Birth of ball lightning

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[1] Many observations of ball lightning report a ball of light, about 10 cm in diameter, moving at about walking speed, lasting up to 20 s and frequently existing inside of houses and even aeroplanes. The present paper reports detailed observations of the initiation or birth of ball lightning. In two cases, navigation crew of aircraft saw ball lightning form at the windscreen inside the cockpit of their planes. In the first case, the ball lightning occurred during a thunderstorm, with much lightning activity outside of the plane. In the second case, large "horns" of electrical corona were seen outside of the plane at the surface of the radome, just prior to the formation of the ball lightning. A third case reports ball lightning formed inside of a house, during a thunderstorm, at a closed glass window. It is proposed, based on two-dimensional calculations of electron and ion transport, that ball lightning in these cases is driven and formed by atmospheric ions impinging and collecting on the insulating surface of the glass or Perspex windows. This surface charge can produce electric fields inside of the cockpit or room sufficient to sustain an electric discharge. Charges of opposite sign to those outside of the window accumulate on the inside surface of the glass, leaving a ball of net charge moving inside of the cockpit or room to produce a pulsed discharge on a microsecond time scale.

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1. Introduction

[2] There have been many observations of ball lightning, seen as a glowing ball 10–20 cm in diameter, or about the size of a grapefruit, usually during thunderstorms, and lasting about 10 s [*Rakov and Uman*, 2003, Ch. 20; *Stenhoff*, 1999]. The features of ball lightning have so far defied any generally accepted credible explanation. Unexplained features are that ball lightning almost always moves, that the motion is independent of any prevailing breeze and that it does not rise, as would occur from heating if oxidation was involved. Perhaps the most perplexing observation is that ball lightning is frequently observed to appear inside of houses and even aeroplanes, from a closed glass window, with no apparent damage to the window.

[3] Previous theories of ball lightning have assigned a very wide range of energy sources and structures for this phenomenon. Examples of proposed energy sources are microwave radiation from thunderclouds [*Kapitza*, 1969], nuclear energy [*Altschuler et al.*, 1970], atmospheric masers [*Handel and Leitner*, 1994], antimatter [*Ashby and Whitehead*, 1971], dark matter [*Rabinowitz*, 2001], oxidizing aerosols [*Aleksandrov et al.*, 1982] and confined electromagnetic energy in a "plasmoid" [*Finkelstein and Rubinstein*, 1964; *Endean*, 1976; *Dijkhuis*, 1980].

[4] Notable recent theories are the theory of *Abrahamson and Dinniss* [2000], which has been widely quoted and the theory of *Bychkov* [2002], which proposes that ball lightning is a condensed polymer. In both theories the source of ball lightning is assigned to melting phenomena associated with a lightning strike. The first of these theories proposes that Ball lightning results from the oxidation of silicon dendrites from condensed silicon vapor that is produced after the reduction by carbon of vaporized silica formed from arc melting in a lightning strike to the earth. In support of this theory, *Paiva et al.* [2007] reported the production of luminous white balls on striking an arc to pure silicon wafers, although free floating balls were not observed. However, a subsequent experimental investigation of *Stephan and Massey* [2008] claims that these luminous balls consist of burning molten silicon spheres with diameters in the range 0.1–1 mm.

[5] Effects of vapors produced if ball lightning originates from a lightning strike may occur if ball lightning is produced in the open air, but are considered to be highly unlikely for the ball lightning produced inside of houses and aircraft which is considered in the present paper. The energy source for the present proposal is from ions and space charge electric fields from the atmosphere which produce an electric

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discharge. Motion of the ball lightning is determined by changing space charge fields and so moves independent of any prevailing breeze, and also resists dispersion by the breeze.

[6] In section 2, we present three previously unreported observations of ball lightning appearing from closed windows, two from air navigation staff who observed the apparent formation of ball lightning inside of the cockpits of their aircraft and a third observation where ball lightning appeared from a closed window inside of a room during a thunderstorm. In one of the aircraft, the observations were made during an intense thunderstorm. For the other aircraft there were no reports of lightning existing in the area. However, the observation was made for a flight in thick fog, with the radar transmission operating at full power, and the ball lightning was preceded by observations of large "horns" of corona attached to the radome. None of these observers report seeing the ball lightning initially outside of the cockpit or room, even though the observers in both planes were intently looking outside of the cockpit before the ball appeared at the glass inside of the plane. We know of no observations of ball lightning passing from outside to inside of the glass. In this paper we propose that the ball lightning is formed on the inside of the glass from electric fields induced by the deposition of ions on the outside of the glass.

[7] In section 3, we present predictions from solutions, in two dimensions, of the conservation equations for electrons and ions of the production of a discharge with characteristics similar to ball lightning. This discharge is produced assuming a steady stream of ions to the outside of a glass window. Accumulation of ions on the outside of the window causes high fields on the inside of the window, sufficient to sustain a discharge. Accumulation of ions of opposite sign on the inside of the window can then result in the approximately circular discharge separating from the window due to the reduction in the local electric field near the inside window surface.

[8] In rare situations such a stream of ions is considered to be possible, as is discussed in section 4. During thunderstorms significant streams of plasma and corona, kilometers in length, are produced from the many stepped leaders of lightning during thunderstorms [*Golde*, 1977, pp. 177, 180, and 185; *Lowke*, 2004]. Ions remaining after out of balance recombination of ions from such corona can last for many seconds, as their lifetime depends on their transport to the earth by residual fields from the cloud. For the aircraft observation in which a thunderstorm was not reported, ions could have originated from the steady corona observed on the radome, probably resulting from the radar transmitter being operated at full power in dense fog. It is known that the inception voltage for corona in the presence of fog is reduced by about a factor of 2 [*Peek*, 1929].

2. Observations

[9] The following are excerpts of descriptions of ball lightning formed at closed glass windows taken from more complete descriptions available from the authors.

2.1. Dr. Keith E. Nelson, Logan, Utah, USA

[10] "I am reporting an observation of ball lightning that I made while I was a pilot in the US Air Force in about 1975. We were flying a Lockheed C-130 transport plane from Goose Bay, Labrador, to Frankfurt, Germany. We were flying through a thunderstorm, not really dense, in that visibility from the plane was fair, but there was much sheet lightning in the vicinity. Indeed there was static electricity in the air in that occasional corona was visible from the wire "dissipators" at the wing tips of the plane. There was also the occasional flash of cloud to cloud lightning nearby. We were about halfway across the Atlantic when a ball of light about the size of a soft ball appeared apparently from the inside of the windshield of the plane at the top of the instrument panel in front of us, inside the plane. This ball moved slowly, at about walking speed, from left to right, bouncing along the instrument panel. It was seen not only by myself, the "Aircraft Commander," but also by the copilot, the engineer and the navigator. The speed of movement of the ball was slow enough for me to make the comment to my copilot suggesting that he might like to insert his finger into the ball – which was sufficiently close to him, but he did not do so!"

2.2. Don Smith, Charleston, South Carolina, USA

[11] "In the mid 1960s, I was a lieutenant in the US Air Force and was the crew navigator aboard a C-133A cargo aircraft flying from California to Hawaii. We were at an altitude of 18,000 feet, it was at night and we were flying in a continuous horizontal layer of thin cloud which had the density of "soup." The C-133A had four propellers driven by four turbine engines and, at the time was the U.S. Air Force's largest cargo aircraft. On the nose of the C-133A there was a radome that was visible from inside the cockpit. The radome was a dome shaped shell used to cover the radar antenna and was about 36 inches across and had a rounded dome front. As Navigator I was monitoring the radar for any significant weather clouds in front of us. There was only the "soup." After flying for about 15 min, there developed on the radome two horns of Saint Elmo's fire. It looked as if the airplane now had bull's horns on the radome. The curved horns, each about a foot long, were glowing with the blue of electricity. The two pilots, the on-duty engineer and I enjoyed watching and discussing the horns for a relatively long time. The horns were not at all unusual as we had seen this phenomenon several times previously when in similar flight weather conditions. We thought of it simply as static electricity. Suddenly, within sight of all four of us – we were all looking at the horns – a glowing ball of golden fire about the size of a volley ball appeared just inside the windshield, midway of the windshield and above the central Pilot console. It touched nothing and made no sound but slowly floated downward into the cockpit staying about 3 feet above the floor, then slowly turned left toward the crew lounge doorway, went through the open doorway, turned right 90 degrees and toward where the Loadmaster was sitting. We all exchanged what we each had seen, confirming with each other that we had seen the same thing. The Engineer and Loadmaster searched for any damage to the airplane and, finding no damage, we continued the flight. At no time during this flight were there any thunderstorms along our route. We were flying through a fog-like layer of cloud and there was no turbulence. We never saw any lightning outside the aircraft, neither close by nor in the distance. We did not see any lightning flash whatsoever. No individual clouds ever appeared on the radar which I was monitoring closely; only a

pea-soup-like fog layer was evident. The radar was at full power during the time that the St. Elmo's horns and the ball lightning occurred and the radar beam was in the narrow Pencil shape."

2.3. Mrs. Wheatley, U.K.

[12] "I was sitting in my chair when, without any warning, a great orange ball, rather like a big grapefruit but more orange and fluffy at the edges, came through the front window, which was closed and the blind also closed. It travelled horizontally at about shoulder height for about 10 s and was immediately followed by a clap of thunder just above me which was so loud that I shot out of my chair."

[13] These descriptions are significant in that they are about the first direct observations of the actual initiation or birth of ball lightning. They also give strong evidence that at least these ball lightnings are electrical gas discharge phenomena.

3. Theory

[14] We present calculations that show that a stream of ions impinging on an insulating glass surface produces surface charges and a resulting significant electric field on the opposite side of the glass window that is sufficient to sustain an electric discharge. The conservation equations (1)–(3) for electrons, negative ions and positive ions, together with Poisson's equation (4) to account for space charge effects, are:

$$\frac{\partial n_e}{\partial t} = n_e \alpha W - n_e \eta W - \nabla \cdot (n_e W) - \gamma n_e n_+ \quad (1)$$

$$\frac{\partial n_-}{\partial t} = n_e \eta W - \nabla \cdot (n_- W_-) - \gamma n_- n_+ \quad (2)$$

$$\frac{\partial n_+}{\partial t} = n_e \alpha W - \nabla \cdot (n_+ W_+) - \gamma (n_e + n_-) n_+ \quad (3)$$

$$\nabla \cdot E = \frac{e}{\varepsilon_0}(n_+ - n_e - n_-); \quad (4)$$

n_e is the electron density, n_- and n_+ are the negative and positive ion densities, E the electric field, e the electronic charge, W, W_- and W_+ are the electron, negative ion and positive ion drift velocities, α, η and γ the ionization, attachment and recombination coefficients, x the axial position, t the time and ε_0 the electrical permittivity. These equations take into account ionization from collisions with electrons, electron attachment to form negative ions, the drift of electrons, negative ions and positive ions due to the electric field, and the distortion of the applied electric field due to the charges on the electrons and ions.

[15] In the solution of these equations, approximate analytic forms of the standard values of the material functions α, η, γ, W, W_+, W_- as a function of the electric field have been used, except that the ionization coefficients have been increased so that ionization equals attachment at ~4 kV/cm. This approximation is made because it is known from experimental investigations that glow discharges in air can operate at values of E/N as low as 20 Td., which for atmospheric pressure corresponds to fields of ~4 kV/cm; 1 Td. = 10^{-17} V cm^2, N is the gas number density and is ~2.5×10^{19} cm^{-3} at atmospheric pressure. The value of E/N largely determines average electron energy. The experimental investigations include corona discharges [*Phelps and Griffiths*, 1976], prebreakdown experiments [*Feser and Hughes*, 1988], and low-pressure nitrogen discharges [*Yu et al.*, 2001]. These glow discharges are usually followed by the formation of an arc. Numerical solutions of the glow discharge equations (1) to (4) yield electric fields for the discharge column to be of the order of the field for which ionization equals attachment; e.g., for air [*Morrow and Blackburn*, 2002], sulfur hexa-fluoride [*Morrow*, 1991], and oxygen [*Morrow*, 1985]. This field is known as the "critical field," because at lower fields all electrons become attached to form negative ions.

[16] As well as its basis in experiment, the approximation in our calculations whereby ionization coefficients are increased so that they equal attachment coefficients at 4 kV/cm has strong theoretical justification. It accounts for the known strong influence of metastable states of nitrogen and oxygen that are produced in air discharges, once a discharge has been established, e.g., [*Yu et al.*, 2001]. The metastable states act to reduce the effective attachment coefficients and increase the effective ionization coefficients of air in three separate ways. (1) The metastable states detach negative ions of oxygen produced by attachment. This process is well established for singlet delta atoms of oxygen [*Fehsenfeld et al.*, 1969] and enables the discharge to operate at a significantly lower electric field [*Lowke*, 1992]. Higher vibrational states of nitrogen with excitation energies above 1 eV also have sufficient energy to detach negative ions of oxygen. (2) The metastable states, particularly of nitrogen, introduce species in the gas having a significantly lower threshold for ionization, thus increasing the ionization coefficient. (3) Probably the most significant influence in increasing ionization is due to the metastable character of the vibrational states of nitrogen. Vibrational states can be excited to successively higher metastable levels, both through successive excitations from collisions of electrons with existing excited states and also through collisions of the excited states among themselves [*Capitelli et al.*, 2009]. Excitation is possible up to 60 quantum levels with the highest energy level being ~8 eV, [*Lino da Silva et al.*, 2008, Figure 2]. De-excitation collisions of these highly excited states of nitrogen with low-energy electrons increases the number of electrons in the high energy region of the electron distribution function so that the ionization coefficient is increased by many orders of magnitude, even at E/N = 20 Td [*Brunet et al.*, 1983, Figures 1 and 2].

[17] The approximations to the material functions that have been used are as follows. Electron and ion mobilities, μ and μ_+,μ_-, were taken as 200 and 2 cm^2 V^{-1} s^{-1} respectively, where $W = \mu E$, $W_+ = \mu_+ E$ and $W_- = \mu_- E$; $\gamma = 2 \times 10^{-7}$ cm^3 s^{-1}, $\alpha/N = (E/N - 10^{-16})/200$ cm^2 for $E/N > 10^{-16}$ V cm^2, $\eta/N = 4 \times 10^{-19} - 10^{-3} \times E/N$ for $E/N < 24 \times 10^{-17}$ V cm^2, otherwise $\eta/N = 1.6 \times 10^{-19}$ cm^2, and $N = 2.5 \times 10^{19}$ cm^{-3} where N is the gas number density for air at 1 bar. For these model material functions, ionization equals attachment at E = 3.75 kV/cm, which becomes the

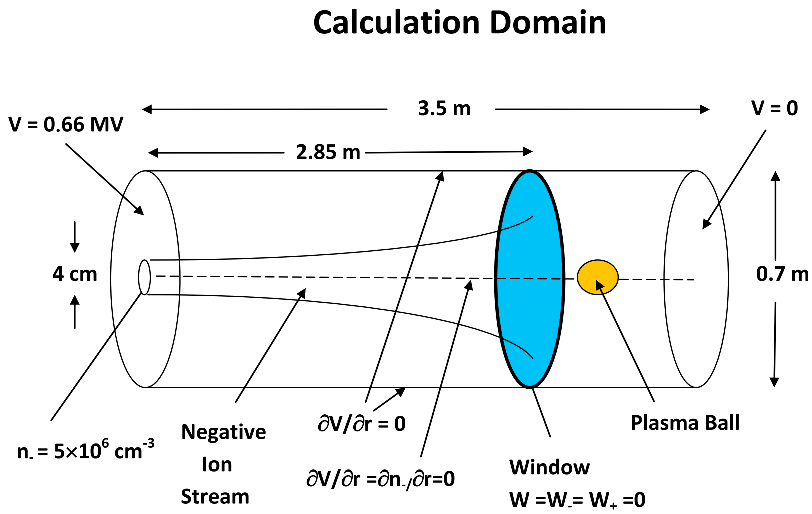

Figure 1. Calculation domain and boundary conditions.

sustaining field for a discharge. To prevent the need for extremely short time steps in the integration resulting from the term $n_e \alpha W$ in equations (1) and (3), limits were placed of $\alpha = 17.5\ \mathrm{cm}^{-1}$ and $W = 10^6\ \mathrm{cm\ s}^{-1}$ at high fields. These analytic representations are approximations to more accurate values [*Lowke*, 1992] as the aim of the calculations has been to derive gross qualitative features of the discharge, such as the movement of charges, rather than to make precise predictions.

[18] The domain and boundary conditions for the present calculations are illustrated in Figure 1. We consider a horizontal cylinder, 3.5 m long and of diameter 0.7 m at the center of which is a stream of negative ions impinging on a glass and insulating window placed at 2.84 m from the left hand end of the cylinder. The diagram is not to scale, either axially or radially. We calculate effects of a stream of negative ions impacting on the glass surface of the window under the influence of an imposed average background field of ~1.9 kV/cm. This field is produced by a negative potential of 0.66 MV applied to the left hand face of the cylinder. This potential is small in magnitude compared with known potentials of thunderclouds of the order of 100 MV [*Rakov and Uman*, 2003, p.111].

[19] Boundary conditions of zero axial and radial velocities for ion and electron flow are imposed at all grid cells at this axial position to simulate insulation properties of the glass. A boundary condition of $5 \times 10^6\ \mathrm{cm}^{-3}$ for the negative ion density is imposed for radii less than 2 cm at the left hand surface of the cylinder to provide the flux of ions at the surface of the window. Such a horizontal flux of ions could be provided to the windscreen of aircraft flowing through thunderclouds or to the window of a house after a downward flux of ions from a thundercloud hits the relatively insulating surface of the earth and spills out radially. The Poisson equation (4) is solved for the cylindrical region to account for space charge effects on the electric fields by taking boundary conditions of zero gradients in the potential with respect to radius at the outer boundary of the cylinder and potentials of 0.66 MV and 0 MV at the left hand and right hand surfaces. The convective flow effects of the charged particles were calculated using "backward differences" for the velocity derivatives with respect to position in equations (1–3). The nonuniform mesh had 100 × 100 cells, minimum mesh sizes being 1 cm in the axial direction and 1 mm in the radial direction.

[20] After several seconds there is an accumulation of charge n_s at the glass surface calculated to be $1.5 \times 10^9\ \mathrm{cm}^{-2}$. This surface charge density is consistent with an electric field $\Delta E = n_s e/\varepsilon_0 = 2.7$ kV/cm from Poisson's equation (4) which largely cancels the applied field at the outside surface of the glass but doubles the field on the inside surface of the glass to be ~5 kV/cm; see the curve marked "Before Ionization" of Figure 2. It is this enhancement of the electric field of the order of a factor of two by the space charge on the outer surface of the window which enables the initiation of the ball lightning discharge at the surface of the window. The initiation point will be at the position of maximum field produced by the external layer of negative ions on the outside of the glass window, which in our calculations is on the axis at the right hand side of the surface of the window.

[21] The critical sustaining field of order 4 kV/cm is determined by the field for which ionization equals

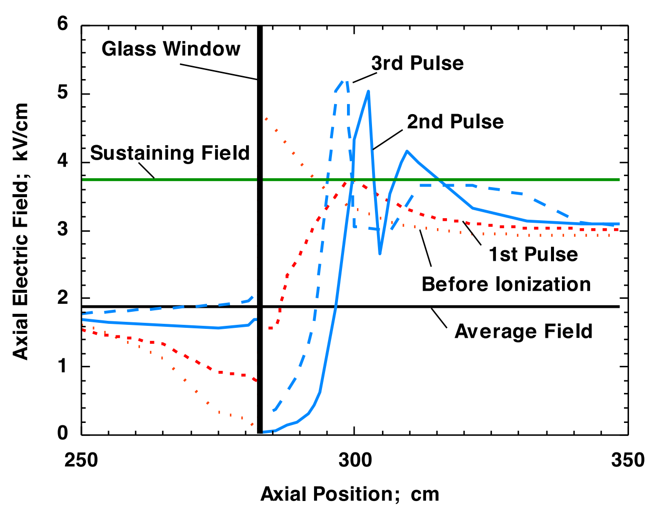

Figure 2. Axial field distributions at various discharge times.

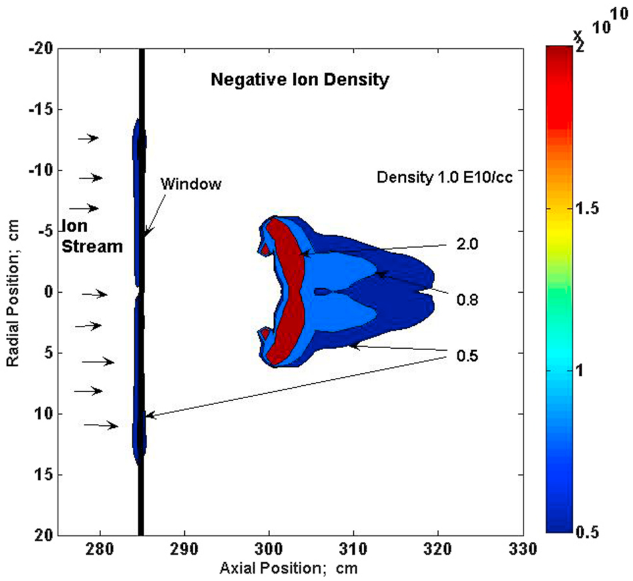

Figure 3. Negative ion density at the end of the second pulse.

attachment in the presence of a discharge with associated excited states of molecules. This field is dependent on average electron energy which is primarily determined by the value of *E*/*N*. Thus the critical field will be dependent on temperature and pressure as these factors influence the value of *N*. For the case of the aircraft observations, although the air pressure external to the plane would be significantly reduced due to altitude, the pressure inside of the cockpit would be approximately atmospheric pressure, so that the critical field would still be approximately 4 kV/cm.

[22] The enhanced field of ∼4 kV/cm produced by the layer of negative ions is sufficient to sustain an electric discharge on the right hand side of the glass provided that an initiating ionization event, such as a cosmic ray shower, provides the densities of energetic metastable molecules necessary to sustain the discharge. Without such an event fields of the order of 25 kV/cm would be necessary for breakdown. This requirement, involving cosmic rays, provides an explanation for the rare occurrence of ball lightning. After initial ionization in the high field region on the far side of the glass window, electrons and negative ions move away from the glass and positive ions move toward the glass and accumulate on the glass, tending to balance the electric field away from the inside glass surface from the negative ions on the outside of the glass. Such electric fields inside the glass window are shown to be reduced from ∼5 kV/cm to ∼1.5 kV/cm in the curve marked "1st Pulse" of Figure 2, and to even lower values for the second and third pulses.

[23] When the field is everywhere reduced below the sustaining electric field used in the calculations of 3.75 kV/cm, ionization is less than attachment and all electrons become attached to form negative ions. The discharge then "goes out," no longer emitting radiation. However, there is still a net negative electric field, causing the remaining positive and negative ions to move, and indeed separate from one another, particularly at the leading and trailing edges of the approximate sphere of charges. There is then an intensification of the electric field in these regions, so that there are regions where the field is again above the field at which ionization is possible of 3.75 kV/cm, as shown by the curve marked "2nd pulse" of Figure 2. These fields again produce ionization, particularly at the edges of the "ball" in a second pulse. Electron motion again causes a later reduction of the electric fields to be below the sustaining field of 3.75 kV/cm, so that the discharge is again extinguished. Our calculations have extended to three such pulses. It is proposed that ball lightning consists of such a pulsating discharge, which is very similar to that of normal corona, except that the sphere of charges constituting ball lightning is free to move away from the glass window, which is effectively an electrode, instead of the ball of a corona discharge which stays near the metal point of the cathode.

[24] The pulsating electric discharge from the present model is similar to that predicted in the ball lightning model of *Lowke* [1996], where it was proposed that the driving electric fields were from dissipating currents in the earth after a lightning strike. However, the decay time of such dissipating currents is generally a few milli seconds, much shorter than the lifetimes of ball lightning, which are of the order of 10 s.

[25] In the calculations, the calculated electric fields produced on the inside of the glass are only of the order of 5 kV/cm and do not attain the fields of 25 kV/cm required to initiate ionization in normal air, because the radial flow of ions outward along the external surface of glass limits the accumulation of ions at the glass surface. Thus a cosmic ray shower would be required to produce discharge conditions where excited states of nitrogen are present to enable a discharge at low fields of ∼4 kV/cm to be sustained. Ball lightning is, as a consequence, predicted to be a very rare event.

[26] Figures 3 and 4 show two dimensional plots of negative and positive ion densities for a time near the end of the "2nd Pulse" of Figure 2, when electrons have almost all become attached to form ions. The plots are almost identical, except that Figure 3 shows accumulation of negative ions on the side of the glass where the ions are incident and Figure 4

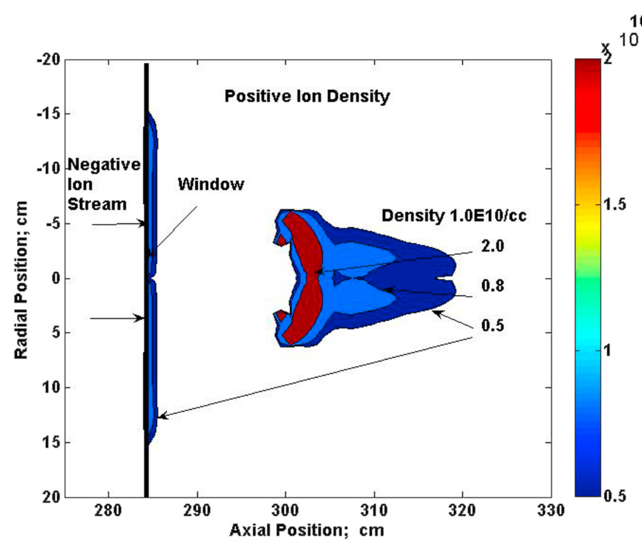

Figure 4. Positive ion density at the end of the second pulse.

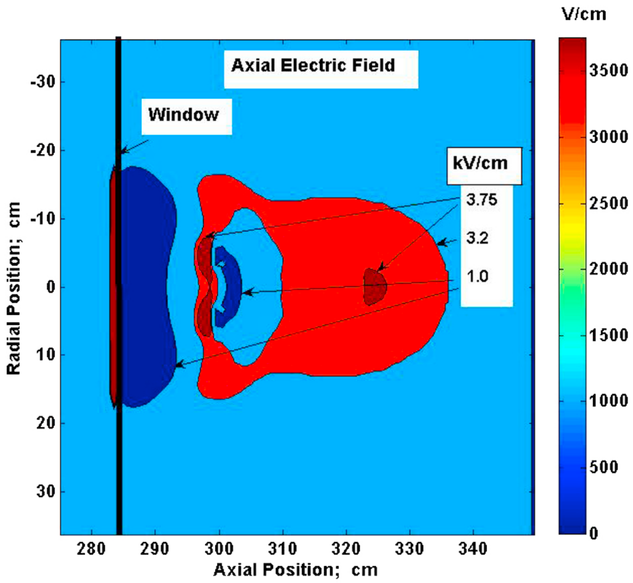

Figure 5. Electric field distribution at the end of the second pulse.

shows an accumulation of positive ions on the discharge side of the glass. The "ball" region of the discharge has a small negative charge equal to the total of the positive charges at the inside surface of the window, as ionization processes of the discharge always produce equal numbers of positive and negative charges. Figure 5 shows the calculated electric field distribution for this pulse. The ball discharge is completely separated from the initiating glass window with an almost zero electric field between the window and the ball. There is an accentuated electric field around the whole circumference of the ball, giving an effective "edge" to the ball. There is a region of almost zero electric field within the ball. The calculated length of time for the pulses when electrons produce light is $\sim$30 μs. The dark time between electron pulses is $\sim$300 μs, so that to human eyes the discharge will appear steady. Our calculations do not yield particularly spherical "balls" and are also not able to give features beyond the third pulse. However, the calculations omit the effect of gas heating. As ionization effects are a very sensitive function of E/N, where N is the gas number density, inclusion of heating effects is likely to give predictions of electron regions that are significantly more spherical. Furthermore, as we have used a simple explicit scheme for the numerical integration and backward differences for the convective terms, the predictions will be subject to errors due to numerical diffusion. The calculated potentials at the center of the window for the conditions of Figures 3–5 are 0.184 MV to the left of the window and 0.177 MV to the right of the window, with variations over the surface of $\sim$7 kV.

[27] Details of the shape and positions of the regions of high field of Figures 3–5 change continuously throughout any given pulse. Points within the discharge for which the electric field is high have large rates of ionization and thus enhanced production rates of electrons. But these electrons rapidly move due to the high electric field leading to a redistribution of the electric field, generally tending to reduce the extent of the region of high field. The "dark" times between pulses arise when the electric field is everywhere below the sustaining electric field. Ion motion during the time interval between the pulses cause the electric field to again increase above the critical field and thus produces renewed ionization and the formation of a new discharge pulse.

[28] It is found that the character of the predicted discharge depends markedly on the electric field present at the time of ignition of the initial discharge. A low field produces only a single pulse, where all of the positive charges from the first pulse are expended in the double layer at the glass surface. The "ball" then consists almost entirely of negative ions, which then dissipate as there can be no enhanced electric fields for ionization within the ball resulting from the relative motion of positive and negative ions. On the other hand, a very high field produces a long streamer-like discharge which dissipates the charges over a large distance. The intermediate initiating field of the present calculations produces enough ions so that although positive ions collect on the inside of the window to balance the charge on the outside of the window, the total number of remaining ions in the ball is so large that the number of positive and negative ions in the ball are approximately equal. The relative movement of these ions in the time interval between discharge pulses enhances local fields to be above the threshold for net ionization, so that electrons and light are produced in a continuously pulsating discharge that is free to move away from the window.

4. Discussion

[29] It is proposed that a stream of ions can produce space charge effects near insulators that makes possible the initiation of ball lightning. The most likely source of the stream of ions is from lightning discharges, particularly the stepped leaders of lightning discharges; the observations presented in sections 2.1 and 2.3 occurred during thunderstorms. Before the return stroke of any lightning flash, many stepped leaders are formed and remain in the atmosphere after a stepped leader initiates a return stroke from the ground to the cloud. Although equal numbers of positive and negative ions are produced by the ionization process in these stepped leaders, there is a flow of charges, particularly electrons, that produces significant out-of-balance local charge [*Lowke*, 2004]. After the return stroke of any lightning strike, electric fields are reduced and electrons attach to oxygen molecules, the effective attachment coefficient then being larger than the ionization coefficient. In a subsequent process that takes place on a millisecond time scale, positive ions recombine with negative ions. After recombination there remains the small out-of-balance charge that is necessary to produce the distribution of electric field required to maintain the corona and streamer discharges associated with the stepped leader. The density of these remnant ions used in the present calculations is 5×10^6 cm^{-3}, whereas the ion density in the original streamers of air are typically 10^{10} cm^{-3} [*Lowke*, 1992, 2004] to 10^{14} cm^{-3} [*Morrow and Lowke*, 1997]. The remaining ions will have a lifetime of 10 to 20 s, this being determined by the time necessary for them to be swept to earth by remaining electric fields between the thunderclouds and the earth.

[30] For the observation of ball lightning in aircraft presented in section 2.2, electrical corona was observed at the radome of the aircraft; this could be a source of an ion stream at the cockpit windows. In this observation, maximum electric power was being used for the production of radar, as the aircraft was flying through dense fog. It is known that breakdown fields for the inception of corona can be reduced by about a factor of two due to fog, [*Peek*, 1929; Figure 161]. The radar aerial would be designed to avoid electrical breakdown or the production of corona in normal operation, but in the exceptional conditions of dense fog and maximum power operation, corona could have been produced, resulting in the observed "horns" from the aircraft radome. This observation of the production of ball lightning without the presence of a thunderstorm is of interest since it indicates that it might be possible to produce ball lightning in a laboratory without the need for the replication of the extreme conditions of natural lightning.

[31] The aircraft observations of the present paper were made in 1975 and the 1960s. There do not seem to have been recent observations of ball lightning in the cockpits of aircraft, probably because most modern aircraft have an electrically conducting layer over the surface of the cockpit windows, usually to provide a means of electrically heating the windows to prevent the accumulation of ice.

5. Conclusions

[32] Detailed and reliable observations are presented of the formation of ball lightning at windows, in two cases at the windows of the cockpits of aircraft by the pilot and navigation staff. These observations support many previous reports of ball lightning appearing from the windows of houses and aircraft, with no damage to the windows.

[33] Calculations of effects from a stream of ions impinging on an insulating glass window predict the possibility of the production of an electric discharge on the far side of the window, with properties similar to ball lightning. Solutions of the electron and ion continuity equations, together with calculations of space charge effects, give an approximately spherical discharge separate from the window, with ion densities much larger than those of the incident ions. The discharge is pulsed, on a microsecond time scale. It is proposed that the observed ball lightning was produced from electric fields caused by the accumulation of ions on the windows, which are assumed to be insulating.

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