL temperatures are presented in Table 5.2.1. The change in the color of the melt with temperature during a making a glass product is shown in Fig. 5.2.1; there is a general agreement in chromaticity with the calculating results from Table 5.2.1. However, the brightness of the ball lightning and the product may differ due to different thicknesses of the melt layers.

Table 5.2.1. Luminance L_{BL}, luminous flux Φ_{BL}, and chromaticity of ball lightning. (D_{BL} = 0.2 m, δ=30 μm, k=0.2 cm^{-1}).

T_{BL}, K	2500	2000	1500
L_{VBL}, cd/m^2	1.0E+04	8.3E+02	1.4E+01
Φ_{BL}, lm	8.0E+03	6.6E+02	1.1E+01
Chromaticity			

This is an image of African people at work from Eswatini by *HHahn glass*, via Wikimedia Commons, CC BY 4.0.

Fig. 5.2.1. Here we see color of glass melt. With decreasing temperature, the color changes from bright orange to dark red.

Based on the above considerations, one can predict how a ball lightning with the parameters given in Table 5.2.1 will be perceived by eyewitness.

T_{BL}=2500 K, L_{BL}=10000 cd/m^2. Ball lightning is bright orange and can cause blinding effects in the dark. Observation of such ball lightning is a rare event. The temperature of around 2500 K persists only for a short time after the BL formation and then drops rapidly due to cooling.

T_{BL}=2000 K, L_{BL}=830 cd/m^2. Ball lightning is perceived as an orange object. This type of ball lightning is most often observed. Here is an excerpt from an eyewitness report that gives an idea of this (From *BL Reports*, the eyewitness was Jerry Greenberg, the report was posted on July 16, 1997).

> In about 1986 I did see what I believed was ball lightning. This was up in the Laurentian Mountains north of Montreal. It appeared as a reddish orange ball

> floating around in a parking lot. It seemed to be about 2 feet or so in diameter and was about 20 feet above the ground. After a minute or so, it disappeared. It seemed to travel in a sort of slow erratic way…

T_{BL}=1500 K, L_{BL}=14 cd/m^2. In the dark, this ball lightning is perceived as a clearly visible, faintly luminous red object. During the day, it is translucent or visible in reflected light. We believe that the following description corresponds to this type of ball lightning (excerpt from *Case 3* in Section 3).

> As I arrived at the doorway to the kitchen, I looked above my sister's head to see a ball that glowed but had no color. It was about 9 inches in diameter. It had sort of a transparency to it, I think.

It should be noted that the subjective perception of brightness by a person is not a linear function of the luminance of glowing object (more detailed information can be found in the example on page 103).

5.2.4. Wavelength-varying absorption coefficient – ball lightning of different colors

Above we have considered the light characteristics of ball lightning, the shell of which is formed from a silicate glass melt that does not contain a significant amount of radiating impurities. This melt has a constant absorption coefficient in the visible region. However, the presence of the fourth period transition metal ions has a great effect on the visible spectrum of the melt. Even small amounts (less than 1 wt.%) of Fe2O3, V2O3, MnO, CoO, etc. lead to the appearance of absorption bands in the visible region. A detailed description of these effects can be found in other sources; here we will give only a brief explanation.

During melting the sandy soil in electrical discharge (2500-3000 K), numerous chemical reactions occur. If the oxides of transition metals are present in the soil, they also participate in the reactions. The result of the reactions (mainly redox) is the formation of transition metal ions Fe^{2+} and Fe^{3+}, Mn^{2+} and Mn^{3+}, Co^{2+}, V^{4+} etc. These ions have a degenerate ground state and being free, do not have any radiative transitions in the visible region. However, in the glass or melt, the metal ions build a coordination complex with surrounding anions (ligands). In the nonuniform field of the ligands, the degeneracy of the ground state is removed, and new transitions between the splintered energy levels arise. The absorption bands appear partially in the visible region, and they determine the visible radiation of the melt and the color of cold glass (*Capobianco et al. 2019*).

Although the theoretical basis for the optical properties of melts is known, calculating their quantitative values is a complex task. Firstly, there are difficulties in correctly determining the chemical composition and structure of the melt. During commercial glass production and in experiments, the process of forming homogeneous and chemical equilibrium samples can last up to several hours. Since the lifetime of ball lightning is about 10 seconds, the equilibrium is unlikely to be established in the glass melt forming the BL shell. Moreover, the network that forms the internal structure of the melt is destroyed, Section 4.2. The consequence of this is a very short lifetime (about 10 fs) of the coordination complex including transition metal ions. Under these conditions, establishing a relationship between the concentration of transition metal oxides in the melt and the absorption coefficient of the melt in the visible region of the spectrum is difficult. In view of this uncertainty, we will give estimates of the BL photometric and chromatic characteristics based on very general considerations, the results obtained are purely illustrative. Here, as before, we will use the optically thin layer approximation, Section 5.2.2.

Iron oxide Fe2O3, which is a common component of sands, decomposes in the melt to form the Fe^{3+} and Fe^{2+} ions. The spectral absorption coefficient of the melt is shown schematically in Fig. 5.2.2 (according to *Choudhary et ai. 2005* and *Calas et al. 2020*, oxide content of about 2 wt%). Because of lack of complete high-temperature data, we will not consider the temperature dependence of the absorption coefficient. The calculation method is described in Section 5.2.2. Calculated values of the luminance and chromaticity of ball lightning are shown in Table 5.2.2. As seen, the iron oxide dyes ball lightning in various shades of purple. This is due to a significant contribution of the short-wavelength part of the spectrum at 350-450 nm.

Case 3. An example from *Stakhanov 1985*, p. 93, Case 46 (fragment). Eyewitness L.A. Khromova, a teacher, was in April 1943 in Kirovsk.

> On the day she saw the ball lightning, the sky was overcast. The window and door were open. After a strong clap of thunder, she saw a dark purple ball the

size of a soccer ball floating across the room from the door. It seemed transparent. Moving towards the window, the ball flew up to the loudspeaker and, bending, "licked" it. There was a crackling sound, and the metal parts of the loudspeaker began to glow like hot iron. The ball lightning slowly continued its way to the window and, slightly flattened, went out the window.

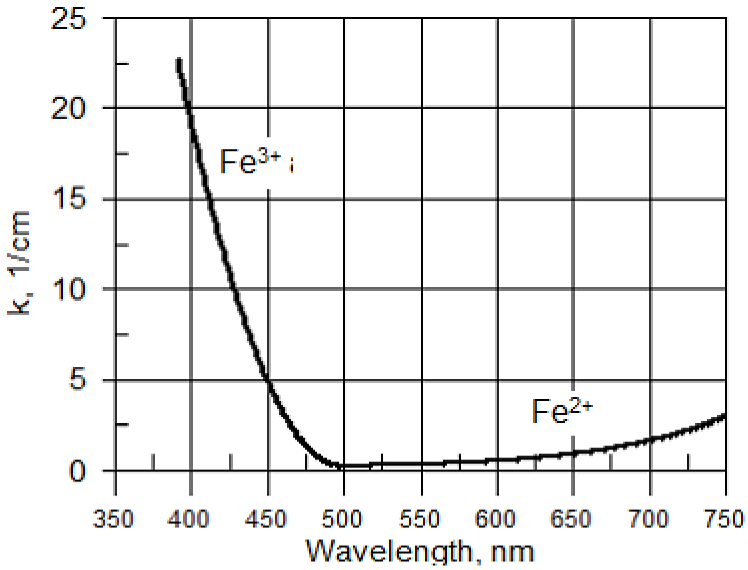


Fig. 5.2.2. Absorption coefficient of the BL shell of glass melt containing Fe2O3 (Schematic representation).

Table 5.2.2. Luminance L_{BL} and chromaticity of ball lightning, the shell consists of glass melt doped with Fe2O3 (δ=30 μm).

T_{BL}, K	2500	2000	1500
L_{BL}, cd/m^2	2.7E+04	2.2E+03	4.1E+01
Chromaticity			

Manganese oxide MnO is also commonly found in sandy soils. In a silicate glass melt, it forms the ion Mn^{3+}, the absorption coefficient of which is shown schematically in Fig. 5.2.3 (according to *Choudhary et ai. 2005* and *Thiemsorna* et *al. 2008*), oxide content of about 1 wt%). As before, we used temperature-independent values due to the lack of necessary data. The calculation results are presented in Table 5.2.3. As seen, the BL color is lighter than in the previous cases and, more importantly, the luminance is significantly higher (compared with Tables 5.2.1 and 5.2.2). This happens because the maximum absorption coefficient (480 nm in Fig 5.2.3) is close to the maximum of the relative luminous efficiency functions of the human eye *V(λ)* (555 nm in Fig. 5.1.1). In this case the value of the integral in Eq. (5.2.7) is large and correspondingly the luminous emittance and luminance of ball lightning are also great.

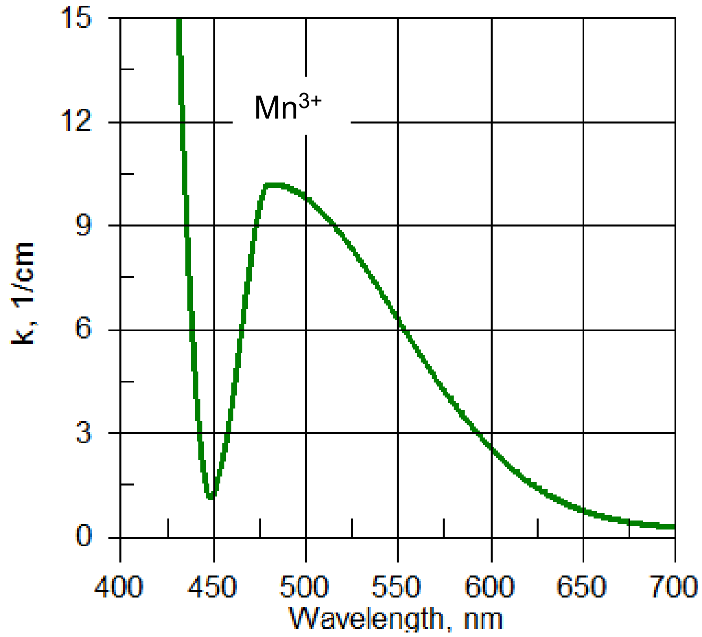
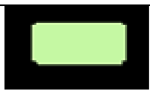
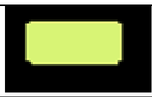
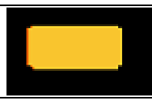


Fig. 5.2.3. Absorption coefficient of BL shell of glass melt containing MnO (Schematic representation).

Table 5.2.3. Luminance L_{BL} and chromaticity of ball lightning, the shell consists of glass melt doped with MnO (δ=30 μm).

T_{BL}, K	2500	2000	1500
L_{BL}, cd/m^2	2.3E+05	1.7E+04	2.4E+02
Chromaticity			

In the conditions of a soil electric discharge, it is unlikely that the composition of the BL shell will be uniform. In this case, some areas of the BL surface will have different colors. If, in addition, the ball lightning rotates around its axis, then we will get the picture described in the following eyewitness report.

Case 4. From *Grigoriev et al. 2019*, p. 10, Case 4. Orenburg, July 7, 1977. Observer – O. L. Yakhimovich.

> …a deafening clap of thunder sounded outside the window. I looked toward the balcony and froze: a fiery yellow ball the size of a soccer ball was rolling across the floor from the open balcony door. The ball was so bright it was painful to look at. Moreover, it was uneven: red tongues of flame were moving around inside it. The ball had already flown about three meters into the room when I closed my eyes in horror. I can't say how long I sat there with my eyes closed, but when I opened them, the room was empty. It was raining outside.

5.3. Summary

According to our model, ball lightning is a bubble of molten glass filled with a gas transparent to light. In this case, light can only be emitted by the shell, which has a temperature T_{BL} above 1500 K. Since molten glass is transparent in the visible region of the spectrum, the observed color of BL is due exclusively to the presence of impurities. Considering that the concentration of radiating impurities is small and the thickness of the shell is also small, the radiation of the shell can be calculated in the approximation of an optically thin medium.

If the impurities produce an absorption coefficient that varies only slightly over the entire visible spectrum, the color of ball lightning is close to the color of a black body at T_{BL}. In this case, the color of the BL can change from red to orange depending on the temperature.

The observed diversity of BL colors is due to the presence of small concentrations of oxides of the 4th period transition metals (from Ti to Cu). The absorption coefficient of these metal ions has peaks in the visible region, and the BL color depends on the position of these peaks: iron oxide produces a blue tint, and manganese oxide produces a yellow-green tint. Other color shades arise in the presence of oxides of other transition metals or their mixtures.

References

Bychkov, V. L. (2012). Unsolved mystery of ball lightning. In *Atomic Processes in Basic and Applied Physics* (pp. 3-24). Berlin, Heidelberg: Springer Berlin Heidelberg.

Calas, G., Galoisy, L., & Cormier, L. (2021). The color of glass. *Encyclopedia of Glass Science, Technology, History, and Culture*, *1*, 677-691.

Cao, D. (2012). Color vision and night vision. *Retina E-Book: 3 Volume Set*, 284.

Capobianco, N., Hunault, M. O., Balcon-Berry, S., Galoisy, L., Sandron, D., & Calas, G. (2019). The Grande Rose of the Reims Cathedral: an eight-century perspective on the colour management of medieval stained glass. *Scientific Reports*, *9*(1), 3287.

Choudhary, M. K., & Potter, R. M. (2005). Heat transfer in glass-forming melts. *Properties of glass-forming melts*, Chapt.9, CRC Press .

Gevers, T., Gijsenij, A., Van de Weijer, J., & Geusebroek, J. M. (2012). *Color in computer vision: fundamentals and applications*. John Wiley & Sons.

Grigor'ev, A.I. & Shiryaeva S. O., . (2019). *Ball lightning through the eyes of eyewitnesses*. Григорьев, А. И., & Ширяева, С. О. *Шаровая молния глазами очевидцев*. ООО ДиректМедиа.

Howell, J. R., Mengüç, M. P., Daun, K., & Siegel, R. (2017). *Thermal radiation heat transfer*. CRC press.

Kerr, D. A. (2010). The CIE XYZ and xyY color spaces. *Colorimetry*, *1*(1), 1-16.

Page, C. H., & Vigoureux, P. (1977). *The International System of Units (SI)* (No. 330-331). US Department of Commerce, National Bureau of Standards.

Piccoli R, Blundelli R. *A statistical study of ball lightning events observed in France between 1994 and 2011*. International Journal 'Unconventional Electromagnetics and Plasmas' (UEP), New Delhi, India, Vol. 6(1-2) (2014).

Rogers, K. (Ed.). (2010). *The eye: the physiology of human perception*. Britannica educational publishing.

Smirnov, B. M. (1992). Observational properties of ball lightning. *Soviet Physics Uspekhi*, *35*(8), 650.

Stakhanov, I. P., (1985). *The physical nature of ball lightning*. Стаханов И. П, *О физической природе шаровой молнии*. М. Энергоатомиздат

Thiemsorn, W., Keowkamnerd, K., Phanichphant, S., Suwannathada, P., & Hessenkemper, H. (2008). Influence of glass basicity on redox interactions of iron-manganese-copper ion pairs in soda-lime-silica glass. *Glass Physics and Chemistry*, *34*(1), 19-29.

Tilley, R. J. (2020). *Colour and the optical properties of materials*. John Wiley & Sons.

Yeraliyev, A., & Fan, K. (2014). Use of a DSLR camera and integrating sphere to determine the luminance of the Moon.

Adopted from *Stakhanov 1985*

The birch trunk damaged by a ball lightning explosion (photo by Nazarkin S. I.)

6. Energy of ball lightning

During observation of a ball lightning, eyewitnesses can directly get an idea of its shape, size, color, lifetime, but not of the energy. The energy content can only be assessed based on the results of the SM's impact on surrounding objects, such as wood, a metal object, a tub of water, etc. However, only a small number of these observations are known, and the evaluable information is extremely insufficient to get reliable energy characteristics. In this situation, researchers must enter some values instead of missing parameters, and this choice is largely subjective, which affects these estimated values. This circumstance must be considered, and therefore, we should not expect high accuracy of predicted values.

6.1. Observed energy characteristics of ball lightning

The commonly used BL energy characteristics are the total BL energy E_{BL} and the energy density e_{BL}. These quantities are related by the expression

$$e_{BL} = \frac{E_{tot}}{V_{BL}}. \qquad (6.1)$$

where V_{BL} is the BL volume. It should be noted that this quantity is relevant for homogeneous medium. For inhomogeneous systems, such as a ball with a thin shell, it is not clear what physical parameters this value corresponds to. However, so far as the energy density value is used, we will discuss it.

The most complete summary of BL energy parameters can be found in books *Barry 1980*, *Stenhoff 1999*, *Stakhanov 1999*, *Nikitin at al. 2018*, *Bychkov 2022*, *Nikitin 2025*. These data show a wide range of BL energy densities; the values vary from very low 10^3 to extremely high 10^{12} J/m^3. The upper limit has been a subject of discussion and in some works it was recognized as unrealistic. Here we give the opinion of scientists on this matter.

> Ball lightning may be a phenomenon of relatively low energy density with a median value of the order of 10^6 J/ m^3 and a range of about $2 \cdot 10^3$-$2 \cdot 10^8$ J/m^3 (*Barry 1980*).
>
> The energy content in ball lightning can range from a few kilojoules to several tens of kilojoules, in some cases (especially with large lightning sizes) it can reach 100 kJ. The energy density is (1-10)$\cdot 10^6$ J/m^3 (*Stakhanov 1985*).
>
> Note that the internal energy of ball lightning is relatively small and cannot lead to great damage. … the most probable internal energy is 6 kJ; the average internal energy is 60 kJ. (*Smirnov 1992*).
>
> Ball lightning is therefore, in my view, probably a relatively low-energy phenomenon, perhaps with energy of up to 3 kJ; e_{BL}=$4.6 \cdot 10^4$-$7.2 \cdot 10^5$ J/m^3 (*Stenhoff 1999*).

However, there are works that provide energy density estimates several orders of magnitude higher. In recent surveys, these values are presented as reliable and are recommended for the formation of BL models.

> So, we estimated the ball lightning energy spent on heating, melting, evaporation, and boiling for various materials; the maximum values of the energy density are in the interval 10^{10}-10^{11} J/m^3 (*Bychkov 2022*).
>
> Once in a container of water, ball lightning can heat the water to a boil. Based on the analysis of such cases, it was found that the energy density stored inside ball lightning can be about 10^{10} J/m3 (*Nikitin et al. 2023)*.

Below we will consider events for which the available data allows researchers to estimate the energy of ball lightning. Among these events, there are some where the energy of ball lightning is estimated to be extremely high. In our opinion, some of these estimates are questionable, and this will be the subject of discussion.

To understand how the BL energy estimated and to determine what difficulties arise in this regard, we will consider several events previously published in the literature and give a brief comment.

Case 1. This event occurred at Warley, Smethwick, West Midlands, England on August 8, 1975, and is described in detail in *Barry 1980* and *Stenhoff 1999*.

> A fireball appears suddenly within a room. The ball had an apparent bright blue to purple core (diameter ~2 cm) surrounded by a flame-coloured halo. with an overall diameter of about 10 cm. The ball struck the observer's clothing and brushed against her hand. The contact burned a hole in the fibre, melted an area of the polyester material (about 100x70 mm) and burned her ring finger by heating her gold ring. The ball disappeared with an explosion. The event lasted for about 1 sec.

In the work *Barry 1980*, based on these data, estimates of the energy required to cause this damage were made. The energy spent to melt the material and create the hole, heating the golden ring to 100 °C, and the radiation losses were considered. The total energy was found to be 440 J. The uniform energy density e_{BL}, Eq. (1.1), was calculated using two assumptions.

- All the BL energy is concentrated in the core of 2 cm diameter - e_{BL}=1.05·10^8 J/m^3.
- The BL energy is evenly distributed in visible BL glow with a diameter of 10 cm - e_{BL}=0.8·10^6 J/m^3.

We see the great uncertainty in the estimate of the BL energy density; the obtained values differ by two orders of magnitude. If we consider a discussion in the literature about whether there was the fact of the appearance of the ball lightning, then the confidence that we obtained the necessary information decreases even more. Unfortunately, this situation often occurs when determining the energy characteristics of ball lightning.

Case 2. The most famous and widely discussed case involves the publication of a letter about ball lightning falling into a tub of water (The Daily Mail, November 5, 1936).

> A Thunderstorm Mystery - Explained by the Astronomer Royal
>
> To the Editor of "The Daily Mail"
>
> Sie, during a thunderstorm I saw a large, red hot ball come down from the sky. It struck our house, cut the telephone wires, burnt the window frame, and then buried itself in a tub of water which was underneath. The water boiled for some minutes afterwards, but when it was cool enough for me to search, I could find nothing in it. Dorstone, Hereford. W. MORRIS

This event came to the attention of the scientific community after the presentation of a review paper by Prof. B. J. Goodlet entitled "Lightning" at the Institution of Electrical Engineers in London on January 7, 1937. In response to the discussion, Prof. Goodlet gave two estimates of the energy content of the ball using the following data: the mass of water in the tub was 18 kg and the ball diameter was 10 cm. The total released energy E_{BL} and the energy density of the ball $e_{BL} = E/V_{BL}$ have been estimated (here, v_{BL} is the ball volume).

- The temperature of all the water rises from 20°C to 60°C: E_{BL} = 3 MJ and $e_{BL} = 0.6 \cdot 10^{10}$ J/m^3.
- The temperature of all the water rises from 20°C to 100°C and then a mass of 1.8 kg was vaporized: E_{BL} = 10 MJ, $e_{BL} = 1.9 \cdot 10^{10}$ J/m^3.

As can be seen, very high energy density values were obtained. But as noted in *Stenhoff 1999*, the conditions considered were not supported by Mr. Morris's description of the event. However, these high values are still unreasonably used in shaping the development of ball lightning theory.

Case 3. Let us pay attention to the following event where ball lightning also interacts with water, *Stakhanov 1985*, p. 83, event 31.

> It happened in 1935, in Gatchina city, Leningrad region. Four people were sitting near the house, including the author of this letter, who was 20 years old. It was raining a little. Suddenly, they noticed a ball about 10 cm in diameter,

> glowing with a light-orange light, like a 10-watt lamp. The ball went down, fell to the ground 3 m from the people and 1 m from a puddle of water. Then it rolled towards the water and exploded in it. The water splashed and splashed the people. The drops were warm but not hot. From the place where the ball lightning fell, to the puddle along the path of its movement, the earth dried up (which indicates a temperature above 100 °C). At the place of the explosion, a depression in the ground was formed with a diameter of about 0.5 cm and a depth of several centimeters.

Please note that in cases *2* and *3* the diameters of the ball lightning were the same, D_{BL} = 10 cm, but in case *3* no high energy was observed. We quote from the book of *Stakhanov 1985*: "... it raises the possibility that [Goodlett's] estimate was incorrect. Indeed, it's possible that the boiling in the bath was caused not by the high temperature of the entire mass of water, but by the formation of steam bubbles in areas of localized heating (i.e., where ball the lightning hit) at a low average water temperature."

The events described above demonstrate the difficulty of obtaining reliable data on the interaction of ball lightning with water, since it is difficult to determine the amount of heated, evaporated and splashed water. Let us consider this in more detail using the following.

Case 4. The frog event is described by *Imenitov et al. 1980*. The event occurred in 1962 near the town Perechin in Western Ukraine in August at about 11 PM. The discussion of this event can also be found in *Bychkov at al. 2010*.

Ball lightning hit a cattle water trough (the water mass was 112.5 kg), where frogs were at that moment. The eyewitness observed a rainbow glow above the trough for 10 s and then found an almost empty trough with dead (boiled?) frogs at the bottom. Dead frogs were also found in two adjacent troughs. Based on this description and assuming that the water mass m_W = 100 kg was evaporated from the trough because of boiling, the energy of the BL was estimated as E_{BL} = 269 MJ.

Here we pay attention to the fact that the boiling of water is accompanied by the formation of steam. If the steam has the density of an average fog (Liquid Water

Content *LWC*=0.25 g/m^3, *Rec. ITU-R P.840-6*) then volume of the steam cloud in the evening cool air is

$V_S = m_W / LWC = 4 \cdot 10^5$ m^3

Even if not all the evaporated water turns into fog, it will be a huge cloud. The eyewitness should have noticed it, but he saw only a rainbow glow over the trough in clear air.

It can be assumed that the water did not evaporate but was thrown out of the trough by the BL explosion. The presence of dead frogs in the neighboring troughs also indicates that an explosion occurred; these frogs were thrown out of the affected trough by the explosion. The energy required to throw water out of the trough (several kilojoules) can be taken as a lower estimate. This energy is many orders of magnitude less than the evaporation energy of the same mass of water. The gap between the upper and lower limits is so great that it makes no sense to talk about any reasonable estimate of BL energy.

It should be noted that the book by *Imenitov et al. 1980* does not claim that the calculated energy E_{BL} = 269 MJ is realistic. However, some ball lightning models are based on excessively high energy densities (up to10^{12} J/m^3) obtained under the assumption that a significant portion of the water was evaporated.

Above we discussed the impact of a ball lightning on textile and water. In these cases, the question did not arise of how the BL energy is transferred to the object of the impact. Near the interface between the ball lightning and the object, temperature gradients arise which lead to heat flows from the ball lightning to the object. When BL impacts textile (*Case 1.*), the damage could be caused also by the thermal radiation. Another type of impact is shock wave that occurred due to the BL explosion; the resulting pressure difference leads to the movement of masses of water. Now we will consider the effect of ball lightning on solid objects where the process of energy transfer requires more detailed consideration.

Case 5. From *Barry 1980*, p. 49, case 2. The BL energy is estimated based on the information that a ball lightning descended into a wharf piling and shattered it into splinters. Barry suggested that the log was soaked with water that heated up and turned into steam due to release of the BL energy. When the steam pressure exceeded the tensile strength of the wood, the log exploded and shattered into pieces. The destroyed part of the log had a length of 1.2 m and a diameter of 15 cm. Believing that the log contained 57.4 cm^3 of water and taking the strength properties of the log is the same as oak wood, Barry calculated the energy required to destroy the log as $0.15 \cdot 10^6$ J. The BL energy density, assuming a uniform BL energy distribution and a ball diameter of 15 cm, would be $e_{BL} = 8.5 \cdot 10^7$ J/m^3.

And here again the question arises of how the energy enclosed in a ball with a diameter of 15 cm could be transferred to a log of 1.2 m long. Heat conduction is a slow process, and it could not cause the explosion. Of course, the explosion of the ball lightning itself could lead to the destruction of the log, but in this case, it would be another calculation. We believe that the explosive heating of water in the log was caused by a large electric current that could have been initiated by a ball lightning electric charge, if it had the charge. It is possible that it was a strike of ordinary lightning, as stated in the book of *Stenhoff 1999*: “The most energetic damage following such events may be attributed to the effect of an ordinary CG flash. The scale and nature of such damage often suggests that it was caused by large electric currents, perhaps hundreds of amperes or greater. It seems quite implausible that ball lightning could contain within its small volume sufficient charge per unit volume or sufficient electric potential energy to deliver such large currents. It is much more credible that an ordinary CG flash was responsible.”

Case 6. *Stenhoff’s* above remark is fully applicable to cases of house destruction, presumably by ball lightning. A similar event occurred in Buryatia on May 27, 2013, and is described in the work of *Nikitin et al. 2018*. Here is a short excerpt. “A usual rain began, but suddenly a thunder struck with such a force that passers-by and the cattle, being at this time in the street, crouched with horror and fled their several ways. A minute later after that the bright shining ball descended from the sky and forced its way into the house…” In the description, there is no other information about the “shining ball”.

As can be seen, the description does not contain the BL parameters, which are usually reported by eyewitnesses (size, color, speed of movement, observation time).

Despite the rather vague description of the event, the authors *Nikitin et al. 2018* concluded that the house was destroyed by a ball lightning and made an estimate of the required energy. According to their calculations this value is equal to 132 MJ, which is equivalent to 33 kg of trinitrotoluene. Taking the BL diameter D_{BL}=0.3 m, they obtained the energy density e_{BL} = $2.1 \cdot 10^9$ J/m^3. Here we pay attention to the fact that the volume of required trinitrotoluene (density 1.654 g/cm^3) exceeds the volume of the ball lightning. *Nikitin et al.* did not make any assumptions about the BL material.

In our opinion, there was no ball lightning, and the destruction was caused by ordinary lightning, the flash of which was observed by eyewitnesses.

Case7. In this work, we do not consider events associated with power electrical grids because a situation is possible when a short circuit is mistaken for ball lightning phenomenon. We believe that such a situation could have happened at the event described in *Dmitriev 1981*. Here we give only a summary of the description, a more detailed description is given in *Bychkov 2022*, p. 43, Case 15.

> This event occurred in Khabarovsk city near the cinema “Zarya” on Khasanovskaya street on August 24, 1978, at 23:20. The event was seen by many people.
>
> It was raining heavily. An orange bubble 1.5 m in diameter appeared above the roof of the cinema, from which sparks flew. The bubble began to descend and, passing through the branches of trees, approached the ground. Then it rose slightly and exploded with a loud bang. An area about 1.5 m in diameter formed on the surface of the earth, exposed to heat. In addition, damage to electrical networks occurred in a residential area with a radius of up to 100 m.

Based on this description, *Dmitriev et al. 1981* concluded that eyewitnesses observed ball lightning and, after conducting subsequent studies, estimated its energy density as e_{BL}=$6 \cdot 10^8$ J/m^3.

The case described here involves a large amount of energy. The question arises: where did this energy come from? There was no thunderstorm, and no one saw lightning flashes, only heavy rain. In this case, the source of energy could be the

power grid, and its release occurred because of a short circuit. This is evidenced by the failure of the power grid in a large residential area.
In movie theatres of mid-20th century, the main consumers of energy were the movie projectors and the devices that powered them. This equipment was in a separate annex, where electricity was supplied via high-power cables. We believe that the short circuit occurred in this annex.

In our opinion, the above description of the event is only an emotional reaction to a short circuit and its accompanying phenomena. The falling fiery object could have been burning elements of the roof structure.

Case 8. Consider event *44* from *Stakhanov 1985*. Eyewitness: Novgorodsky G.M., born in 1905, mechanical engineer. The event took place on August 15, 1925.

> It flew into the window opened by a gust of wind after a strong thunderclap. It was a ball of bright yellow with a bluish-violet tint, 15-16 cm in diameter. In addition to the author of the letter, his father and younger brother saw lightning, and according to the brother, the diameter of the lightning was 30 cm. Bright white sparks in the form of needles flashed on the surface of the ball, and a slight crackling or rustling was heard. Lightning moved smoothly horizontally at a height of 1.5 m over the floor. It walked around the table where people were sitting. Near the fireplace, it sank down and, speeding up twice, flew into the half-open door of the firebox. It stretched out and shrank sideways to go through a gap of about 5 cm wide. There were no marks on the door. In 2-3 seconds, there was a roar of an explosion on the roof. All this lasted for about one minute. It turned out that the brick chimney on the roof was destroyed. Some of the bricks were found at 30-40 meters from the house.

Stakhanov estimated the energy required to throw bricks; this value is 10-20 kJ. Assuming that this value is equal to the total BL energy and taking D_{BL}=15 cm, he calculated the energy density e_{BL}=5-10 J/cm^3. If we accept D_{BL}=30 cm (the opinion of another eyewitness), the e_{BL} value will be about 0.6-2.5 J/cm^3. These energy characteristics are in reasonable agreement with our calculations (see Section 7, Table 7.1). It should be noted that the BL explosion occurred in a small, confined space, which allows us to equate the energy of the destructive consequences of the explosion with the energy of ball lightning.

6.2. Summary

Here we have discussed only a few events. Consideration of these and other similar cases shows that currently there is not enough information to obtain reliable data on the energy characteristics of ball lightning. Some papers give the highest possible value of the energy density, while ignoring lower estimates, despite the high uncertainty of eyewitness data. This presentation of material creates the impression that a significant number of cases have been discovered where ball lightning had extremely high energy. There are no prohibitions on the existence of high-energy ball lightning, but, in our opinion, there is no sufficient reason to believe that such objects have been discovered. In this regard, extremely large values of BL energy density (say, e_{BL} >10^8 J/m^3) must be used with great caution as a criterion for truth in model development. Such criteria are not used in this work.

References

Barry, J. (1980). *Ball lightning and bead lightning: Extreme forms of atmospheric electricity*. Springer Science & Business Media.

Bychkov, V. L. (2022). *Natural and Artificial Ball Lightning in the Earth's Atmosphere*. Cham: Springer.

Bychkov, V. L., Nikitin, A. I., & Dijkhuis, G. C. (2010). Ball lightning investigations. In *The Atmosphere and Ionosphere: Dynamics, Processes and Monitoring* (pp. 201-373). Dordrecht: Springer Netherlands.

Dmitriev, M.T., Bakhtin, B.I., & Martynov, V.I. (1981) Investigation of the Thermal Factor of Ball lightning. *Zhurnal Tekhnicheskoi Fiziki*, 51, 2567-2572.

Imianitov, I., & Tikhii, D. (1980). *Beyond the laws of science*. M.: Atomizdat, 190.

Nikitin, A. I., Bychkov, V. L., Nikitina, T. F., Velichko, A. M., & Abakumov, V. I. (2018, March). Sources and components of ball lightning theory. In *Journal of Physics: Conference Series* (Vol. 996, No. 1, p. 012011). IOP Publishing.

Nikitin, A. I., Nikitin, V. A., Velichko, A. M., & Nikitina, T. F. (2023). Explosions of Ball Lightning inside Enclosed Spaces. *Atmosphere*, *15*(1), 2.

Smirnov, B. M. (1992). Observational properties of ball lightning. *Soviet Physics Uspekhi*, *35*(8), 650.

Stakhanov, I. P., (1985). *The physical nature of ball lightning*. Стаханов И. П, *О физической природе шаровой молнии*. М. Энергоатомиздат

Stenhoff, M. (1999). *Ball lightning: an unsolved problem in atmospheric physics*. Springer Science & Business.

7. Time evolution of ball lightning

7.1. Introduction

In the previous sections, a model of ball lightning was proposed, and its properties were discussed. Here, a simplified system of equations describing the evolution of ball lightning in time will be presented and solutions for some limiting cases will be given. As before, we consider ball lightning as a thin-walled hot bubble filled with hot gas. The shell material of ball lightning—foamed molten glass—is formed because of a high-temperature and high-pressure electrical discharge in the soil, initiated by a cloud-to-ground lightning strike. Let us begin by discussing the main processes that determine the properties and behavior of such ball lightning.

First of all, we note that ball lightning is a hot object whose temperature is much higher than the ambient temperature. This leads to cooling of the ball lightning due to heat transfer on its surface. In addition, heat exchange also occurs between the BL shell and the gas filling it.

The second important circumstance is that the shell of BL is a foamy structure. This material contains many micron-sized gas bubbles. These bubbles burst upon reaching the shell surface, and nanodroplets of melt are ejected into the air. Hardening in the cold air, the droplets turn into glass nanoparticles. This cloud of nanoparticles, formed around the ball lightning, scatters the light of the BL, which the eyewitness perceives as a halo. Sometimes, these processes form glass threads on the surface of the BL. In addition, gases and droplets ejected into the boundary layer due to explosions of micron-sized gas bubbles significantly affect the heat exchange of the ball lightning with the surrounding air.

Developing a ball lightning model that includes the above-mentioned physical and chemical processes in a glass melt under conditions of intense heat and mass transfer is a complex task. We believe that a complete solution to this problem is currently impossible due to the lack of complete and reliable information. In this regard, we will consider a simpler description of ball lightning. The necessary simplifications will be introduced when discussing the system of equations. Now we will introduce simplifications that concern ball lightning as a whole.

Since the shell of ball lightning is a thin film of melt, the imbalance of transverse forces leads to its rupture. Therefore, the condition for the existence of ball lightning is the equality of the internal and external pressures acting on the film. In other words, the pressure of the gas filling the ball lightning differs only slightly from the atmospheric pressure.

The gas that fills the ball lightning may contain molecules that intensely emit in the infrared (CO2, H2O etc.). Since the BL shell is a thin melt film transparent to infrared radiation, the filling gas with a high content of radiating species will quickly cool. This leads to a decrease in gas pressure and the subsequent collapse of ball lightning. Thus, long-lived ball lightning must be filled with non-radiating hot gas, which can be air containing only a small admixture of radiating species. Accept this we will assume that the filling gas is hot air. In this case, ball lightning is cooled by radiation and heat transfer on its shell.

Ball lightning can acquire an electric charge during its formation. We believe that this charge is not so large as to affect the BL energy characteristics. However, this charge can determine the trajectory of ball lightning due to interaction with external electric fields. Since we are not considering the movement of ball lightning, the presence of charge will not be taken into account.

7.2. Basic definitions

7.2.1. Geometric parameters and mass characteristics

Since ball lightning is a thin-walled bubble, its geometric parameters are the diameter D_{BL} and the shell thickness δ_{shell}. The BL surface area is

$$S_{BL} = \pi D_{BL}^2 \qquad (7.1)$$

The volume of gas filling the ball lightning will be denoted as V_{gas}. Since $\delta_{shell} << D_{BL}$, we will consider the entire BL volume V_{BL} and the gas volume V_{gas} to be equal

$$V_{gas} \cong V_{BL} = \frac{\pi}{6} D_{BL}^3 \qquad (7.2)$$

The BL shell material (glass melt) has a foamy structure. An important characteristic of this material is the volume fraction φ of the condensed phase. The rates of the most processes considered are determined not by the actual shell volume V_{shell}, but by the volume of the melt $V_{melt} = \varphi V_{shell}$ (Section 2, Eq. 2.3). Therefore, instead of the actual thickness of the shell δ_{shell}, we introduce the reduced value $\delta = \varphi \delta_{shell}$. Using this value, we write the volume of the melt as

$$V_{melt} = S_{BL} \delta \qquad (7.3)$$

In addition, we neglect the mass of micron-sized gas bubbles in the shell material. Then the mass of the shell is

$$M_{shell} \cong V_{melt} \rho_{melt} \qquad (7.4)$$

where ρ_{melt} = 2.3 g/cm^3 is density of the melt.

The gas filling the ball lightning is a hot air, and it will be considered as an ideal gas. Then the density of the filling gas is

$$\rho_{gas} = \rho_{atm} \frac{T_{atm}}{T_{BL}} \qquad (7.5)$$

where T_{atm}=293 K and ρ_{atm}=1.204 kg/m^3 are the temperature and density of air at pressure P_{atm} =1 atm (normal conditions). And the mass of the filling gas is

$$M_{gas} = \rho_{gas} V_{BL}$$

The total BL mass is

$$M_{BL} = M_{shell} + M_{gas} \qquad (7.7)$$

Using Eqs (7.1) – (7.4), we can write the ratio of the masses of gas and shell

$$\frac{M_{gas}}{M_{shell}} = \frac{\rho_{atm} T_{atm}}{\rho_{melt} T_{BL}} \frac{D_{BL}}{6\delta}$$

Assuming that the shell thickness δ and the BL temperature T_{BL} are known, we can find the diameter when $M_{shell} = M_{gas}$.

$\overline{D}_{BL} = 6\delta \frac{\rho_{melt} T_{BL}}{\rho_{atm} T_{atm}}$

For T_{BL}=2000 K and two shell thickness values δ=30 and 100 μm, $\overline{D}_{BL}$=2.3 and 7.7 m respectively. This means that for ball lightnings of average diameter D_{BL}=0.1-0.4 m, the mass of the filling air is much less than the mass of the shell, $M_{gas} << M_{shell}$. Below we will consider only such ball lightning.

7.2.2. Thermodynamic characteristics

We understand that during the short time of the BL existence, not all processes of relaxation in the glass melt can be completed. Studies of these processes are far beyond the scope of this work. In this situation, we do not see any other possibility than to use the equilibrium enthalpy values available in literature. That's why we assume that the BL shell and the gas filling it are in equilibrium at a temperature T_{BL}..

The total energy of ball lightning E_{BL} is a sum of the enthalpies of the shell and the filling gas

$$E_{BL} = h_{melt} M_{shell} + h_{air} M_{gas} \qquad (7.8)$$

where h_{melt} and h_{air} are specific enthalpies of glass melt and filling gas (hot air). In the temperature range of interest to us 1000–2500 K, the specific enthalpy of glass melt can be represented as a linear function of temperature.

$$h_{melt} = h^{*}_{melt} + c_{melt} T_{BL} \qquad (7.9)$$

The specific heat capacity c_{melt} of the glass melts is taken from *Priven at al. 2005*. The c_{melt} value for silicate glass melts vary within 1.2-1.7 J/g K. We take a value c_{melt} =1.4 J/g K. The constant h^* is accepted to be -620 J/g. The function $h_{melt}(T)$ is presented in Fig. 7.1; the specific enthalpy of pure silica melt h_{SiO2} is also shown for comparison. The expression (7.9) has an acceptable accuracy in the temperature range from 800 to 2500 K.

It should be noted that curve *2* in Fig. 7.1 for the pure silica melt corresponds to the difference $h_{SiO2}(T) - h_{SiO2}(273\ \mathrm{K})$. If crystallization does not occur during cooling of the melt, this curve represents combined data on the specific enthalpy of the melt and glass. Curve *1* for the silicate glass melt, which we will use in calculating the energy of ball lightning, can be interpreted in a similar way.

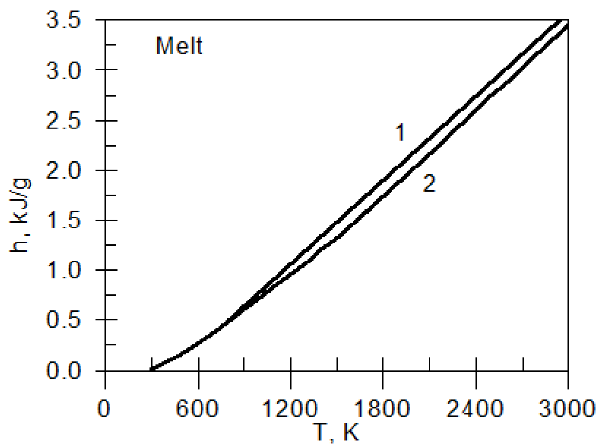


Fig. 7.1. Specific enthalpies for glass melts (curve *1*, Eq. (7.9)) and for SiO2 melt (curve 2 from *NIST-JANAF*).

The specific enthalpy of air does not differ significantly from the specific enthalpy of glass melt. Since we are considering medium-sized ball lightnings, the mass of the filling gas is much less than the mass of the shell (M_{gas}<<M_{shell}, Section 7.2.1). It follows from this that the contribution of the filling gas to the total BL energy is small and can be neglected. Then energy of BL is

$$E_{BL} \cong h_{melt} M_{shell} \quad (7.10)$$

Table 7.1 shows the energy characteristics of average ball lightning with different wall thicknesses and different filling gases. As can be seen, the contribution of gas is insignificant, especially when this gas is air.

Table 7.1. Energy characteristics of ball lightning (D_{BL} 0.25 m, T_{BL} 2000 K).

Gas	δ, μm	M_{shell}, g	M_{gas}, g	M_{BL}, g	E_{shell}, kJ	E_{gas}, kJ	E_{BL}, kJ	e_{BL}, J/cm^3
H2O	100	45.1	0.9	46.0	98.4	5.8	104.2	12.8
H2O	30	13.5	0.9	14.4	29.4	5.8	35.2	4.31
Air	100	45.1	1.4	46.5	98.4	2.8	101.2	12.4
Air	30	13.5	1.4	14.9	29.4	2.8	32.2	3.95
Air	10	4.5	1.4	5.9	9.8	2.8	12.6	1.54

δ is shell thicknesses; M_{shell}, M_{gas} and M_{BL} are masses of shell, filling gas, and entire ball lightning; E_{shell}, E_{gas}, and E_{BL} are energies of shell, filling gas, and entire ball lightning; e_{BL} is energy density. Enthalpy of H2O includes the latent heat of vaporization of 2.5 kJ/g.

7.3. Equations for the time evolution of ball lightning

As mentioned above, the mass of the BL shell M_{shell} decreases due to the ejection of nanoparticles caused by the burst of small gas bubbles on the shell surface. Then the rate of mass loss of the shell is

$$\frac{dM_{shell}}{dt} = -W_{burst}, \quad W_{burst} = k_{burst}S_{BL} \tag{7.11}$$

where t is time, k_{burst} is mass loss rate constant, kg/m^2 s. We don't really know anything about the k_{burst} value. The only thing we can say is that k_{burst} should be a function of melt viscosity. Since the viscosity of the melt increases with decreasing temperature, then the k_{burst} value decreases as the ball lightning cools.

We will consider the shell of ball lightning to be impenetrable. Then the mass of the gas M_{gas} (or the number of gas moles N_{gas}) is constant. Based on this and using Eq. (7.5), we obtain the BL diameter as a function of BL temperature.

$$D_{BL} = D_{BL}\,(0)\left(\frac{T_{BL}}{T_{BL}(0)}\right)^{1/3} \tag{7.12}$$

where $D_{BL}(0)$ and $T_{BL}(0)$ are initial values, i.e., the values at the time t=0. Change in the diameter leads to a change in the surface area S_{BL}, which in turn changes the BL shell thickness

$$\delta = \frac{M_{shell}}{S_{BL}\rho_{melt}} \tag{7.13}$$

Note that here the shell mass M_{shell} is a function of time, Eq. (7.11).

The BL energy equation can be represented as

$$\frac{dE_{BL}}{dt} = -(Q_{rad} + Q_{conv}) - h_{burst}W_{burst} \tag{7.14}$$

where Q_{rad} and Q_{conv} are heat losses due to radiation and convection. The last term in Eq. (7.14) describes the energy loss due to ejection of melt nanoparticles into the environment. This term contains the quantity of specific enthalpy h_{burst} of the ejected particles. It is reasonable to assume that the specific enthalpy of the ejected particles is equal to the specific enthalpy of the shell material, i.e. h_{burst}=h_{melt}.

Using the approximate expression (7.10) for the BL energy, the left side of Eq. (7.14) can be represented as

$$\frac{dE_{BL}}{dt} = c_{melt}M_{shell}\frac{T_{BL}}{dt} + h_{nelt}\frac{dM_{melt}}{dt} \quad (7.15)$$

Substituting Eqs (7.11) and (7.15) into Eq. (7.14) gives

$$c_{melt}M_{shell}\frac{T_{BL}}{dt} = -(Q_{rad} + Q_{conv}) \quad (7.16)$$

Note that the equation contains the time-varying mass of the BL shell, while the rate of mass loss is absent.

Initial values for the equations (7.11, 7.12 and 7.16) are the mass of the shell $M_{shell}(0)$, the BL diameter $D_{BL}(0)$, and the BL temperature $T_{BL}(0)$. So, the system of equations is completely determined and describes the time evolution of ball lightning.

Solving the resulting system of equations requires knowledge of a number of quantities, the most important of which are the structural and thermodynamic properties of the shell material, heat and mass transfer rates. All these quantities are functions of the temperature and size of the ball lightning. The parameters required to set these functions are unknown or their reliability is low. Numerical solutions of the system of equations by sorting through all the unknown parameters to obtain the desired values is labor-intensive and unproductive work. The situation is complicated by the lack of clear criteria for selecting reliable results. In this regard, we will not solve the full system of equations but will consider some limiting cases that allow us to understand the physical processes occurring in ball lightning.

7.4. **Purely radiative cooling, optically thin layer approach**

Here, we will consider a limiting case when the main source of energy loss of ball lightning is radiation. This situation is quite realistic when the mass flow from the BL shell, due to micro explosions of gas bubbles, forms a hot layer that moves away the surrounding cold air. In this case, the convective term in Eq. (7.16) becomes small and can be neglected. Then the temperature equation will take the form

$$c_{melt}M_{shell}\frac{T_{BL}}{dt} = -Q_{rad} \quad (7.17)$$

The heat loss Q_{rad} is the power of energy radiated from the entire BL surface

$$Q_{rad} = q_{rad}S_{BL} \quad (7.18)$$

where q_{rad} is radiation power density, W/m^2. The expression for q_{rad} was introduced in Section 4.4 where the optically thin layer approximation was used ($k_p\delta \ll 1$).

$$q_{BL} = 4n^2 k_P \delta\sigma T_{BL}^4 \tag{7.19}$$

where k_P is Planck-mean absorption coefficient (m^{-1}) of the shell material, n is refractive index of the shell material, and σ=5.67 10^{-8} W/m^2 K^4 is the Stefan–Boltzmann constant. Considering that the mass of the shell is $M_{shell} = \rho_{melt}\delta S_{BL}$ and using expressions (7.16, 7.18 and 7.19), we can write Eq. (7.17) as

$$\frac{T_{BL}}{dt} = -\frac{4n^2 k_P}{c_{melt}\rho_{melt}}\sigma T_{BL}^4 \tag{7.20}$$

If all parameters characterizing the BL shell materials are constant, Eq. (7.20) allows an analytical solution to describe the time evolution of the BL temperature.

$$T_{BL}(t) = T_{BL}(0)\left(1 + 3\frac{t}{\tau_0}\right)^{-1/3} \tag{7.21}$$

where $T_{BL}(0)$ is the initial BL temperature, ands τ_0 is characteristic time of radiative cooling at $T_{BL}(0)$.

$$\tau_0 = \left(\frac{4n^2 k_P}{c_{melt}\rho_{melt}}\sigma T_{BL}^3(0)\right)^{-1} \tag{7.22}$$

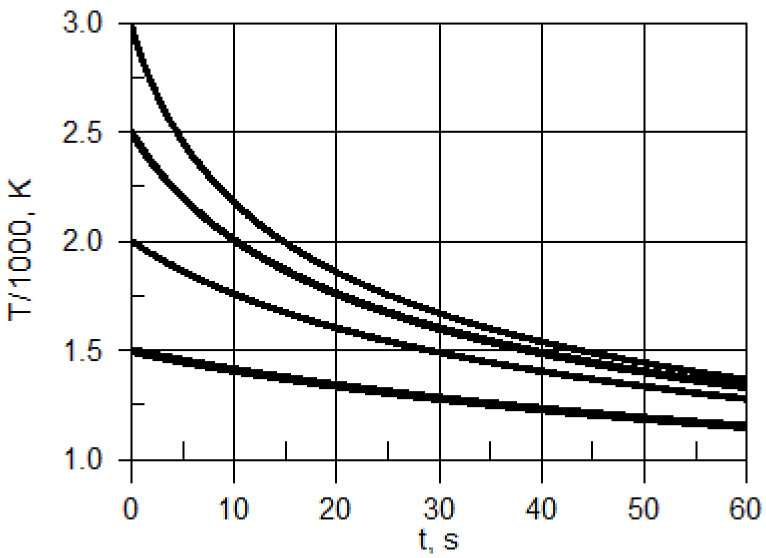


Fig.7.2. Change in the BL temperature due to radiative cooling for different initial values (k_P=0.2 cm^{-1}).

Fig. 7.2 shows examples of the time evolution of the BL temperature for different initial values. As before, the following constant physical parameters of the glass melt were used: c_{melt} =1.4 J/g K, ρ_{melt} = 2.3 g/cm^3, k_P=0.2 cm^{-1}. As you can see, the cooling rate of ball lightning is low, and its temperature remains high for a long time.

We draw attention to an important feature of the temperature equations (7.20) and (7.21), they do not include the geometric parameters of ball lightning. The solution depends only on $T_{BL}(0)$ and is applicable for any $D_{BL}(0)$ and $\delta(0)$. We emphasize that this situation becomes possible when the main source of the BL energy loss is radiation and the condition of optically thin layer ($k_p\delta \ll 1$) is met.

The presence of radiating impurities in the melt increases its absorption coefficient. Since energy losses due to radiation are proportional to the absorption coefficient, Eq. (7.20), impurities accelerate the BL cooling. An example with the absorption coefficient k_P=1.0 cm^{-1} is shown in Fig. 7.3. As can be seen, increasing the k_P value by five times leads to a noticeable decrease in temperature. However, even in this case, the BL temperature remains quite high (>1300 K) during the average observation time of BL, *t*<10 s.

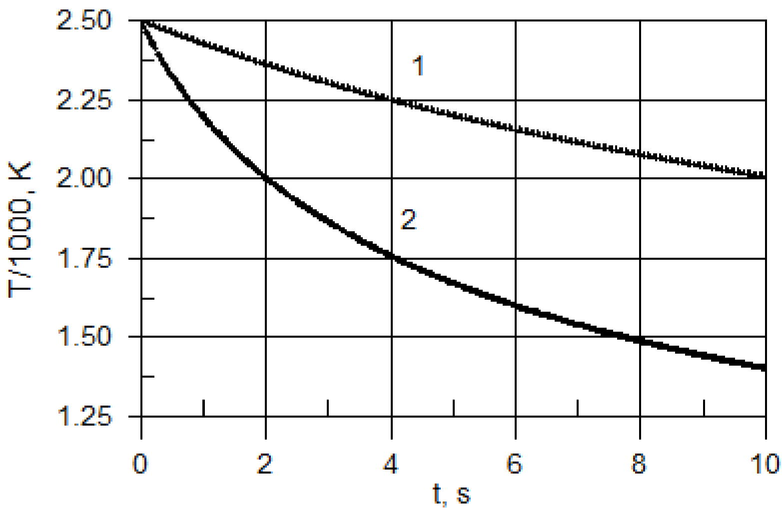


Fig 7.3. Change in the BL temperature due to radiative cooling for different absorption coefficients: 1 - k_P=0.2 cm^{-1}, *2* - k_P=1.0 cm^{-1}.

7.5. Purely free convective heat loss

In this section, we will consider the cooling of ball lightning caused by convective processes, assuming that the energy losses due to radiation are small. Then the Eq. (7.16) for the BL temperature can be written as

$$c_{melt} M_{shell} \frac{T_{BL}}{dt} = -Q_{conv} \quad (7.23)$$

We start with the situation when a smooth hot sphere is immersed in cold air. This situation is realized in the absence of the BL mass loss, i.e. when the right-hand side of Eq. (7.11) is zero. In this case, a laminar boundary layer develops near the sphere, and to describe this process, we will use the common relations for free convection heat transfer. The rate of heat transfer, measured in W, is

$$Q_{conv} = S_{BL} h (T_{BL} - T_{atm}) \quad (7.24)$$

where S_{BL} is the BL surface area, and h is the average heat transfer coefficient.
Using Eqs (7.3 and 7.4) for the shell mass, Eq. (7.23) can be transformed to

$$\frac{T_{BL}}{dt} = -\frac{h(T_{BL} - T_{atm})}{c_{melt} \rho_{melt} \delta} \quad (7.25)$$

The average heat transfer coefficient is

$$h = \frac{\chi}{D_{BL}} \mathrm{Nu} \quad (7.26)$$

where χ is the air thermal conductivity, W/m K. The average Nusselt number for sphere can be expressed by (*Incropera at al. 2007*)

$$\mathrm{Nu} = 2 + \frac{0.589 \mathrm{Ra}^{0.25}}{\left[1 + \left(\frac{0.469}{\mathrm{Pr}}\right)^{9/10}\right]^{4/9}} \quad (7.27)$$

where Pr is the Prandtl number and Ra is the Rayleigh number based on the characteristic length D_{BL}.

$$\mathrm{Ra} = \frac{g(T_{BL} - T_{atm}) D_{BL}^3}{T_m \nu \, \alpha} \mathrm{Pr} \quad (7.28)$$

where g is the acceleration due to gravity, and T_m is a medium temperature that is defined as

$$T_m = \frac{T_{BL} + T_{atm}}{2} \quad (7.29)$$

The required values of kinematic viscosity ν, thermal diffusivity α, and thermal conductivity k for air are calculated at T_m using correlation expressions from *McQuillan at al. 1984*.

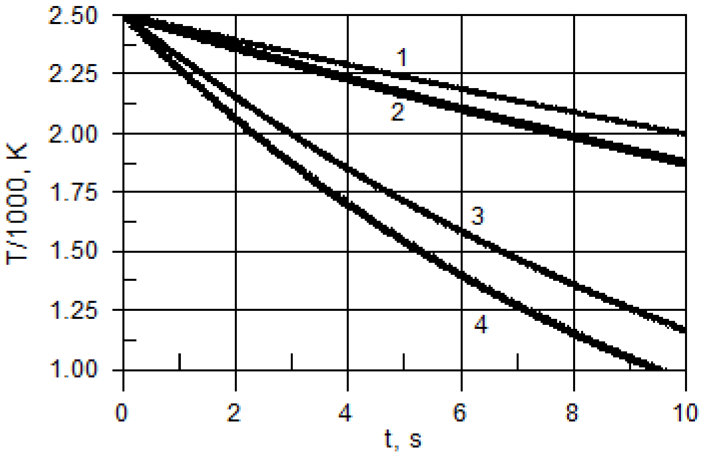


Fig. 7.4. Change in the BL temperature due to free convection cooling.

Curve number	1	2	3	4
D_{BL}, m	0.2	0.1	0.2	0.1
δ, µm	100	100	30	30

Fig. 7.4 shows examples of the change in the temperature of BL due to free convective heat transfer for different diameters D_{BL} and shell thickness δ. It should be noted that, unlike Eq. (7.20) for radiation losses, Eq. (7.25) contains the geometric parameters of ball lightning: the diameter and thickness of the shell. The latter parameter has the most significant effect on the cooling rate, which is inversely proportional to the thickness of the shell.

The given expressions and calculation results refer to the cooling of ball lightning by free convection. However, this regime is violated when a mass (gas and droplets of melt) ejections from the BL shell into the hydrodynamic boundary layer (Section 3.4). Considering this process will require significant efforts, which is beyond the scope of this work. We can only say that the ejection of mass reduces convective heat exchange, and when a large amount of mass is ejected, the boundary layer disappears, and heat exchange ceases. Since we do not have data for this cooling mode, the approximation of conductive heat transfer can be used for rough estimates. In the limit as Ra→ 0, Eq. (7.27) reduces to Nu=2, which corresponds to heat transfer by conduction between a spherical surface and a stationary medium (*Incropera at al. 2007*). Examples of calculations are given in Fig. 7.5. It is obvious that in this case the cooling rate is an order of magnitude less than with free convection.

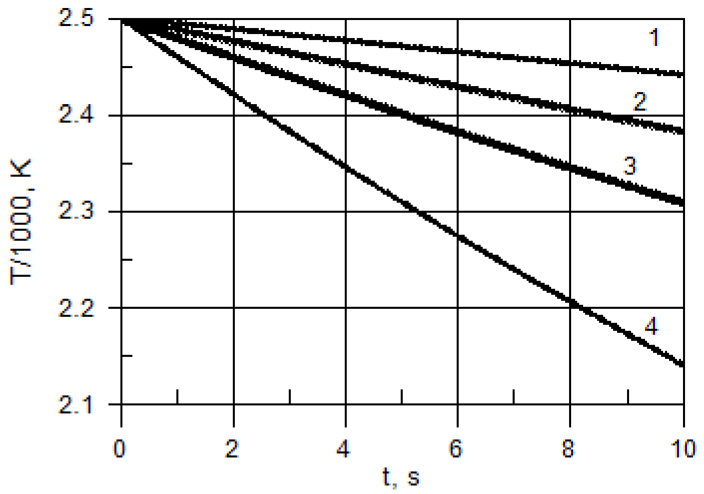


Fig. 7.5. Change in the BL temperature due to conductive heat transfer.

Curve number	1	2	3	4
D_{BL}, m	0.2	0.1	0.2	0.1
δ, μm	100	100	30	30

Example

To conclude this section, we give an example of time evolution of ball lightning, using the event description from the Introduction (Section 1, *Case 1*). Here we give only a fragment of the description.

> Lightning struck the dam. Two things happened simultaneously: the eyewitness felt a strong electric shock in his bare feet, and 20 meters away from him, a blinding ball the size of an orange rose into the air, appearing at the place where the lightning struck. The ball was red and glowed brighter than a 200 W incandescent lamp. Its surface was clearly defined, and it made a hissing sound with a rare crackling sound. It got to a height of 3-4 m and then flew along a smooth trajectory 10 m at a speed 1 m/s, descended to the ground, and exploded with a loud bang.

We can see inconsistencies in the description of the ball lightning by eyewitness. *The ball was red*, which corresponds to the color temperature of about 1500 K. At the same time, the eyewitness estimates the brightness of the BL as greater than the brightness of a 200-watt incandescent lamp. The correlated color temperature (CCT) of such a lamp is 3000 K (Lighting Design and Simulation Knowledgebase). It is hard to imagine that having seen a red object, we could confidently compare it with another very bright light orange object. So, we would interpret the situation simply: the object was bright and had an orange-red color.

The BL trajectory consists of two sections: a rapid rise to a height of 3–4 m and subsequent smooth movement by 10 m over 10 s. We will consider only the second section of the trajectory. At the moment of appearance, the BL temperature can be quite high. However, during the ascent, the ball lightning cools down, and we will assume that at the beginning of the second section of the trajectory its temperature is 2100 K. We will also accept the following initial parameters of ball lightning: diameter $D_{BL}(0)$=0.15 m and the thickness of the shell δ=50 μm.

When calculating the BL temperature, two sources of energy loss were considered: radiation and conductive losses. The radiation losses are calculated using the melt absorption coefficient k_P=0.2 cm^{-1}. To describe the heat exchange between the ball lightning and ambient air, the conductive heat transfer approximation is used (instead of free convection). We chose this approximation because the ejection of matter from the BL surface prevents the occurrence of free convection. The noise produced by the ball lightning indicates the ejection of matter.

The calculation profiles of temperature and heat loss power are shown in Fig. 7.6. As can be seen, the cooling of the ball lightning occurs mainly due to radiation losses, although their power is relatively small.

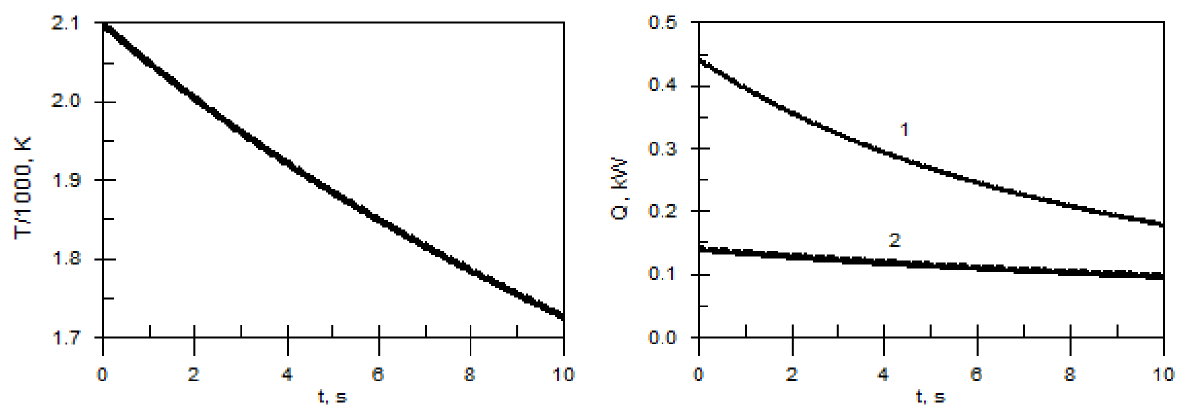


Fig. 7.6. Changes over time in temperature and power of heat losses due to radiation (1) and conductive transfer (2); $D_{BL}(0)$=0.15 m, δ=50 μm.

To maintain the integrity of the BL shell, the pressure of the filling gas must remain equal to atmospheric pressure when the ball lightning cools. This is achieved by reducing the BL volume and thereby increasing the density of the filling gas. The BL diameter decreases respectively, and this decrease at the end of the BL existence is about 6%. The eyewitness would hardly have noticed this. The BL color has also changed little during this time (see Section 5, Table 5.2), it was orange-red.

The luminance of ball lightning (L_{BL}) was calculated as a function of time. This value is highly dependent on temperature and decreased from 1500 to 100 cd/m² over the last 10 s of the ball lightning's existence. The 15-fold change in luminance contradicts numerous eyewitness reports: the brightness of ball lightning changes insignificantly. And here we would like to comment on this circumstance.

The brightness of an object can be determined by two quantities:

- objective photometric quantity obtained by measurements or calculations - luminance, measured in cd/m²,
- subjective impression—a relative strength *S* of visual perception of light.

Subjective impression *S* is a nonlinear function of the intensity of the source of perceived radiation. According to *Stevens 1961*, the *S* value could be described by a simple power law:

$$S = \left(\frac{L_{BL}}{\overline{L_{BL}}}\right)^n \qquad (7.30)$$

where $\overline{L_{BL}}$ is a reference value of luminance. This dependence is applicable when the luminous object is in a dark, undisturbed environment. The *n* value depends on the visual angle *ω* at which the luminous object is seen. For circular light spots covering a visual angle of $\omega = 5°$, *n*= 0.333. The exponent *n* increases with distance from the observer and in the point limit ($\omega \to 0$) *n* is close to 0.5 (*Ware 2019*).

The law (7.30) can be used to describe the perception of brightness by a person observing ball lightning. The condition of a luminous object being in a dark environment is met during a thunderstorm. Taking the ratio of the maximum and minimum values of the BL luminance equal to 15 and substituting it in Eq. (7.30), we get *S*≅2.5. The movement of the BL relative to the eyewitness causes a change in the exponent *n* in expression (7.30), which also smooths out the change in the perceived brightness. Thus, the observer will perceive a change in the brightness of the object of less than two times, whereas this change is 15 times. We believe that this result is quite consistent with the eyewitness observations presented in the description.

7.6. Summary

This section examines the time evolution of ball lightning immersed in cold air. A system of equations describing the change BL parameters over time is derived. The system includes two differential equations for mass and temperature, as well as algebraic equations for the geometric and thermodynamic characteristics of the ball lightning elements. The initial conditions for the system are the diameter, shell thickness, and temperature of the ball lightning. An exact solution to the system is currently impossible due to the lack of rate constants for the main processes. Therefore, two limiting cases are considered: purely radiative and purely convective heat transfer.

When considering the thermal radiation, we assume that the gas filling the ball lightning is transparent (and accordingly does not emit), and the source of radiation is only the BL shell formed from molten glass. We believe that the absorbing and emitting energy levels are in equilibrium at the BL temperature T_{BL}. In addition, the optical thickness of the shell is small, and we can use the optically thin layer approximation. Calculations based on these approximations have shown that at the initial stage of cooling (about 10 s), T_{BL} does not fall below 2000 K if the initial temperature exceeded 2500 K. The next cooling stage is slow and T_{BL} remains above 1500 K for the following 30 s. Based on this, it can be argued that for long-lived ball lightning, radiative cooling is not a limiting factor for its existence at a high initial temperature.

Another process of cooling ball lightning is natural convection. Numerical results were obtained for smooth surfaces of ball lightning. The cooling rate was calculated using generally accepted correlation expressions (*Incropera et al. 2007*). Calculations showed that ball lightning with a thin shell, δ < 50 μm, cools down quickly and is unlikely to remain hot for more than 5 s. Ball lightning with a thicker shell, say, more than 100 μm, can remain quite hot (> 2000 K) for about 10 s. The activity of micron-sized gas bubbles, which form a foamy structure of shell material, leads to mass ejections (gas and droplets of melt) from the ball lightning shell into the boundary layer. As a result, convective losses are reduced or may disappear completely.

References

Incropera, F. P., DeWitt, D. P., Bergman, T. L., & Lavine, A. S. *Fundamentals of Heat and Mass Transfer*, 6th edn, 2007.

Priven, A. I., & Mazurin, O. V. (2005). Heat capacity of glass melts. *Properties of Glass-Forming Melts*.

Stevens, S. S. (1961). To Honor Fechner and Repeal His Law: A power function, not a log function, describes the operating characteristic of a sensory system. *Science*, *133*(3446), 80-86.

Ware, C. (2019). *Information visualization: perception for design*. Morgan Kaufmann.

8. Conclusion

8.1. Main results

The work proposes a model of ball lightning. We consider ball lightning as a thin-walled bubble of foamed molten glass filled with hot gas. The shell material of the BL—glass melt—is formed from soil components because of an electric discharge initiated by an ordinary lightning strike into the ground. The bubble is inflated by gases escaping from the discharge channel.

The parameters of the BL are as follows. The thickness of the shell may be from tens to hundreds of micrometers, and the mass of the BL reaches several tens of grams for average BL sizes (20–40 cm). The pressure of the hot gas filling the ball lightning is only slightly different from the atmospheric pressure, which ensures the integrity of the BL shell. Ball lightning may not have internal energy sources; it acquires energy at birth—this is the total enthalpy of its shell and filling gas. The initial temperature of long-lived ball lightning is about 2500 K, this value decreases due to the cooling of the BL. Ball lightning may or may not have an electric charge, this is not a decisive factor for its existence.

The appearance of the surface of ball lightning is largely determined by the activity of micron-sized gas bubbles that form the foamy structure of the shell material. When approaching the surface of the shell, these bubbles burst. As a result, hot gas and nanodroplets are ejected into the surrounding air. The eyewitness perceives this as sparks from the surface of BL and hears a buzzing or hissing sound. The nanodroplets cool in the air, turning into glass nanoparticles. The resulting cloud of nanoparticles scatters the light of the ball lightning, which the eyewitness perceives as a halo. In addition, the release of hot matter from the surface of BL creates a protective layer that prevents direct contact between the ball lightning and the surrounding cold air, which reduces heat loss.

The physical properties of the shell material—molten glass—depend on the conditions of formation of ball lightning in a soil electric discharge. If the initial BL temperature is low, T_{BL}< 1500 K, the glass melt has a strong network of unit cells. Collective vibrations of the network generate intensive IR radiation, which causes rapid cooling of the ball lightning and its collapse. If the initial BL temperature is high, about 2500 K, no network is formed. As a result, the radiating vibrational modes cannot arise, and the melt becomes non-radiating in a wide spectral range (approximately 0.5-25 μm). If the filling gas also emits weakly (hot air with a small admixture of radiating components) then the radiation losses of BL are small. This means that high-temperature ball lightning with a shell of foamed molten glass is well protected from heat loss and can exist for a long time, >10 s.

Ball lightning can have different colors, which are due to the presence of minor concentrations of oxides of the fourth period transition metals (from Ti to Cu). The absorption coefficient of ions of these metals has peaks in the visible region, and the BL color depends on the position of these peaks: iron oxide gives a blue tint, and manganese oxide gives a yellow-green tint. Other shades of color occur in the presence of other transition metal oxides.

8.2. Some additional comments and a possible future direction

This work presents general features of ball lightning but does not consider its movement and interaction with other objects. We believe that all these facts can be explained using the model proposed here.

Regarding the free movement of ball lightning in open air, electrostatic force and an upward air current can support ball lightning. The electrostatic force arises from the interaction of the electric charge of BL with the field of residual charge in the ground where ordinary lightning struck. The upward air current is formed due to contact of cold air with the ground surface, heated by solar radiation before thunderstorm. Furthermore, if ball lightning spins within this upward air current, the Magnus force acting on the ball lightning is generated. The horizontal component of this force sets the ball lightning in horizontal motion, which explains why ball lightning can move against a light wind. The nature of ball lightning's movement in enclosed spaces requires special consideration.

Since ball lightning has a high temperature (>1500 K), it leaves traces when it comes into direct contact with objects: burn marks appear on organic objects, and melt marks appear on metal objects. It is quite natural that a bubble of molten glass can cut a hole in window glass.

Ball lightning can also pass through window glass without leaving a noticeable trace. This requires the following conditions. The air pressure on the side of the glass where the ball lightning was appeared must be slightly higher than the pressure on the opposite side of the glass. In addition, the ball lightning must slowly approach the glass and touch it without deforming. At the point of contact, the glass heats up and melts, forming a small channel of melt across the entire thickness of the glass. Due to the pressure difference, ball lightning can pass through the glass along this channel. After the ball lightning detaches, the liquid channel solidifies and becomes barely noticeable. It should be noted that the material of the BL shell (glass melt) wets the window glass surface, and therefore capillary forces play a significant role in this process.

We have not studied in detail the mechanism of disappearance of ball lightning. Estimates have shown that ball lightning has sufficient energy to cause damage to objects near it at the moment of explosion. In open spaces—in the open air or in large rooms—ball lightning, as a rule, does not cause destruction.

In this work, not all structural elements, properties and behavior of ball lightning are defined with sufficient accuracy and detail. A more complete and accurate description of ball lightning would require a more complex model. However, in our opinion, the development of such a model makes sense after conducting experiments to obtain bubbles from molten glass that have the properties of ball lightning. This means that it is necessary to create a foamed molten glass at a temperature of about 2500 K using a pulsed electrical discharge. The next stage—blowing the bubble—should be carried out with hot air at a temperature close to the temperature of the melt. Obviously, a very important issue is the component composition of the material for the melt. The best solution would be to take soil material from the place where eyewitnesses observed ball lightning because of the strike of ordinary lightning to the ground.

Perhaps it would be more reasonable to study the phenomenon of ball lightning not as a whole, but to investigate its individual properties. For example, to create a foamed melt under high pressure, tens of bars, and quickly transfer it to the environment. The goal of the study is the reaction of foamy material to abrupt changes in external conditions. Another important subject of research is the change in the spectral optical properties of glass melts with temperature: a comparison of the optical properties at low temperatures, <1500 K, when a network of unit cells is formed and at high temperatures, >2500 K, when the network is absent.

The behavior of bubbles is more conveniently studied using non-oxide glass melts. Among the materials employed in infrared optics, one can find glasses with a low melting point and weak radiation in a wide IR spectral region. These materials can be used to illustrate the passage of a bubble of melt through small holes or a thin, cold sheet of glass of the same chemical composition.

In conclusion, we note that the material of ball lightning can be not only molten glass but also molten polymer. This is evidenced by eyewitness reports of the occurrence of ball lightning from electrical networks or electrical appliances in residential premises, which could be associated with the melting of polymer insulation. Probably, for the same reason, ball lightning occurs in airplanes.