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Ball lightning caused by a semi-relativistic runaway electron avalanche

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ABSTRACT

Ball lightning (BL) is observed as a luminous sphere in regions of thunderstorm activity. There are many reports of BL forming in total absence of thunderclouds, associated with earthquakes and volcanoes. In this latter case, BL has been known to appear out of “nowhere”. In this work, a hypothesis on BL formation is presented involving the interaction between very low frequency (VLF) radio waves and atmospheric plasmas. High-velocity light balls are produced by ionic acoustic waves (IAWs) interacting with a stationary plasma. Several physical properties (color, velocity, and fragmentation) observed in the BL phenomenon can be explained through this model.

1. Introduction

BL is an unexplained atmospheric electrical phenomenon. The term refers to reports of luminous, usually spherical objects which vary from pea-size to several meters in diameter. It is usually associated with thunderstorms (Paiva et al., 2010). BLs can be red, blue, yellow, white or even green. They may meander along the ground or drop out of the sky. Sometimes these fireballs appeared from “nowhere” (Abrahamson et al., 2002; Paiva and Taft, 2010, 2011). The problem of ball lightning has attracted the attention of scientists for a long time. Theories that have been put forward to explain BL, which include antimatter (Ashby and Whitehead, 1971), electromagnetic standing waves within a ball of plasma (Watson, 1960), retinal afterimages (Argyle, 1971), oxidation of nanoparticles (Abrahamsom and Dinniss, 2000), corona discharge generated by dissipating electrical ground currents (Lowke, 1996), microwave interference (Ohtsuki and Ofuruton, 1991), plasma surrounded by hydrated ions (Turner, 1994), superconducting plasma vortices (Dijkhuis, 1980), polymer composites (Bychkov and Bychkov, 2002), light bubbles (Torchigin and Torchigin, 2007) and even black holes of cosmic origin (Muir, 2007). However, no one has been able to propose a theory that can account for the full range of observed characteristics of ball lightning. A number of groups have managed to produce artificial luminous objects with a number of the characteristics common to the fireballs seen in nature (Paiva et al., 2007). The properties attributed to the BL phenomenon have been deduced from reports collected from hundreds of witnesses in the past two centuries (Stenhoff, 1999; Barry, 1980; Rakovand and Uman, 2003). Glowing balls can also occur in total absence of thunderclouds, associated with earthquakes and volcanoes (Durand and Wilson, 2006). Hughes (2011) has presented evidence of an apparent connection between BL and a green fireball. According to this theory, a meteor can create an electrically conductive path between the ionosphere and the ground, providing energy for the BL phenomenon. In this work, evidence is presented that BL is formed by a relativistic runaway electron avalanche which is produced by the electric fields during rapid fracture of piezoelectric rocks under the ground. Piezoelectric rock fracture can be produced by water expansion during freezing in the lithosphere or by earthquakes. High-velocity light balls are produced by ionic acoustic waves (IAWs) interacting with an initial, stationary plasma. Several physical properties (color, velocity, and fragmentation) observed in the BL phenomenon can be explained through this present model.

2. The model

Relativistic runaway electron avalanche (RREA) is defined as an avalanche growth of a population of relativistic electrons in air by a strong electric field. RREA can occur at electric fields an order of magnitude lower than the dielectric strength of the material. This mechanism has been related to sprite lightning (Lehtinen et al.,

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1999), terrestrial gamma-ray flashes (Dwyer and Smith, 2005), lightning initiation (Gurevich and Zybin, 2005), and to spark development (Betz et al., 2009). When an electric field is applied to a material, free electrons will drift slowly through the material as described by the electron mobility. For low-energy electrons, faster drift implies higher friction; so, the drift speed tends to stabilize. For electrons with energy above about 100 keV, however, higher speeds imply lower friction. An electron with a sufficiently high energy therefore may be accelerated by an electric field to even higher and higher energies, encountering less and less friction as it accelerates. Such an electron is described as a "runaway". As runaway electrons gain energy from an electric field, they occasionally collide with atoms in the material, knocking off secondary electrons. Secondary electrons also have high enough energy to run away. These secondary electrons can accelerate to high energies and produce further secondary electrons. As such, the total number of energetic electrons grows exponentially in an avalanche. The radioactive decay of lead-214 (half-life 26.8(9) min) produces beta particles (electrons) with energy of about 1000 keV (Wu, 2009). These electrons can produce a local runaway avalanche in the atmosphere when an electric field is produced by piezoelectricity from rocks under the ground.

Let us consider the electric potential in the air on the rock fracture. The electrical charge is homogeneously distributed on an imaginary disk of radius R. The potential at a distance z from the disk is given by $\Delta V = K\sigma 2\pi[(z^2+R^2)^{1/2}-z)]$, where σ is the area charge density, and $K=1/4\pi\varepsilon_s\varepsilon_0$ where $\varepsilon_0=8.85\times10^{-12}\ \mathrm{F\,m^{-1}}$. The mean electrical charge developed during rock fracture is $q=1$ C (Enomoto and Hashimoto, 1990). We found ΔV to be $\sim$2 GV. Let us calculate the electron number produced by the runaway electron avalanche (RREA) mechanism in the HL phenomenon. The runaway electron avalanche multiplication factor is given by Dwyer (2003) as

$$N_{RE} = \exp\left(\frac{\Delta V - 2.13\times10^6 I}{7.3\times10^6}\right) \quad (1)$$

In the equation above, ΔV is the potential difference of the avalanche region (volts) and I is the column depth of the avalanche region (g/cm^2). The vast majority of the lights were reported to occur below the tops of mountains (Bjorn, 2007). The Hessdalen light phenomenon (HL) generally occurs in a few tens of meters over the treetops. Mountainous soil has a mean dielectric constant (permittivity), $\varepsilon_s\sim5$ (Saveskie, 2000). Atmospheric depth is $I=103$ g/cm^2 for HL altitude occurrence. Inserting these values in Eq. (1), we found $N_{RE}=\exp(9.5)=10^4$ electrons. This value is 10^{12} times lower than that produced by terrestrial gamma-ray flashes at high altitudes on thunderclouds. According to our model, BL is formed by an initial energetic electron from atmospheric radioactivity (Fig. 1). According to Fig. 1, rock fractures (A) produced by tectonics or water (B) expansion during freezing into andesite rocks (C) causes charge formation (D) and strong electric fields on the ground (E); radioactive decay of lead-214 in the atmosphere (F) produces beta particles (G) with energies of about 1000 keV; acceleration of beta particles (H) in the atmosphere by the RREA mechanism produces an electron avalanche (I), and stationary ball lightning (J) due to local ionization of oxygen and nitrogen molecules; VLF radio waves, irradiated by electrical discharges from fractured rocks (K) or produced by electrical power lines (M) are guided by the magnetic field to the plasma ball and strongly interact with its trapped counter-streaming energetic electrons. As a result of this wave–particle interaction, electrons are ejected (N) by the stationary plasma ball. The VLF waves do not interact directly with ions in the plasma. However, ejected electrons can cause density perturbations in the surrounding plasma, forming ionic acoustic waves (IAWs). Thus, a high concentration of positive

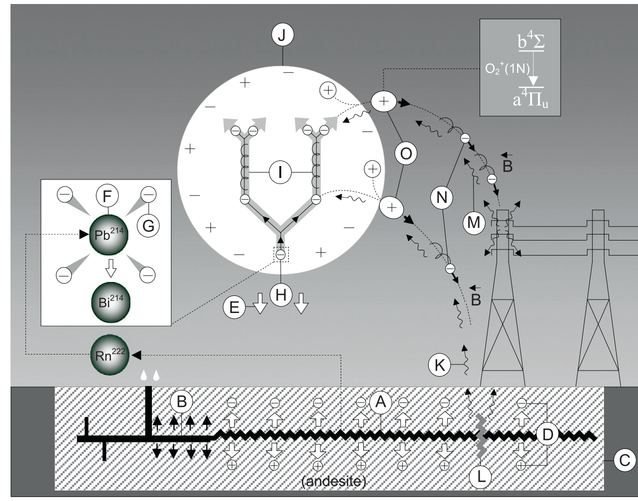

Fig. 1. Mechanism of BL formation in the absence of thunderstorms.

oxygen ions will follow in the direction of ejected electrons by electrostatic forces of attraction, forming a high-velocity green light ball (O). This can explain the attraction of light balls by power lines.

The mechanism of electron ejection in the magnetosphere by radio waves (VLF) was explained in detail by Park and Helliwell (1978). Electron ejection by VLF can explain some reports of ball-lightning attraction from electric power lines (Stenhoff, 1999). It is possible to estimate the energy of electrons that interact with the VLF waves. The interaction mechanism is believed to be cyclotron resonance, where the resonance condition is given by

$$f\left(1+\frac{v_{//}}{v_p}\right) = f_H \quad (2)$$

where $v_{//}$ is the electron velocity along the geomagnetic field, f is the wave frequency, f_H is the electron gyrofrequency, and v_p is the wave-phase velocity in the opposite direction. Let us consider v_p as being IAW velocity, i. e. $v_p=V_{IAW}$ in the light ball. Ogawa et al. (1985) showed in laboratory experiments that rocks radiate wide-band EM waves (10 Hz to 100 kHz) when they are struck by a hammer and are fractured. IAW is a longitudinal oscillation of the ions, like acoustic waves traveling in neutral gas. Ionic acoustic waves require an energy source for their excitation. Typically, ionic acoustic waves are driven by an electron current in the plasma. Electrons feed energy into the waves and the ions take away energy from it. When electrons are driven to travel with high velocity, an unstable situation arises. At this point, electrons can cause density perturbations in the surrounding plasma, forming ionic acoustic waves. The IAW velocity is given by Alexeff and Neidigh (1961) as

$$V_{IAW} = \sqrt{\frac{\gamma_e Z_i k_B T_e + \gamma_i k_B T_i}{\langle m_i\rangle}} \quad (3)$$

where $\langle m_i\rangle$ corresponds to the mean mass of the ion, Z_i is its charge, k_B is the Boltzmann's constant, T_e is the electron temperature, T_i is the ion temperature, $\gamma_e=1$, and $\gamma_i=3$, corresponding to one-dimensional motion. Electrons in the plasma are much hotter than the ions. In this case, the second term in the numerator can be ignored. Thus, we have

$$V_{IAW} \sim \sqrt{\frac{\gamma_e Z_i k_B T_e}{\langle m_i\rangle}} \quad (4)$$

According to Teodorani (2003), the HL spectrum gives a gas (ion) temperature of about $T_i=6000$ K. Generally, the radiant species present in atmospheric plasma are N_2, N_2^+, O_2, and O_2^+,

NO^+ (in dry air) and OH (in humid air). At higher temperatures, atomic emission lines of N and O, and (in the presence of water) H, are present. Probably only O_2^+ ions (electronic transition $b^4\Sigma_g^- \rightarrow a^4\Pi_u$), with green emission lines, are predominantly transported by IAW. Thus, considering $\langle m_i \rangle \sim m_i(O_2^+)$ and $T_e = 10 \times T_i = 60{,}000$ K, we found $V_{IAW} \sim 10^3$ m s^{-1}. The Earth's magnetic-field strength on the ground ranges from 25×10^{-6} to 65×10^{-6} T; hence, the mean electron gyrofrequency will be $f_H = 2.8 \times 10^{10} B$ (in Tesla)$= 1.3 \times 10^6$ Hz. Inserting this value in Eq. (2) for $f = 20 \times 10^3$ Hz (mean VLF wavelength), we found the electron velocity along the geomagnetic field as being $v_{//} = 6.4 \times 10^4$ m s^{-1}. This is the velocity of the energetic electrons ejected by the ball of plasma due to the incidence of VLF waves on it. Positive oxygen ions in the light ball will follow the ejected electrons due to electrostatic forces of attraction (see Fig. 3), forming a high-velocity green light ball of ions. This value is close to the observed velocity of some ejected light balls from BL, which is estimated as being 2×10^3 m s^{-1}.

Charged particles can be emitted from the indentation fracture of rocks (Enomoto and Hashimoto, 1990). For example, the net production rate would be ~ 0.6 C/m^3/s in andesite. If a massive fracture occurs during one second on the ground, over an area extending some meters, the charge generated may be compared to the total electric charge produced by one bolt of lightning (1 C). When water freezes, it expands by 9 per cent. If it seeps into rocks and then freezes, the rocks can fracture. This phenomenon is known as frost weathering (Hallet, 2006). Therefore, weathering can fracture hydrophobic andesite and produce high electric potentials above the ground.

Local air breakdown and RREA can explain BL which seems to appear out of "nowhere" (Abrahamson et al., 2002; Paiva and Taft, 2010, 2011). BL can eject small green light balls presenting high velocity (Teodorani, 2004) due to interaction between the plasma ball and very low frequency (VLF) radio waves from rocks or power transmission lines, forming ionic–acoustic waves (IAWs). Power transmission lines throughout the world usually operate at either 50 or 60 Hz. However, nonlinear loads (rectifiers and imperfect machinery) may introduce higher frequency components in the electrical line due to harmonics up to many kilohertz (Park and Helliwell, 1978). Power transmission lines presenting these harmonic currents can radiate VLF radiofrequency waves which are guided by the earth's magnetic field and that penetrate into a stationary plasma ball where waves and electrons interact (Fig. 2).

According to our model, high-velocity green lightning balls observed by Teodorani (2004) from stationary BL are produced by the interaction between VLF and atmospheric ions (conducting in the stationary BL) through ionic–acoustic waves (IAWs) (see Fig. 1). Low-frequency oscillations in the electric field in the fractured rocks induce simultaneously electric-field oscillation in the plasma ball. Consequently, the oscillating electric field can produce IAW in the plasma. In fact, the light ball phenomenon is often accompanied by a pulsating magnetic perturbation with a period of a few Hz and by small- and very-short-duration pulsating "spikes" in the HF radio ranges (Teodorani, 2004).

IAW interacts with O_2^+ ions (electronic transition $b^4\Sigma_g^- \rightarrow a^4\Pi_u$), with green emission lines. The estimated ion temperature of HL is about 6000 K (Teodorani, 2004). In this case, electron temperature will be $T_e = 60{,}000$ K. At this electron temperature, the rate coefficient of dissociative recombination (Mehr and Biondi, 1969) of oxygen and nitrogen ions will be, respectively, $\alpha(T_e)_{O_2^+} \sim 10^{-8}$ cm^3 s^{-1} and $\alpha(T_e)_{N_2^+} \sim 5 \times 10^{-8}$ cm^3 s^{-1}. Thus, the nitrogen ions will be decomposed in the manner $N_2^+ + e^- \rightarrow N + N^*$ (where N^* represents an excited nitrogen atom) more rapidly than oxygen ions in the HL plasma. Only ionic species are transported by IAW. Therefore, high-velocity green light balls will be ejected from a stationary lightning ball (see Fig. 3).

2.1. Experimental proposal

We suggest a simple experiment to test the present hypothesis (Fig. 4).

In this experimental apparatus, high voltage (1 MV) is produced by a Marx generator. In this experiment, we propose the use of lead-214 (> 1 μg). The geometry of this radioactive metal is not critical. This metal should be placed on the center of a large metal plate (round copper plate, 4 m in diameter), which is connected to the Marx generator through an electrical wire. The copper plate should be placed on a polymeric (polyethylene or polymethyl-methacrylate) block to isolate the high-voltage plate from the

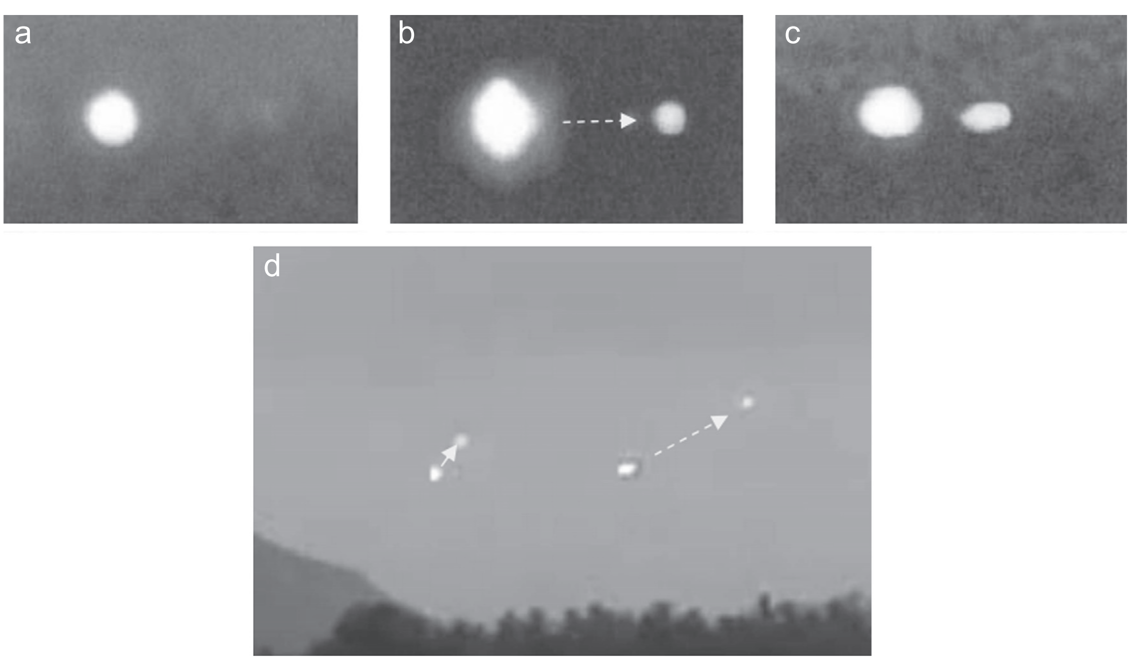

Fig. 2. (a–c) Three photographic examples of ejection of a small green light ball from a larger white ball (Teodorani, 2004). (d) One selected video frame of green light ball ejection. (Amazing real-looking UFO sightings in INDIA Jan 26 2008, http://www.youtube.com/watch?v=pSKu2tlgoRY&feature=related).

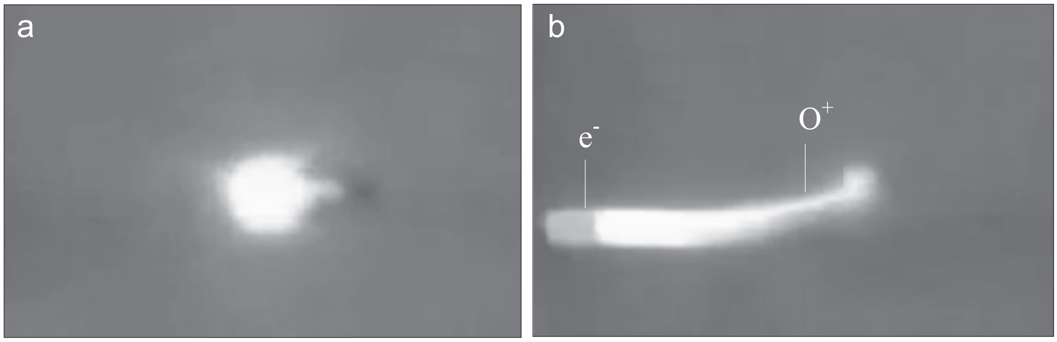

Fig. 3. Two selected video frames (a, b) of light ball ejection by a stationary ball lightning that occurred in total *absence of thundercloud*. This green light ball occurred on power transmission lines. Light Anomaly-Marshall County, Kentucky (http://www.youtube.com/watch?v=f-S6t7pUO5k). According to the author's model, the front of the ejected light ball is formed by high-speed electrons and the tail portion of the light ball is formed by oxygen ions.

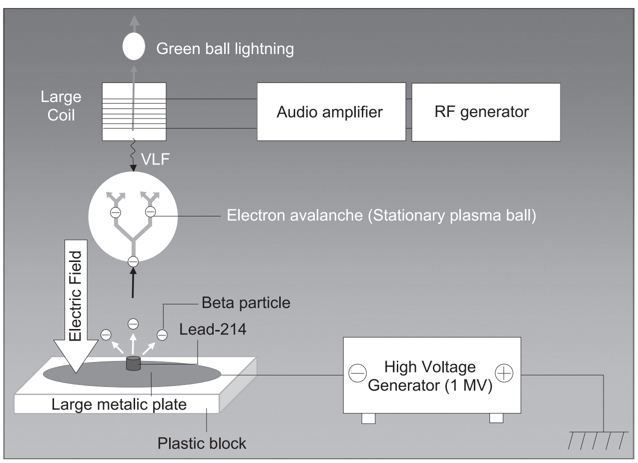

Fig. 4. Experimental apparatus to test the present hypothesis. Beta particles, which are emitted by radioactive lead, are accelerated in air by an electric field produced by a high-voltage generator (for example, Marx generator) connected to a large metallic plate (copper, aluminum, etc.). High-velocity electrons will form an electron avalanche by the RREA mechanism. A radiofrequency generator can produce VLF radio waves through a large coil connected to an audio amplifier. Thus, a stationary ball lightning can be formed in the region of an electron avalanche. The interaction of VLF in the stationary plasma can eject high-velocity green light balls.

ground. Efforts in exploring such experiments are in progress. On the other side, the radiofrequency coil will produce the VLF waves on the plasma. The VLF power can be 10 W or more. The coil can be a VLF loop antenna (1 m diameter).

3. Conclusion

We conclude that BL is caused by local breakdown of air due to the RREA mechanism. This process resembled some descriptions of unexpected appearances of BL. The plasma ball can eject a small green light ball with high velocity due to interaction between VLF radio waves and the plasma ball. A runaway electron avalanche is triggered by energetic electrons from radioactive atoms that exist naturally in the atmosphere such as lead-214 atoms (electron energy > 1000 keV). We believe that contradictory explanations of the origin of BL could be discarded if BL was treated as a package of dissimilar phenomena with a variety of causes in different circumstances.

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