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Ad Initio Principles of the Dipole Dynamical Model of Ball Lightning

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Abstract There are exposed principles of the dipole dynamical model of ball lightning (DDM BL) which was proposed recently and studied in detail for the first time by the author [3]. Longitudinal asymmetry of dipole BL with the recoil force of rear jet which compensates force of acting atmospheric electrical field on ions, leads to BL steady movement in atmosphere with the energy pumping of traveling forward electron cloud by atmospheric field that in turn explains the very long BL lifetimes. Stability of ball lightning is due to the presence of two free parameters of BL as it is thermodynamically non-equilibrium plasma. Energy balance is achieved with influx of energy from the atmospheric electric field and radiation losses and related with them energy losses of resistance to fireball movement in atmosphere. To all this we must add the condition of integrity BL as a whole with non-electrostatic friction clutch coupling BL electron cloud with the all BL particles mass. The proposed theoretical pioneering model of Ball Lightning is the only one of this kind, with no analogues, explaining the most part of the observed versatile features of BL. Detailed calculations, evaluations, studies and tables of variant options are presented in my manuscript on DDMBL in ArXive.org [3].

Keywords Ball lightning, Dipole dynamical model of ball lightning, Stability and model predicted features of ball lightning heuristic theory of ball lightning, Long life ball lightning

1. Introduction

Ball lightning (BL), as a mysterious manifestation of atmospheric electricity, has generated a lot of hypothetical explanations, as a rule, only for some of its observable separate characteristics. Results of numerous sporadic observations and some of the most developed models of BL, sometimes with an very exotic character, are set out detailed in a recent comprehensive review [1]. At the same time, I proposed a new dipole dynamic model of BL (DDM BL) based on the observed features of BL and natural relations that characterize the thermodynamically nonequilibrium rarefied weakly ionized air plasma $T_{\mathrm{m}} \sim 10^3 K \ll T_e \sim 10^4 K$, which qualitatively explains almost all of the observed features of BL in their entirety [2-6] with the most detailed and conclusive exposition in [3]. In the following we present the fundamental principles of the model, confirmed by estimates and calculations given in [3] which can be used in the following calculations.

Any model must explain and quantify the properties of BL, the most frequently observed in the aggregate: BL sizes of about 5 - 20 cm; BL speed, often of the order of a few m/s; related to BL energies of explosion with energy densities up to $\gtrsim 10^{12} J/m^3$ [1]; rounded form, sometimes transforming into a "snake", with penetration through the cracks; the BL lifetime up to many tens of seconds; moderate brightness, such as a 100-watt lamp; a relatively low temperature T_{m} of about 1000 - 3000 K, sometimes enough to cause a partly burn or to melt and to press out the glass pane; BL behavior at the end of its life: the disappearance or explosion.

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2. Basic Principles

1. The dipole model BL can exist only at the observed forward movement of BL under the force influence of the atmospheric electric field. The driving force of BL translational motion are electrons which are affected by the effective force f of the external electric field $f = |e| N_e E_{eff}$. With a uniform translational motion of BL electrons entrain ions, and with them the whole mass of BL consisting of a rarefied weakly ionized plasma of charged and neutral particles of air at a pressure of ~ 1 at. External electric force $-|e| N_e E_{eff}$ acting on the ions is almost completely compensated by the recoil jet produced by collisions of ions with molecules of cold dense air behind the BL. It is also possible accelerated BL motion in a certain range at which electrons gain energy and momentum from the external electric field which is then

redistributed to the whole BL due to predominantly inelastic collisions of electrons with molecules while maintaining integrity of BL as a whole. Condition of BL movement as an integer with a predominance of transport of acquired by electrons momentum to BL by elastic and inelastic collisions is the equation [3]

$$E_{eff} = \gamma E_{env} = \frac{\pi}{3}\frac{m_e}{m_{av}}|e|\frac{r_{FB}}{n_m}n_e n_i, \qquad (1)$$

where E_{env} is real atmospheric electric field, γ is polarization factor m_e is electron mass, m_{av} is average mass of the particle in BL, n_m is density of BL particles, $r_{FB} \equiv r_{BL}$ is BL radius, $n_e \sim n_i \ll n_m$ are electron and ion densities.

2. The observed integrity of BL can only be explained by the fact that at BL movement with the same effective acting forces of atmospheric field on the electrons $|e|N_e E_{eff}$ and the dipole interaction electrons/ions (respectively electronsall BL mass), the coupling BL with electrons ("friction clutch") at enough small acceleration is ensured by the necessary to equalize the accelerations with mass ratio M_{BL}/M_e times larger BL pushing force of mainly inelastic collisions of electrons with molecules of BL. Formula (1) is obtained by equating the force of interacting of the atmospheric electric field and the electron cloud of BL to the full force of dipole interaction electrons with all BL mass. Due to the existence of observed BL as a single identity, electrostatic part ions-electrons of this interaction is a fraction M_e/M_{BL} of the total force of the nonelectrostatic friction clutch of electrons-BL mass.

Atmospheric electric field tracks with the force $f_{tr} = |e|\gamma E_{env} N_e$ electron cloud which is firmly tied to BL by the friction clutch force $|e|E_{eff}N_e \bullet (M_{BL}/M_e)$ at the force of atmospheric electric field acting on the ion cloud with the force $\left(-|e|E_{eff}N_i\right)$ which is compensated by the rear recoil jet.

Note that the friction force is a force of special kind which does not possess direct attraction property.

Transmission of excess electron momentum to a huge (as $M_{BL}/M_e \sim 10^5$) mass of BL is accompanied with very large rate of this process with an estimated very small time τ of momentum transfer in multiple collisions

$$\tau \sim \frac{m_m}{m_e} \bullet \frac{1}{n_e \overline{v}_e} \bullet \frac{1}{\sigma_e(T_e)N_e}, \qquad (2)$$

where m_m is average mass of BL particle, n_m is their density, $\overline{v}_e \sim \sqrt{kT_e/m_e}$ is electron velocity, $\sigma(T_e)$ is momentum transfer effective cross section of inelastic (and elastic) electron-molecule and ion collisions in BL. At the same time there is acceleration growing of T_e, n_e, the polarization factor γ and attractive field $E_{eff} \sim \gamma E_{env}$. The exponential dependence of cross sections of inelastic collisions electron-molecule on T_e c an lead to the presence of the lower threshold $E_{eff} \sim E_{th}$ of existence BL.

This expression determines some critical acceleration with the destruction of BL as $a_{crit}\tau^2/2 \ll r_{BL}$, where a_{crit} is maximum permissible acceleration. Nonetheless, analysis of kinematical instability of BL with the ability of its "rupture" remains, apart from the acceleration/ deceleration instability, an open problem.

3. Because of the polarization of the plasma fireball as collective phenomenon, effective field acting on the charged particle can be estimated approximately as γE_{env} where E_{env} is real atmospheric electric field reaching several kV/cm but less than the field tension of a lightning streamer breakdown. Polarization coefficient γ is determined by the critical ratio of the impact force on the electron $|e|E_{env}$ and the Coulomb interaction between neighboring BL electrons of the order: $e^2 n_e^{2/3}$, i.e. usually $\gamma \lesssim E_{eff}/|e|n_e^{2/3}$. Thus, values E_{env} used in [2] ought to be renamed to E_{eff} and to confront them much more greater values of the external atmospheric electric field E_{eff}/γ, which in [2] are not given, keeping all other results. Typical values [3] are: $0.01 \lesssim \lambda < 1$; E_{eff} in the range from about 10 V/cm to several hundreds V/cm, and E_{env} up to ~ 10 kV/cm

4. Due to the ambipolar diffusion, BL has a significant positive charge [3], what does not prevent its forward movement (due to the effect of momentum compensatory air jet behind BL), but creating the effect of a large surface tension. At sufficiently high electron temperature at which the ionization rate is much greater than the loss rate of ambipolar diffusion, the positive charge of BL provides its integrity. BL always travels with its negative charge directed forward.

5. DDM BL is not possible without account for substantial thermodynamic non-equilibrium $T_e \gg T_i = T_m$ of plasma fireball. This was accounted by introduction of the free non-equilibrium parameter α with which the equilibrium radiation at a temperature T_e and pressure 1at (using the estimated blackness degrees ε at the base of hemispherical volume [7]) was decreased in α^2 while reducing the density of electrons in α times. Parameter α and the size of BL (or, equivalently, the size r_{BL} and E_{eff} or E_{env}, either equivalently any other pair combinations of parameters) can be regarded as two

independent free parameters of BL.

6. The presence of two free parameters leads to a natural presence of local minima, for example, for the radius of BL in its dependence on the electron temperature T_e that corresponds also to the potential energy minimum depending on the temperature, or equivalently in other similar pair combinations determining the stability of BL. Such minima not exist in the case of the plasma fireball thermodynamic equilibrium, which in this case has moreover impossible enormous energy radiation [2, 3].

7. The energy rate $|e| N_e E_{eff} dx / dt$ that fireball gets at its movement in atmospheric electric field is spent mainly to the radiation (with the account for non-equilibrium parameter α) and on the resistance to movement in atmosphere. However, loss of the energy by radiation, it would seem, does not create a direct mechanical momentum of resistance to movement of BL. The mechanism for the creation of the momentum loss is electron-ion recombination with transfer of the electron momentum to forming neutral molecules, creating a counter recoil jet in air in front of the electronic part of BL. Thus, the radiation carries away half of the incoming energy, and the other half is spent in overcoming the resistance of counter recoil momentum resulting from recombination and make up half of the recoil momentum $f \bullet \Delta t$ opposing movement of BL. The balance of these energies and BL traction determine the wide range of calculated speeds of BL movement.

8. In the framework of DDM, parameters of various BLs were calculated in the form of tables that are estimative in nature (toy calculations) demonstrating the possibility of simultaneous good agreement with numerous observations [3].

9. It should be noted that the estimated maximum energy density in DDMBL does not exceed $(10^8\text{-}10^9)$J/m^3, respectively, thus the value given in [1] up to -10^{12} J/m^3 can be attributed to the impact of BL as a trigger of largescale local atmospheric discharge collecting electricity from a large volume of thundery electrified air. In this case, BL is an indicator of its supporting large electric fields in surrounding atmosphere, but BL itself has relatively limited resource of energy.

10. BL can be accompanied with low-frequency noise (generated by the air recoil jet behind BL) and high frequency sound (generated by an analogue of the Langmuir oscillations of electrons in moving BL [3]).

11. BL lifetime reaching many tens of second, is determined by inhomogeneity of the atmosphere, fluctuations of the atmospheric electric field and acceleration instability of BL.

12. BL requires for its emergence the seed discharge creating a hot rarefied cloud of non-equilibrium plasma with low density. Let imagine two hypothetical extended (flat or linear) parallel virtual electrodes between which the electric field is of the order of a few kV/cm , which causes a breakdown on accident windblown object (wet leaf of a tree, etc.) or small roughness or sharp on the electrode to form narrow plasma channel. We can assume that the energy imparted to electrons by the electric field will be transported to heavy atoms and molecules, and the latter will not spend so much energy by heat conduction, as for the across expansion, which will result in a volumetric highly rarefied moderately hot plasma cloud to form BL mainly near objects at the Earth surface. BL is a fairly rare phenomenon because of the incidental occurrence of a seed discharge.

13. Continuously ongoing virtual "collapse" of BL (recombination) is offset by an opposite polarization repulsion of ion and electron clouds by an external electric field and the simultaneous recovery processes of ionization at high enough (~ 10 000 - 12 000 K) electron temperatures. The "dissipation" of BL is prevented by attraction of electrons with the excess positive BL charge and at the same time with filling up ions by ionization which compensates the loss of ions as in the ambipolar diffusion and recombination. BL existence is due to balance of these processes (plus the stability condition in the presence of two free parameters) with the energy supplying by the atmospheric electric field at BL movement in the positive direction (the electron part of the dipole forward) along the electric field lines and at the same time inseparable from BL recoil jet of air behind generated by the energy of the atmospheric electric field expended in equal amounts to creating the backward jet and the summed energy loss of radiation and resistance to BL movement.

3. Cluster Model

In this paper we have not considered the completely different widespread cluster model of ball lightning [8], [9] that binds a fireball with a very complicated fine-cellular structure of clusters of burning or excited impurities produced during a lightning impact to a particular object. It is assumed that the cluster forms a rigid frame which supports the shape of a fireball with a very high energy content of the surface electric charge.

This model seems to have a visible confirmation in observations the behavior of the tiny "ball lightning" produced under specific electrical discharges between metal electrodes in electric/magnetic field and may explain, in our opinion, with all its plausibility, only special forms of ball lightning. The main problem of such (static) models is the presence of an energy reserve (obtained from linear lightning?) which is required to explain the observed BL lifetime up to ~ 100 s. Only movement along the lines of the atmospheric electric field gives life to a fireball and is inseparable from it.

4. Conclusions

All above mechanisms with their close interconnection make the DDMBL very natural and at the same time

consistent with the most part of available observations. Region of BL existence parameter space is constrained by the calculation of the many BL toy variants [3]. The estimates and toy calculations set out principles of DDMBL within which it ought to perform future improved calculations to create a complete theoretical model which includes the entire set of multiple processes responsible for existence of BL.

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