Ball lightning: elusive behaviour depending upon proton conductivity

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Ball lightning is pictured as a negatively charged spherical bubble with a shell of oriented dipolar water molecules. The bubble is balanced by outward electrostatic stress and inward forces of atmospheric pressure and/or surface tension forces. Because of the low electronic conductivity of condensed water, electrons slowly leak away from the surface in the radial direction, forming a corona. The charge on the ball decays exponentially with a characteristic mean life time depending on the electronic conductivity of the shell. Protons confined in the shell induce an electric conductivity to the shell in the tangential direction. When the bubble is deformed by an inductive field, mobility of the protons develops a higher charge density in the more curved regions of the shell. Differential electrostatic stress generates a feedback propelling force enabling it to bounce off from surfaces or penetrate through holes.

Keywords: Ball lightning, corona discharge, electrostatic stress, proton conductivity, surface tension.

THE fascinating phenomenon of ball lightning (BL) continues to resist complete theoretical explanation and reproducible laboratory demonstration[1–9]. BL originates in the regions of electrical activity in the atmosphere as a luminous sphere of diameter 10–30 cm, drifting at near neutral buoyancy. It bounces away from surfaces and sometimes emits bright sparks on encounter with an obstacle. The ball lasts for several seconds and vanishes either explosively or silently. Most intriguing are the reports which indicate that the BL passes through minute cracks and holes and restructures to its original spherical form[4]. The models proposed to understand BL fall into three main categories: (i) plasma confinement in air, (ii) source of electromagnetic energy and (iii) chemical reaction in a confined region[7,8]. In appearance and properties, BL resembles a bubble and the possibility that it is a structure with a flexible outer shell seems to be a reasonable suggestion.

Here we present a simple model of BL based on the above idea, capable of explaining many of its observed properties. It is suggested that the BL is a negatively charged spherical object consisting of a shell of oriented dipolar water molecules with low electronic conductivity in the radial direction and high proton conductivity in the tangential direction of the inner region of the shell. The outward electrostatic stress and inward forces of atmospheric pressure and/or a surface tension balance the ball. Low electronic conductivity in the radial direction, slowly releases the negative charge from the surface forming a corona discharge which accounts for the luminosity of the object. Proton confinement in the inner shell and its mobility along the inner surface results in the movement of charge to regions of higher curvature, when the BL is deformed by an inductive field. The unbalanced electrostatic stress enables the BL to bounce-off from a surface or pass through holes and cracks.

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As in bubble models of BL proposed previously[5], we assume that the bubble wall consists of a spherical shell of water molecules (Figure 1). If the charge Q of this sphere of radius R is distributed over the inner surface of the shell, water molecules will orient themselves against thermal agitation provided,

$$Qm/4pe_0R^2 \geq kT, \qquad (1)$$

where m is the dipole moment of a water molecule (isolated water molecule ~ 2D, highly polarized molecules in the condensed phase ~ 3D)[10], k is the Boltzmann constant and T the temperature (K). For a ball of radius 10 cm, constraint (1) yields $Q \geq 1.4 \times 10^{-4}$ C. The ball could remain in equilibrium under forces originating from the atmospheric pressure P and the outward electrostatic stress ($s^2/2e_0$, s is the surface charge density = $Q/4pR^2$), if

$$P = Q^2/32e_0p^2R^4. \qquad (2)$$

Hence, a bubble of radius 10 cm in equilibrium carries a charge of 1.7×10^{-4} C, order of magnitude needed for the orientation of dipoles. The total energy (electrostatic and work done against the atmospheric pressure in formation of the bubble) of a bubble of radius r can be written as,

$$E(r) = Q^2/8pe_0r + 4pr^3P/3. \qquad (3)$$

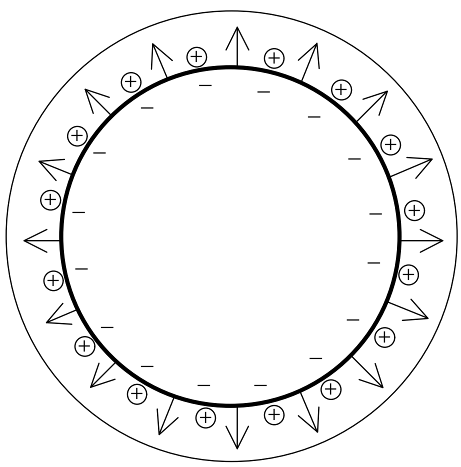

Figure 1. Schematic diagram showing structure of the ball lightning bubble. Outer shell consists of condensed water (arrows depict aligned water molecules and small circles with plus sign inside are protons radially confined, but free to move in the tangential direction).

$E(r)$ is minimum when $r = R$, showing that a BL of radius R is stable and has an energy,

$$E = 16/3pR^3P = Q^2/pe_0R. \qquad (4)$$

The model does not contradict the virial theorem[8,11], which can be expressed in the form,

$$1/2[d^2J/dt^2] = 2K + W_E + W_B - 3\ Pdv, \qquad (5)$$

where J is the radial moment of inertia, K the kinetic energy, W_E the electrostatic energy, W_B the magnetic energy and the last term represents the work done by the external pressure. For a spherical BL with a shell of mass m, eq. (5) reduces to,

$$1/2d^2[mr^2]/dt^2 = m[dr/dt]^2 + Q^2/8pe_0r - 4pr^2P. \qquad (6)$$

When the derivatives of r in eq. (6) vanish, we again obtain eq. (2) as the condition of quasistatic equilibrium. Equation (6) also enables calculation of the period of radial oscillations of the ball. Setting $r = R + dr$ ($dr \ll R$) in eq. (6), we obtain,

$$d^2/dt^2[dr] = -[16pPR/m]dr. \qquad (7)$$

Thus radial displacements of the shell generate a simple harmonic restoring force.

From eq. (4), we find that $E = 1.7$ kJ for a BL of radius 10 cm, a value which is not inconsistent with the estimation of BL energies. The electrostatic potential ($Q/4pe_0R$) and the potential gradient at the surface ($Q/4pe_0R^2$) turn out be 1.5×10^7 V and 1.5×10^8 V/m respectively. Thus avalanche processes can cause electrical breakdown and corona discharge, accounting for the luminance of BL. The rate of discharge is determined by the electrical conductivity s of the shell and the potential gradient at the surface of the ball. Therefore we obtain,

$$dQ/dt = -[s/e_0]Q. \qquad (8)$$

Thus the charge decays with a mean life time $(s/e_0)^{-1}$ and the resulting instability disrupts the ball from releasing energy (i.e. BL disintegrates before complete discharge). Using eq. (2), eq. (8) can also be written as,

$$dR/dt = -[s/2e_0]R. \qquad (9)$$

Thus the radius of BL undergoes exponential contraction with a rate constant half that for the decay of charge. It follows that the BL life time is of the order $(s/e_0)^{-1}$.

A shell of water molecules of thickness ~ 0.04 cm maintains neutral buoyancy of a 10 cm radius ball. Equation (7) gives 2×10^{-3} s as the period of radial vibrations of a ball with the above characteristics. Thus BL may be excited to emit audible noise. Due to dielectric screening by the condensed water, only the molecules in the inner region of the shell will feel the effect of the electric field sufficient for orientation. It is known that strong electric fields could disrupt hydrogen bonds in condensed water and the resulting defects enhance proton conductivity[12,13]. If BL is negatively charged, the protons will remain confined to the inner region of the shell and conductivity of the inner layer of the shell in the tangential direction should be quite high. However, proton confinement allows only movement of electrons in the radial direction. Thus the conductivity of the shell in the radial direction would be low because of the poor electron mobility in condensed phases of water. For $s \sim 10^{-12}$ S m^{-1}, the mean life time for decay of charge happens to be ~ 10 s. Experimental values for electrical conductivity of ice[14] depend on impurities and vary from about 10^{-6} to 10^{-9} Sm^{-1}. The main contribution comes from the mobility of protons. As the band gap of ice is ~ 10 eV, its intrinsic electronic conductivity should be many orders less than the lower experimental limit. The value we have chosen gives a BL life time of the order of 10 s.

Some mysterious properties of BL can be explained on the basis of conductivity properties of the shell of condensed water. Low conductivity in the radial direction will prevent the sudden electrostatic discharge when BL touches an earthed conducting object. When BL strikes a surface, flattening due to the compression of the impact will ensue flow of mobile charges, so that the more curved surface on the opposite side accumulates a higher charge density. Therefore, the resultant electrostatic outward stress directed backwards, bounces the BL away from the surface (Figure 2). The propelling force originating from the unbalanced stress will also direct the BL toward regions of higher inductive field, elongating and constricting the ball. Elongation and constriction will induce a more localized opposite charge on the surface and the feedback response tends to direct the BL towards the point of localization. Thus if the BL approaches a hole or a crack on a

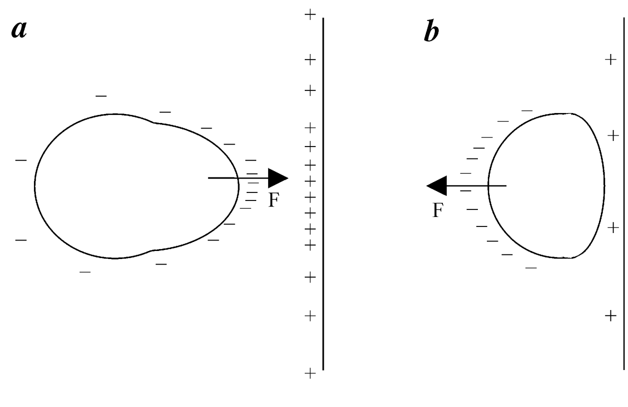

Figure 2. Deformation and redistribution of charge on a ball lightning due to inductive field created in approaching a surface (***a***) and immediately after impinging on a surface (***b***). (F indicates direction of the resultant stress force).

surface where the inductive field strength is high, the forward electrostatic thrust developed from the difference in the surface charge distribution pushes it through the opening (Figure 3). Charge redistribution in deformation of the ball generates transient currents with relaxation times of the order $(s_T/e_0)^{-1}$, where s_T is the proton conductivity of the shell in the tangential direction. As $s_T \gg s$, the model naturally explains that the process of BL passing through holes or bouncing-off from walls is fast in comparison to its life time. If s_T is assumed to be of the order of magnitude of the proton conductivity of ice ($\sim 10^{-6}$ Sm^{-1}), the relaxation time happens to be $\sim 10^{-5}$ s.

From eq. (2) it is seen that the electric field $Q/4pe_0R^2$ at the surface is independent of the radius of the ball. Thus a BL of every radius possesses a surface electric field of similar strength sufficient to polarize the dipole water molecules. A question that arises is what determines the thickness of the outer shell? To maintain neutral buoyancy, the thickness D of the shell should be related to the radius of the BL via the relation following from the Archimedes principle, i.e.

$$D = 1/3R\ (r_a/r_s), \tag{10}$$

where r_a is the density of air, r_s the density of the shell material (~ 1). It is difficult to conceive a mechanism leading to eq. (10) to assure that a BL of every size retains neutral buoyancy. Apart from shell weight, other factors (i.e. an electrostatically bound dense cloud of gas) contribute to buoyancy. Furthermore, there is evidence that many BLs spotted fall to the ground and are heavier than air[6].

An electrostatically charged stable bubble can also be formed if the shell possesses a surface tension S. Here, the condition for equilibrium can be expressed as,

$$(Q/4pR^2)^2/2e_0 + (P_i - P_o) - 4S/R = 0, \tag{11}$$

where, P_i and P_o are the pressure inside and outside the bubble. If the shell is thin, near neutral buoyancy is realized, if we set $P_i = P_o$ in eq. (11) giving,

$$Q^2 = 128p^2e_0R^3S. \tag{12}$$

The energy of a bubble of radius r can be written in the form,

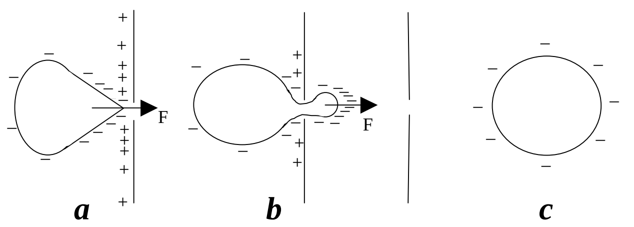

Figure 3. Deformation and charge distribution when a ball lightning approaches a surface with a hole. Movement towards the hole (***a***), protrusion into the hole (***b***) and restructured state after penetration through the hole (***c***). Arrows indicate direction of the resultant stress force *F*.

$$E(r) = Q^2/8pe_0r + 8pr^2S. \tag{13}$$

$E(r)$ minimizes when $r = R$, showing that the equilibrium is stable and total energy can be expressed in terms of Q or S as follows:

$$E = 3Q^2/16pe_0R = 24pR^2S. \tag{14}$$

From eqs (1) and (12), the condition for dipole orientation can be expressed in the form,

$$S > (kT/m)^{1/2}(Q^{1/2}/64\pi^{3/2}e_0^{1/2}). \tag{15}$$

For a BL of radius 10 cm, the constraint (15) yields $S > 6$ kJ m^{-2}. It is difficult to conceive a way of assigning such a high surface tension to a shell of condensed water molecules without invoking other effects. Interfaces of dusty plasmas are believed to be endowed with high interface tensions[15]. In the models proposed above, corona discharge establishes plasma just above the surface of the outer shell. An alternative possibility is that the tension is generated by a polymer network formed by action of lightning on organic material in the environment[16]. However, models of this nature cannot explain observations of the BL falling from clouds. Environment near the clouds clearly excludes organic material needed for the formation of a polymer network.

The model also suggests a mechanism of BL formation. There seems to be two distinct types of BL. Those created near the ground and those falling from the clouds. A positively charged cloud induces high negatively charged densities on earthed, sharply pointed objects. The excessive outward electrostatic stress could lead to instability with detachment of the charge and expansion to create a ball. The tip of the stepped leader from a negatively charged cloud is also a region of high negative charge density; hence BL could also be created at such positions near clouds via the same mechanism. Thus the present model connects ground and cloud-based BL to positive and negative lightning respectively (Figure 4). As the balls are formed after charge separation, rapid dissipation from recombination is not encountered.

The model also at least partly explains formation of the BL in underwater electrical discharges. Here again, the ball can be stabilized by hydrostatic pressure and electrostatic stress. An oriented and condensed outer shell of water molecules will ensure slow release of the negative charge, just as in atmospheric conditions. It is well known that corona-type discharges occur underwater. The charge dissipation process and the boundary conditions are different underwater. However, it follows from eq. (2) that if a BL is formed deep underwater, the initial charge would be high and sufficient charge may remain when the ball reaches the surface. If the bubble bursts into the atmosphere from water before decay, it will continue as a BL in air.

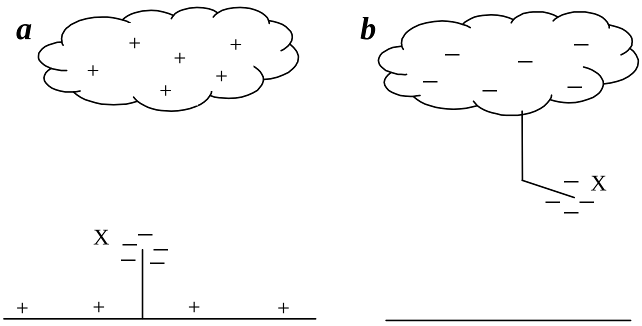

Figure 4. Ball lightning could be triggered (***a***) at the sharp point of an earthed object when a positive cloud is above or (***b***) at the tip of a stepped leader coming from a negatively charged cloud. Points of high negative charge density are marked as X.

We have shown that the bubble models of BL with an outer shell of oriented water molecules have the ability to explain more elusive properties of BL, such as bouncing from surfaces and penetration through holes. It is interesting to note that the present BL model accounts for ground- and cloud-based and underwater phenomena within one single mechanism and also explains how the BL could bounce off from flat surfaces and penetrate through holes. Proton conductivity of the outer shell in the tangential direction and their confinement in the radial direction explain these effects. Frequent spotting of BL inside houses and its entry through windows and chimneys could also be understood as the result of a forward propelling force which develops when the BL approaches objects. The high resistivity of the shell in the radial direction prevents rapid discharge of the BL if it happens to touch a conducting surface. It is interesting to note that the rate of decay of the charge (eq. (8)) is independent of the bubble radius but depends only on the electronic conductivity of the shell. As the charge decays, the bubble contracts at rate proportional to its radius (eq. (9)). However, the assumption leading to derivation of eq. (8) is approximate and any space charge layer at the surface could deviate the electric field from the Coulomb form $Q/4pe_0R^2$. Bubble models of the above type with net positive charge are not ruled out. However, because of high proton conductivity of condensed water, they are expected to decay faster. If the shell material has low hole (positive) and higher electron conductivity, long lived positively charged BL structures can be formed. Negative and positive corona discharges have distinct differences. However, variations of BL as reported are too complicated to classify as negative or positive coronas. Observational data on BL do not give information sufficient to decide the sign of its charge. An important question that arises is; what are the precise conditions needed for creation of a BL? Here the point we have to keep in mind is that lightning happens to be a terrestrial process involving the highest current densities (frequently exceeding 10^6 A cm^{-2}). Although we go for very high energies in particle accelerators at miniscule luminosities (currents), processes at high current densities are not fully investigated or understood. Observations generally classified as BL could have their origins in more than a single phenomenon; other models proposed are relevant in gaining a full understanding of the problem[17–23]. The final solution to the problem depends on reproduction of the BL and other fire-ball structures under laboratory conditions. It is encouraging that several workers have taken up this challenge[5,24,25].

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