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On the relation between theoretical and experimental components in the papers on ball lightning

(reply to M L Shmatov's comments [*Phys. Usp.* **63** 96 (2020); *Usp. Fiz. Nauk* **190** 107 (2020)] on the paper "On the possibility of making natural ball lightning using a new pulse discharge type in the laboratory" [*Phys. Usp.* **62** 92 (2019); *Usp. Fiz. Nauk* **189** 95 (2019)])

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Abstract. In his letter [*Phys. Usp.* 63 97 (2020); *Usp. Fiz. Nauk* 190 107 (2020)] Shmatov expresses a high opinion of the experimental part of Shabanov's paper [*Phys. Usp.* 62 92 (2019); *Usp. Fiz. Nauk* 189 95 (2019)] but presents some critical remarks on the theoretical character. We show in this reply that these remarks are based on a misunderstanding related to an excessively unambiguous treatment of elementary physical laws ignoring the possible variety of their manifestations under particular conditions.

Keywords: Gatchina discharge, long-lived luminous formations, macroscopic charge separation, charged bodies, average breakdown electric field strength, ball lightning

Not all of that which seems obvious at first glance occurs in reality under certain conditions. For example, it is known that the interaction between two like charged conducting spheres does not follow the Coulomb law at close distances, but not to such a degree that they attract each other. But Saranin considered this problem in 1999 [1] and found numerically that the attraction of two like charged conducting spheres is a common phenomenon, like their repulsion. Later, Saranin and his coauthor refined the theory and showed this experimentally in their paper "Theoretical and experimental investigations of the interaction of two conducting spheres" [2].

This is a short introduction to the statement in [3], which is additionally taken out to the abstract in front of the main text and is formulated as follows: "... the estimate of the average ball lightning charge presented in that paper corresponds to an impossible situation with an approximately 100-fold excess of the electric field strength near the outer boundary of the ball lightning over the air breakdown field under nearly standard conditions." It seems that having repeated this statement twice, the author of [3] considers it the main absurdity in [4]. We turn to book [5] (a textbook for students) by Bazelyan, an experimenter with 30 years of experience, and Raizer, a well-known theoretician in gas discharge physics. This book, together with paper [2], is an excellent guide to analyzing processes involving charged bodies. This question was not considered in detail in [4], and only reference [6] to our paper was given (reference [15] in [4]), where this 'problem,' in the opinion of the author of [3], was considered. In [6], we cited book [7] because it was published later than book [5] by the same authors, and these two books supplement each other. The question about the existence of charged bodies with electric fields on their surface exceeding the 'breakdown' field (according to the terminology in [3]) was considered in [5, 7] at the level of laboratory work. In his calculation, the opponent [3] used the 30 kV cm^{-1} 'breakdown' field required, in his opinion, to break a virtual gap (because it is necessary to break through some specific millimeters, centimeters, or meters) and obtained the 'impossible situation' with the '100-fold excess' of the breakdown field for this air gap. Indeed, to initiate a corona discharge, the 30 kV cm^{-1} field is required on the electrode surface. It is known that a corona discharge can last for many hours [5]. But in general, the breakdown requires the electrode voltage that is calculated based on 'the average breakdown field strength' for air gaps under standard atmospheric conditions [5]. This quantity is the average electric field in the gap (that is where a virtual gap appears) and has a rather broad range depending on many parameters and, with good accuracy, lying in the interval from 30 kV cm^{-1} to 5 kV cm^{-1}.

We now consider a problem for laboratory work. We assume that ball lightning 5 cm in radius (the size that is often observed) moves parallel to the ground at a height of 1.5 m (a typical height). It is necessary to calculate the voltage that must be applied to this ball (ball lightning) with respect to the ground to cause the possible breakdown of the air gap and to find 'the electric field strength near the outer boundary of the ball lightning' (according to the terminology in [3]). To produce the breakdown of this air gap, a voltage of 5 kV $\text{cm}^{-1} \times 150$ cm $=$ 750 kV is required (disregarding the specificity presented in [5–7], which increases this voltage manyfold). The required value of 5 kV cm^{-1} of the average breakdown electric field strength is chosen to maintain the options for a discussion with the opponent, because the electric field on the ball lightning surface in this case is minimal and does not coincide with the '100-fold excess' given by the opponent, which would make

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further discussion meaningless. This gives a 150 kV cm^{-1} field 'near the boundary', which is only five times greater than 'the value corresponding to the breakdown' (using the terminology in [3]). The opponent uses relative quantities; therefore, already for the possible 150 kV cm^{-1} field on the surface in the given example, the average ball lightning would exhibit not '100-fold excess', which is awful, but only a 20-fold excess of the field on the ball surface, which does not seem so awful.

Physical mechanisms of the existence of bodies with a surface electric field exceeding the breakdown field ($E > 30$ kV cm^{-1}, according to [3]) were considered many times already in the introduction of [5]. Several types of corona discharges were discussed under different physical conditions by varying the type and diameter of electrodes and changing the interelectrode gap and the average field between the electrodes, the voltage increase rate, the polarity, etc. The last paragraph of the introduction, entitled "What should be called a breakdown," clearly explains the breakdown concept. We consider particular conditions for the average ball lightning to exist as a body with a unipolar charge. This requires the study of its formation conditions, which was performed in our paper [6]. This work uses the basic ideas and experimental data on the possibility of bodies with a relatively large electric unipolar charge to exist [5, 7] and knowledge of the mechanism of a downward negative leader stroke [8] and is based on data obtained in our experimental work. A theoretical analysis of the sources presented above allowed us to state the following in our paper [6]:

"Let us estimate the minimal formation time of an average ball lightning based on our model of ball lightning formation from the head of a linear lightning leader. Bazelyan and Raizer [2] (reference [7] in this paper), describing a stationary corona, point out that, if the ball potential (they consider a lightning rod with a ball at the end) increases slowly enough, less than 3.6 kV μs^{-1}, then due to stabilization of the field in the corona, the ionization wave is not detached from the electrode and the initial streamer flash does not occur, etc. To confirm this statement, they present an experiment in which the average electric field was increased up to 20–22 kV cm^{-1} in a gap about tens of centimeters without a breakdown, whereas the gap breakdown usually occurs beginning from 5 kV cm^{-1}. They use in calculations the field in the corona $E_{cr} = 30$ kV cm^{-1}, which is assumed constant. We will use data on the maximum rate of the ball potential increase without the air gap breakdown applied to the liner lightning leader, its stop and creation of a ball lightning. The mean potential carried to Earth by the leader is about 30 MV. Based on the maximum rate 3.6 kV μs^{-1} of the potential increase on the forming ball lightning body, we find that the minimal time required for formation of the average ball lightning is no less than 8.5 ms $\approx$ 0.01 s."

A charge on any charged body tends to 'drain'. The electric field on a body can be reduced when the volume charge around the body (for example, draining from the body) induces a charge of the opposite sign on it [5, 7]. Charge draining and the corona discharge that can appear if the field on the body exceeds the corona ignition threshold 'can be distinguished only in a dark night' [5]. We have been fortunate in obtaining a photograph of the corona in a dark room, where the corona is seen worse, being mainly distinguished as a region through which the distorted details of the environment behind the ball lightning can be seen.

As pointed out in [6], we can estimate the charge of our object: "Let us estimate the charge of a laboratory ball lightning (Fig. 1) 13 cm in diameter with the 2-cm thick corona by the maximum corona-field criterion ($E_{cr} = 30$ kV cm^{-1}). The charge of the ball lightning presented in Fig. 1 is about 2×10^{-6} C according to this criterion." Here and hereafter, the charges are given in the absolute value.

The charges of our objects measured in experiments and estimated from the corona diameter (see above) and the energy released during melting of a nichrome wire are presented in [4]. The charge value depends on the time when the charge is measured or estimated, and is about 2×10^{-6} C in the particular case that corresponds to the 43 kV cm^{-1} apparent field on the ball lightning body, exceeding the breakdown field quoted in [3] by a factor of almost 1.5.

The corona discharge radius of the 'average ball lightning' [4, 9] slightly exceeds one meter and cannot 'reach' the breakdown, for example, with the ground under the conditions described above (in the laboratory work).

A detailed answer to Shmatov's comments (almost four times longer) will soon be presented on the site: https://www.researchgate.net/profile/Gennady_Shabanov2/research.

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