J. Phys. D: Appl. Phys. **29** (1996) 1237–1244. Printed in the UK

A theory of ball lightning as an electric discharge

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Received 30 May 1995, in final form 7 November 1995

Abstract. It is proposed, on the basis of solutions of electron and ion transport equations, together with Poisson's equation , that ball lightning is an electric discharge which is continuously varying on a microsecond time scale. It is further proposed that this corona-like discharge is sustained by electric fields associated with charges from a lightning strike dispersing along preferred conducting paths in the earth. The theory gives an explanation of the formation, lifetime, energy source and motion of ball lightning.

1. Introduction

Although ball lightning has been observed for centuries (Hill 1960, Singer 1971, Barry 1980, Ohtsuki 1988) there is as yet no generally accepted explanation of its occurrence. Ball lightning usually occurs after a local lightning strike and is seen as a 1–25 cm diameter luminous ball with about the intensity of a 20 W incandescent lamp. It almost always moves, has a speed of about 3 m s^{-1}, and is about 1 m above the ground. The motion can be counter to the prevailing breeze and can change direction erratically. Lifetimes are up to 10 s, whereupon the ball extinguishes, either noiselessly or with a bang. There have been many observations of ball lightning inside houses and even in aeroplanes (Uman 1968). There have been quite a number of observations of ball lightning passing through closed glass windows, with no apparent damage to the glass. Some reports state that there is no observable heat production associated with the ball, but Keunen (1993) reported heat sufficient to singe a wooden plank. Singer (1971) reviewed a report of the smell of ozone and nitrogen oxides after ball lightning and also static in a transistor radio's reception.

Theories which have been proposed in the past, apart from claims that observations are an optical illusion (Argle 1971), generally attempt to assign an external power source to explain the constant luminosity of the ball over periods as long as 10 s. Proposed power sources have included (i) a standing wave of electromagnetic radiation (Kapitsa 1955; Endean 1976, 1993), (ii) an electric arc powered by the electric field from a cloud (Uman and Helstrom 1966), (iii) nuclear energy (Altschuler *et al* 1970), (iv) antimatter (Ashby and Whitehead 1971) and (v) chemical combustion (Fischer 1981). It is difficult to see how these theories can explain how ball lightning can exist inside houses or pass through glass windows. A theory that ball lightning is simply hot luminous air with trapped radiation fails because it should then rise like a hot air balloon (Lowke *et al* 1969). A recent theory claims that ball lightning is a complex chemical phenomenon involving water vapour (Turner 1994).

Attempts to produce ball lightning in the laboratory using electric arcs have generally only produced balls originating from molten particles from the electrodes, which do not have the general properties of ball lightning (Silberg 1962, Barry 1968, Golka 1994). Aleksandrov *et al* 1990, simulated ball lightning with a spherical wire mesh in a high electric field.

When lightning strikes a point on the earth's surface, an amount of charge, usually negative, is transferred via the lightning arc from the cloud to the ground. Positive charge is then transfered from the ground to the cloud in times of up to 1 ms. This 'return stroke' has been successfully modelled to give theoretical magnetic and electric field waveforms as a function of time and distance from the lightning discharge in reasonable agreement with experimental results (Uman and McLain 1969, Little 1978). These models have assumed that the earth is a perfect conductor for the dispersing charge, although calculations assuming that the earth is an insulator of zero electrical conductivity give quite similar results for the vertical component of the electric field (Kamra and Ravichandran 1993). Recent photographs from experiments with triggered lightning (Fisher *et al* 1993, Fisher and Schnetzer 1994) and also with ordinary lightning (Krider 1977) indicate that lightning can produce filamentary arcing along the surface of the ground to distances of at least 20 m. These arc channels and also the 'fulgurites' of fused rock that are formed in the ground for many metres will be highly conducting during this initial stage of the dispersal of electric charge. It has been shown that the velocity of such charge dispersal during electrical breakdown in a gas is generally greater than 10^7 cm s^{-1} and greater than the electron drift velocity (Davies *et al* 1971, Morrow 1991).

Beyond this region of electric breakdown in the earth, the dispersing charge will encounter material which is usually an insulator such as rock, earth and water. The

0022-3727/96/051237+08$19.50

electrical conductivity, σ, of this region, is orders of magnitude less than that for a lightning arc or a solid conductor; for example, typical values of σ for water and sandstone are 10^{-2} and 10^{-6} S cm^{-1} (Touloukian 1989) compared with values for an arc and copper of 100 and 10^6 S cm^{-1}. Velocities for the dispersion of charges in insulators are determined by the mobility, μ, of the charges in the material (Ashcroft and Mermin 1976). The measured electron mobilities in such insulators are orders of magnitude less than those in conductors; for example, for water and polymers, values of μ are 1.8×10^{-3} and 10^{-6} cm^2 V^{-1} s^{-1} (Bartnikas 1983, 1994), compared with 10^4 cm^2 V^{-1} s^{-1} for an arc. It may well be that the dispersing charges at these large distances from the lightning strike are negative ions rather than electrons and negative ions have lower mobilities; for negative ions in water $\mu \simeq 10^{-3}$ cm^2 V^{-1} s^{-1} (Schmidt 1994).

In the present paper it is proposed that these dispersing charges at large distances from the point of a lightning strike, travelling along a filamentary path near the surface of the earth, produce an electric field above the earth which is the source of power and motion for the ball lightning. It is further proposed, on the basis of solutions of electron and ion transport equations together with Poisson's equation, that the ball lightning is an electric discharge which is continuously varying on a microsecond time scale. It is shown that space charge distortions by positive and negative ions can produce a local maximum in the electric field about 1 m above the earth's surface and sustain a time-varying discharge with properties similar to ball lightning.

2. Charge motion in the ground

Ball lightning is almost always seen immediately after a local lightning strike. Most lightning strikes are of less than 35000 A peak current and of duration less than 1 ms. In a typical lightning flash, approximately 20 C of negative charge is delivered to the ground from the electric arc that constitutes lightning (Uman 1987). The arc radius at these currents is only of the order of 1 cm (Lowke 1979).

2.1. Charge motion during the initial breakdown period

The electric fields, E, produced by a charge of 20 C are extremely large. For 20 C in a sphere of radius $R = 1$ cm, $E \simeq 10^{13}$ V cm^{-1}, as calculated from $E_s = q/(4\pi\varepsilon_0 R^2)$, obtained from a solution of Poisson's equation, $\nabla \cdot \boldsymbol{E} = -en_e/\varepsilon$; $e = 1.6 \times 10^{-19}$ C is the electronic charge, n_e is the negative charge density and $\varepsilon = \varepsilon_0 = 8.85 \times 10^{-14}$ C V^{-1} cm^{-1} is the permittivity of free space. This field is very much larger than the 1 MV cm^{-1} which is sufficient for the electrical breakdown of most solids (O'Dwyer 1973). The electrical breakdown proceeds similarly to breakdown in a gas through the formation of filamentary discharges from the point of the lightning strike (O'Dwyer 1973). Such filaments have been observed at the surface of the ground extending out to at least 20 m in triggered lightning (Fisher and Schnetzer 1994).

On theoretical grounds we would also expect the extent of this breakdown region to be very large. Firstly, if the dispersion of the 20 C of the negative charge from the lightning strike were perfectly spherical, the radius of the sphere, as calculated from the above expression for E, would need to be 40 m for the field to be reduced to 1 MV cm^{-1}. This distance will be reduced by the square root of the effective dielectric constant, K, of the earth; values of K for most substances are less than 10. However, the distance will be increased because charge dispersion will not be uniformly spherical, but rather along preferential filaments or fingers because of local non-uniformities in the conductivity of the earth. The local electric field at the tips of cylindrical fingers will be very much more than the field at the surface of a uniform sphere, so that the fingers will extend to a greater distance before effects of the electric field become negligible.

Expansion of the charge along 'fingers', rather than as an isotropic spherical expansion, will occur, even in a medium of uniform conductivity, if the initial charge distribution is non-spherical, for example cylindrical. An analytic expression for the field, E_c, at the centre of the end of a cylinder is derived to be

$$E_c = \frac{q}{2\pi\varepsilon R_c^2}\left[\left(1+\frac{R_c}{L}\right) - \left(1+\frac{R_c^2}{L^2}\right)^{1/2}\right]$$

using the method of Davies *et al* (1964), where the cylinder is of radius R_c, length L and has a uniform distribution of total charge, q. The ratio of the field E_c for a cylinder to the field E_s for a sphere, also with total charge q but of radius R_s, using the above expression for E_c and the previous expression for E_s, is then about R_s/R_c for $L = 2R_s$ and $R_c < R_s$. Thus the field at the ends of the cylinder or 'finger' will be strongly enhanced compared with that on a sphere and this field will cause charge dispersion to make the shape of the finger even more elongated. The electric field of self-repulsion driving the finger development will cause negative space charge to form at the tips of the finger, similar to that predicted for the tips of streamers in gas breakdown (Davies *et al* 1971, Morrow 1991), and will produce very high local electric fields.

2.2. Charge motion far from the lightning strike

Further dispersion of the charge, when self-repulsive fields are less than the breakdown field in the earth, will proceed through the various materials of the earth (sandstone, granite, clay, basalt, water and so on), which are insulators rather than conductors. The electrical conductivities of these materials are many orders of magnitude lower than those of conductors, ranging from 10^{-16} S cm^{-1} for powdered dry basalt to 10^{-2} S cm^{-1} for salt water (Touloukian 1989), whereas values for an arc and for conductors are 100 S cm^{-1}, or more. For insulators there are no free electrons in the conduction band, hence when charges from the lightning strike reach the insulating materials, there will be excess and non-equilibrium values of the electron density (Ashcroft and Mermin 1976). The densities will be determined by equations involving the carrier mobilities, μ, where μ for any insulator is defined by W/E, and W is the drift velocity of the carriers under the influence of the local field E.

Again the electric charge will travel preferentially along 'fingers' of low electrical resistance that exist in the earth, with a concentration of charge near the tips of these fingers. The direction of motion of these charges will change if there is a change in the orientation of the preferred conduction path influenced by the carrier mobility and resistivity of minerals in the earth. During thunderstorms it is usually wet at the surface of the earth and, because the electrical conductivity of water is usually higher than that of the drier earth materials below the surface, there will be a tendency for the electric charges to be near the surface of the earth. The direction of motion of the advancing charge will also be influenced by sudden changes in the potential distribution over the earth's surface, as caused for example by the deposition of further electric charge upon the earth by another lightning strike, even if it occurs some kilometres away. It is proposed that the force determining the motion of ball lightning is the electric field associated with the spreading charge along such a finger near the earth's surface. Thus we have an explanation of the fact that ball lightning is frequently observed to move counter to the prevailing breeze or wind.

From this theory, the travelling speed of the ball will be determined by the speed of the advancing charge in the earth and also, to some extent, by the motion of the charges in the air above the charge in the earth, to be discussed in the next section. The experimentally observed electron mobilities in insulating materials have a very large range, 10^{-6} cm^2 V^{-1} s^{-1} for polymers, 1.8×10^{-3} cm^2 V^{-1} s^{-1} for water and about 0.1 cm^2 V^{-1} s^{-1} for organic liquids (Schmidt 1977), compared with 35 cm^2 V^{-1} s^{-1} for copper and generally 10^3–10^4 cm^2 V^{-1} s^{-1} for crystals (Kittel 1966). Charge dispersion could be through ions rather than electrons; negative ion mobilities in water are about 10^{-3} cm^2 V^{-1} s^{-1} (Schmidt 1994). Also, the effective mobility will be a function of voids present in the earth.

Typical observed speeds of ball lightning are 3 m s^{-1}. It is known that the minimum field required to sustain an electric discharge at atmospheric pressure in air is about 5 kV cm^{-1} (Phelps and Griffiths 1976) so that fields of this order need to be present at the tips of the propagating charges. Thus, using $\mu = W/E$, a mobility of about 0.2 cm^2 V^{-1} s^{-1} would characterize the speed of ball lightning. The mobilities of the various negative and positive ions and also of clustered ions in air are all about 2 cm^2 V^{-1} s^{-1} (Viehland and Mason 1995). It is probable that the propagation speed will be due to combined effects on charges in and on the the earth's surface, and also to the motion of the ion cloud surrounding the ball lightning, discussed in the next section. In the present theory, it is proposed that, in the rare event of ball lightning, the effective mobility of charges in the earth has a value sufficient to sustain the charge motion in the earth and the ball in the atmosphere.

It is of interest to evaluate an approximate time constant for the decay of charge density dispersing through its own field of self-repulsion in a uniform medium. The time constant τ for the decay of the charge density can be estimated from $(1/n_e)\partial n_e/\partial t = -1/\tau$, where the time-dependence of the charge density n_e is given by the electron continuity equation

$$\frac{\partial n_e}{\partial t} = -\nabla \cdot \boldsymbol{j}$$

where $\boldsymbol{j}$ is the electron flux density. Thus, using $\boldsymbol{j} = -n_e\mu\boldsymbol{E}$ and Poisson's equation for E, namely $\nabla \cdot \boldsymbol{E} = -en_e/\varepsilon$, we can solve the electron continuity equation assuming that n_e, μ and ε are independent of position and obtain $\tau = \varepsilon/(n_e\mu e)$. Using values for water of $\mu = 1.8 \times 10^{-3}$ cm^2 V^{-1} s^{-1} and the dielectric constant $K = 80$, where $\varepsilon = K\varepsilon_0$, we obtain $\tau = 10$ s when the space charge density is 10^9 cm^{-3}. Such times are the order of magnitude of lifetimes of ball lightning and larger times would be predicted were we to use values of μ for ions rather than electron drift.

In some applications, the above derivation for τ is expressed as $\tau = \varepsilon/\sigma$, where $\sigma = n_{eq}\mu e$ and τ is then called the 'dielectric relaxation time' (Mott and Davis 1971). The electrical conductivity σ is then evaluated from the reciprocal of the resistivity. However, this use implies a constant value of σ with time, determined by a constant value of equilibrium charge density given by $n_{eq} = \sigma/\mu e$. For the unusual situation of expanding charges from a lightning strike in the insulating material of the earth, the density of the charge carriers will not be an equilibrium value that is constant with time, so that evaluations of τ from resistivity values are not appropriate.

Figure 1 shows the three principal changes in the distribution of electric charges that are associated with a lightning strike. (i) The development of strong negative electric charges in the base of a thunder cloud, for example due to the interaction of wind and freezing supercooled rain drops in the cloud (Malan 1963). (ii) The rapid transfer of charge through the highly conducting arc of a lightning strike, positive charge going to the cloud and negative charge to the earth to distances of many metres. (iii) The very much slower further dispersion of negative charge along 'fingers' of relatively high electrical conductivity in the earth, in which the field at the head of the advancing charge in the earth will be less than 1 MV cm^{-1}. It is proposed that, in the air above this advancing charge, there will be occasions when the field will be greater than 5 kV cm^{-1} and hence able to sustain ball lightning.

3. Charge motion in the air

We now examine the development of a ball lightning discharge in the high-field region above the earth where there is a moving finger of charge. The field for electric breakdown in air is about 30 kV cm^{-1}. However, once a conducting air plasma has been formed, it can be sustained by the much lower field of 5 kV cm^{-1} because processes such as two-step ionization and detachment of negative ions by metastable species occur (Lowke 1992). Fields of 5 kV cm^{-1} would be produced by a charge of 20 C that has dispersed symmetrically to a radius of 600 m. For non-symmetric dispersion along the surface of the earth, such fields would be maintained at some points at much larger distances, but would be reduced by the earth's dielectric constant.

We consider a position and time at which the electric field immediately above the earth is 6 kV cm^{-1}. This field without space charge effects in the air will decrease with height, z, approximately according to an inverse square law, as shown in figure 2 for time $t = 0$ μs, calculated for the case of a negative charge centre 1 m below the ground. We now consider effects which follow from there being a few seed electrons immediately above the ground. Such electrons will move upwards in the negative electric field. Their number density will increase due to ionization in high-field regions and will decrease due to attachment to oxygen molecules forming negative ions in low-field regions. The electron density will also decrease due to recombination with positive ions. There will be distortions of the electric field due to space charge effects caused by the separation of positive and negative charges in the electric field.

The temporal and spatial behaviour of these charges (Morrow and Lowke 1995) is determined by the continuity equations of electrons, positive ions and negative ions, namely

$$\frac{\partial n_e}{\partial t} = -\frac{\partial}{\partial z}(n_e W) + n_e \alpha W - n_e \eta W - \gamma n_e n_+$$

$$\frac{\partial n_+}{\partial t} = -\frac{\partial}{\partial z}(n_+ W_+) + n_e \alpha W - \gamma n_e n_+ - \gamma n_- n_+$$

$$\frac{\partial n_-}{\partial t} = -\frac{\partial}{\partial z}(n_- W_-) + n_e \eta W - \gamma n_- n_+$$

where α is the ionization coefficient, η the attachment coefficient, γ the recombination coefficient, n_e, n_+ and n_- are the densities of electrons, positive ions and negative ions, respectively, and W, W_+ and W_- are the drift velocities of electrons, positive ions and negative ions, respectively. Space charge effects are determined by Poisson's equation which is

$$\frac{1}{z^2}\frac{\partial}{\partial z}(z^2 E) = \frac{e}{\varepsilon}(n_+ - n_e - n_-).$$

Poisson's equation has been expressed in spherical coordinates to take an approximate account of the variation of the electric field with distance. The continuity equations are expressed in Cartesian coordinates, which has been found to be a fair approximation in calculations of properties of corona discharges (Morrow and Lowke 1995).

Values of the attachment and ionization coefficients are a function of E/N and for air are equal at $E/N = 120$ Td; N is the gas number density, 1 Td is 1 Townsend or 10^{-17} V cm^2. The electric field corresponding to 120 Td at a pressure of 1 bar is 30 kV cm^{-1}, which is often called the critical field. However, in an electric discharge, the ionization is increased due to effects such as two-step ionization by electrons and possibly also by photo-excitation. Furthermore, the nett attachment is decreased due to effects such as the detachment of negative ions by a$^1\Delta_g$ oxygen metastable molecules (Lowke 1992). Modified effective values of α and η as a function of E/N have been used to account for these effects and were chosen to give a critical field of about 5 kV cm^{-1} when $\alpha = \eta$. Conventional values have been taken for the drift velocities as a function of E/N and for the recombination coefficient (Lowke 1992).

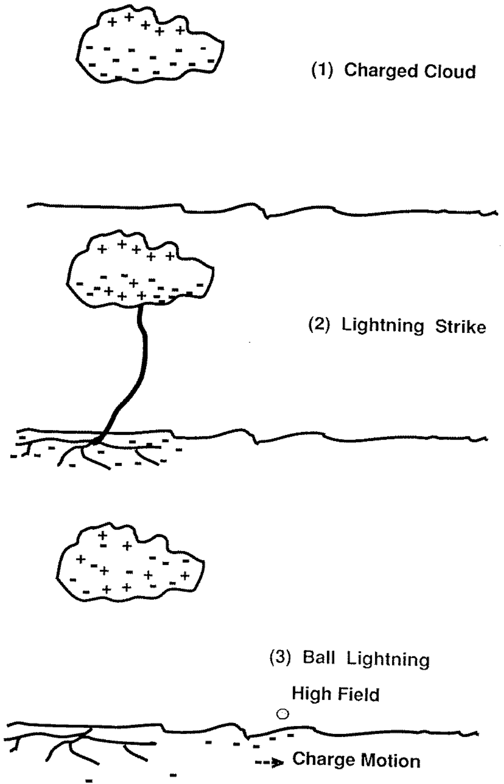

Figure 1. Electric charge redistribution, during and following a lightning strike.

The analytic expressions used to approximate the transport coefficients are as follows: $W = 10^{22} E/N$ cm s^{-1}, $W_- = W/100 = -W_+$ cm s^{-1}, $\alpha/N = (E/N - 10^{-16})/200$ cm^2 for $E/N > 10^{-16}$ V cm^2 and $\alpha/N = 0$ otherwise, $\eta/N = 4 \times 10^{-19} - (E/N)/1000$ cm^2 if $E/N < 4 \times 10^{-16}$ and $\eta/N = 0$ otherwise, $\gamma = 2 \times 10^{-7}$ cm^3 s^{-1} and $N = 2.5 \times 10^{19}$ cm^{-3}

Figures 2–4 show the calculated electric field, electron density and positive ion density, obtained from solutions of the above four equations. The equations give predictions of these four quantities as functions of time and height for a discharge which is initiated by electrons of number density 1000 cm^3 starting at ground level in the high-field region from the finger of dispersing charge below the ground surface. The charge densities were obtained from simple explicit solutions of the continuity equations, using upwind differences for the convective terms for numerical stability.

The numerical solutions of the electric field were obtained from Poisson's equation, subject to the boundary condition that the integral of the electric field is equal to the potential over the integration region, which was taken as 500 kV. Using a value of E at the earth's surface from the previous time step, a particular integral solution to Poisson's equation is obtained by integration of the

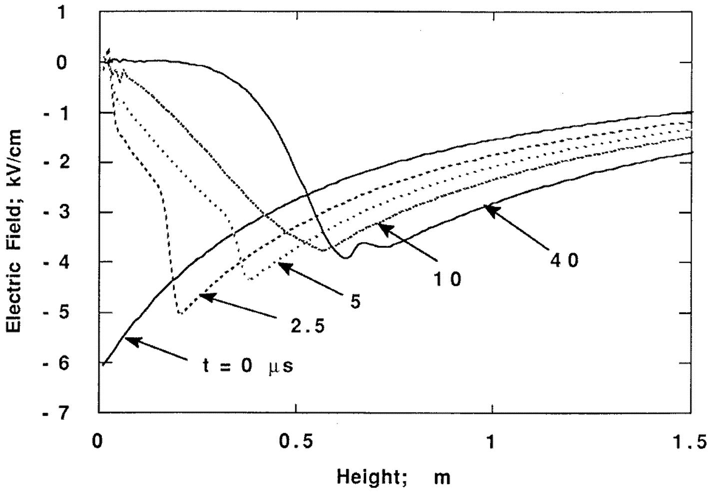

Figure 2. Calculated space charge distortions to the vertical electric field above the ground, due to spreading negative charge below the ground from a lightning strike.

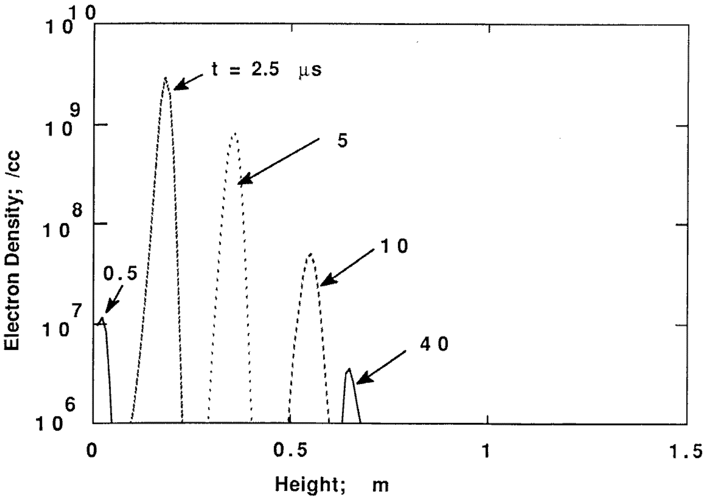

Figure 3. Calculated electron density as a function of time from an initial electron density of 1000 cm^3 in the high-field region immediately above the earth's surface.

equation, taking into account the space charge distribution. Then a term A/z^2 is added to this solution where the value of A is chosen so that the integral of the final solution of E over the integration region is equal to the potential for the input boundary condition. This solution is valid because A/z^2 is the complementary function of the equation, being a solution of $(1/z^2)\partial(z^2E)/\partial z = 0$. The character of the solutions shown in figures 2–4 has been verified by further calculations using a computer package which solves Poisson's equation more accurately and obtains solutions of the electric field in two dimensions.

From figure 2 it is seen that there is a significant distortion of the electric field, so that after 10 μs it has a maximum above the earth's surface at heights of the order of 1 m. Similar maxima in the electric field are obtained in calculations of properties of corona discharges (Morrow 1991). From figure 3 it is seen that the developing electron pulse spends most of its time at a significant height above the surface of the earth. Thus most of the radiation will be emitted in this region above the earth. The initiating electrons grow in numbers by ionization in the electric field, but after 10 μs the electron density is rapidly reduced. The positive ion density as a function of time is shown in figure 4. The negative ion density is equal to the positive ion density to within a few per cent, the difference providing the net space charge which distorts the electric field due to the finger of charge below the earth.

The calculations represented in figures 2–4 were continued for later times. The high electric fields then cause separation of the positive and negative charges, the formation of new high-electric-field regions and a re-ignition of the discharge. These re-ignitions constitute further pulses of current. In our calculations, the detailed structure and frequencies of these re-ignitions are dependent on the mesh size, the initial conditions chosen for the calculations and whether our calculations use a one- or a

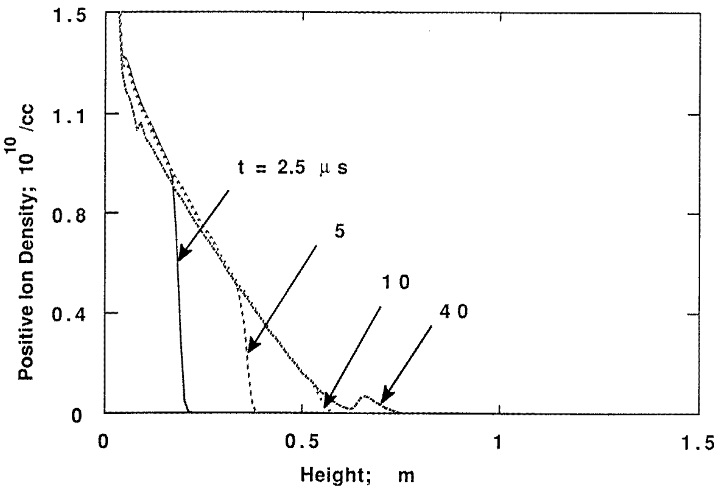

Figure 4. Calculated ion densities as a function of time for the calculations of figures 2 and 3. Positive ion and negative ion densities are equal to within a few per cent.

two-dimensional calculation of the electric field. We note similar complexity in the results of calculations of discharge development with account taken of space charge made by Vitello *et al* (1994). For the present paper the detail of these re-ignitions is unimportant. Re-ignitions do occur and the discharge proceeds as a series of pulses. It is proposed that this continuing series of current pulses constitutes ball lightning.

Accurate calculation of the details of successive current pulses is not feasible because of the following four physical processes. (i) The time for re-ignition will depend on the residual electron density, which will depend on electron densities produced by background radiation processes. (ii) Any increase in temperature from prior pulses will affect the ionization coefficient. This coefficient is a strong function of temperature, because a temperature increase reduces the number gas density, N, and thus increases E/N. Although gas heating effects are not essential for this model of ball lightning, they will have a strong influence by tending to make the discharge spherical. (iii) Space charge effects will be influenced by removal of charges, particularly in the low-field region far from the surface of the earth, by the convective flow resulting from the motion of the ball, which is transverse to the direction of z in the calculations of figures 2–4. (iv) The effective ionization and attachment coefficients will depend on background densities of metastable molecules of oxygen and nitrogen produced from previous current pulses.

4. Discussion

According to the present theory, ball lightning is a time varying glow discharge similar to corona discharges. Glow discharges at atmospheric pressure are difficult to sustain because increases in temperature cause increases in E/N and thus an increase in the level of ionization. Increased ionization causes further increases in electron current with further gas heating which leads to an electric arc. On many occasions ball lightning is observed to terminate in a loud bang, consistent with rapid gas expansion accompanying the rapid formation of an arc. The discharge is then terminated due to the rapid dispersion of the negative charges through the highly conducting arc channel and the consequent removal of the local maximum in the electric field. The convective cooling due to the movement of ball lightning helps maintain the discharge in the glow state. However, if the ball is obstructed in its motion by a solid object, the convective cooling due to gas flow through the air will be greatly reduced and it is more likely that an arc will be formed. Of course cases in which ball lightning is extinguished without a bang are explicable simply in terms of the reduction in the driving field, which occurs as the negative charges below the earth disperse from the point of the initiating lightning strike.

It is of interest that two eye witnesses interviewed by the author, who observed ball lightning at night time, reported faint luminosity between the main ball and the ground. Such observations are consistent with the present theory which predicts some discharge activity and significant ion densities in this region, as shown in figure 4.

The predictions indicate that the discharge will proceed as a series of rapid pulses with a period of the order of 1 μs. Thus radio frequency noise would be expected and audible noise is also possible, as has been noted in some observations of ball lightning (Dimitriev 1969, Singer 1971 pp 30–32) and also occurs in coronae. Because the electrons of the discharge have sufficient energy to ionize the air, there will also be dissociation of air into O and N atoms and we would expect some production of ozone and nitrogen oxides. A quantitative analysis of the gas composition as a function of time made by Dimitriev (1969), of gas samples from the immediate neighbourhood of the path of ball lightning showed concentrations of ozone and nitrogen oxides of about 1 mg m^{-3} which is about 50 times the normal concentration.

The initial formation rate of the discharge, according to the calculations shown in figures 2–4, is of the order of microseconds. Thus the present theory can explain the observations of balls passing through glass windows. As the front of the finger of electric charge that provides the electric field moves in the earth below a window, the electric field will pass through the window. Then the discharge can reform on the other side of the window within a few microseconds.

A requirement of the present theory is that ball lightning be initiated by a lightning strike and that its general direction of motion of the ball be away from the point of contact of the strike with the ground. All of the seven eyewitness accounts of ball lightning reported to the author are consistent with, or at least not inconsistent with, this requirement. Furthermore, the motion of the ball lightning would be expected to be influenced by the composition and electrical conductivity of the ground below the ball. Two of the observations reported the ball following the centre of a roadway, in one case of bitumen and the other of red gravel, and are consistent with this hypothesis.

A further requirement of the present theory is that electric fields of 5 kV cm^{-1} or more exist to make it possible for there to be a gas discharge in air. Electric field measurements have been taken for many years with field mills in the vicinity of lightning strikes (Uman 1987). Fields of this magnitude have not been observed for times as long as 1 s, although fields as high as 2 kV cm^{-1}, 10 m from the strike, have been measured for a few microseconds during the breakdown phase with triggered lightning (Fisher and Schnetzer 1994).

It is proposed that the reason high fields have not been observed for the late period of the charge dispersion is that the relatively small volume of the luminous ball is surrounded by a large cloud of positive and negative ions. Such ions are predicted, as in figure 4, to occur particularly at the surface of the earth, where most field measurements are made. These ions act to shield the electric fields, so that at even a few centimetres from the luminous ball, the electric field is reduced to near zero, as for the curve for 40 μs near the surface of the earth in figure 3. It has previously been recognized that effects of space charge in the atmosphere have a significant effect in reducing the measured electric fields during thunderstorms (Standler and Winn 1979). Such distortion is particularly serious when the time duration of the field is sufficient for charged ions and even charged dust particles that always exist in the atmosphere to drift into the region surrounding the high field, thus distorting the field existing at the field mill.

Ball lightning has been observed inside a metal aircraft during a thunderstorm and St Elmo's fire was also seen at the wing tips of the plane. With the proximity of thunderclouds, which are known to be charged to potentials of hundreds of millions of volts, the existence of fields of 5 kV cm^{-1}, or more, which are necessary to initiate a corona or ball lightning discharge, is highly likely. However, the geometric configuration and potential distribution which determines the electric field is very different from the earth-bound ball lightning of the present study.

5. Summary

It is proposed that ball lightning is produced and sustained by the electric fields associated with the dispersing electric charges from a local lightning strike moving along fingers of high conductivity in the earth. Calculations show that space charge effects would be expected to produce a maximum of the electric field a short distance above the ground and would produce a local discharge that is pulsating on a microsecond time scale that is similar to ball lightning. The theory provides an explanation for (i) the lifetime and energy source of the ball lightning, (ii) why ball lightning does not rise even though the discharge may be warm, (iii) why the ball lightning frequently moves erratically and counter to the wind and (iv) the production of ozone and radio noise, noted in some observations of ball lightning.

Acknowledgments

The author is indebted for discussions and comments to the following eyewitnesses of ball lightning in Australia, many of whom have written to the editor of *Australian Geographic* following an article by Hill (1994), on the observation of Mr Joe Keunen: Mr Joe Keunen, Canberra; Mrs M (Trixie) Webster, Perth; Mrs M Close, Stanley, Tasmania; Mrs Helen Anderson, Bargara, Queensland; and Mr Maurie Keane and Mr Jock Arnold of Sydney. He is also indebted for discussions to his colleague, Dick Morrow, of the CSIRO, on whose work many of the ideas of this paper are based and to Professor R Crompton of Canberra and Professor M Darveniza of Brisbane. He is grateful to John Quartel for checking the calculations using a two-dimensional Poisson solver and to Professor M A Uman of the University of Florida, Gainesville, USA, for a critical reading of an early version of the manuscript.

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