Electric Ponderomotive Forces Cause Explosive Ball Lightning Damages

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ABSTRACT

It is well known that open air ball lightning (BL) often ends with a large explosion, particularly when an unforeseen destructive interaction causes premature demise of the BL. The destructive force of the explosion is known to be mainly of mechanical nature, ripping apart various components of bodies. It is noticed that these components usually differ by their dielectric constant.

On the other hand, the Maser-Soliton BL theory is based on the presence of a large volume atmospheric maser that causes an avalanche of identical photons in a process known as "spiking". The present paper investigates the spiking phenomena in atmospheric masers that cause BL. The rise time of this runaway process is found to decrease when the number of cubic miles in the maser volume increases. This, in turn, leads to the conclusion that there is no time for screening. Extremely high electromagnetic fields are thus created, leading to enormous ponderomotive (Maxwellian) tensions and forces.

1. Introduction

When lightning strikes on flat terrain, a strong homogeneous electric field pulse is present simultaneously in a large volume of moist air, of the order of cubic miles. As shown earlier (Handel 1988, 1989), this pulse can lead to homogeneous population inversion in the rotational energy levels of the H_2O molecule. Close to mountain tops the electric field and the ensuing population inversion is limited to a cone-shaped volume, so this pulse does not lead to maser action without cavity walls. On flat terrain this field pulse will sometimes lead to maser action for a period of the order of seconds, due to the low rate of forbidden transitions between closely spaced pairs of rotational energy levels of the water molecule. The condition for this maser action to take place is that the gain G exceeds the loss L in the number of photons per time unit

$$dn/dt = G-L > 0, \qquad (1)$$

resulting in a net increase in the number of photons n first in a certain, well-defined standing wave mode of oscillation of the decimetric electromagnetic spectrum, or in small number of modes of the same frequency. The loss term can always be represented in terms of an effective cavity lifetime τ_c, and in terms of an effective load lifetime τ_l, the load being represented by the caviton, i.e., by the visible BL. In the open-air case there are no cavity walls, at best some reflecting objects, such as the trees lining an opening in the forest. In the absence of any cavity walls and reflecting objects or boundaries, τ_c assumes the lowest value, of the order of l/c, where l is the diameter or characteristic size of the inverted volume that can be of the order of several miles. With l=3km we get τ_c = 3km/(3 10^5km/s) = 10^{-5}s, better than for many resonant cavities with copper walls. On the other hand, on a high peak, such as K. Berger's Observatory on Mount San Salvatore in Lugano (Switzerland) we have l≈10m and $\tau_c \approx 3\ 10^{-8}$ s, which precludes maser action.

The gain G is from stimulated emission, being proportional to the number N_2 of molecules present in the upper maser level E_2, and to n+1, i.e., roughly to the number of photons already present in the mode under consideration

$$dn/dt = K(n+1)N_2 - n/\tau_c - 1/\tau_l, \qquad (2)$$

$$dN_2/dt = -KnN_2 - N_2/\tau_2 + R_e, \qquad (3)$$

where we added also the rate equation for the upper maser level population N_2 in terms of the relaxation time τ_2 ($>>\tau_c$) of the upper maser level, a time which can be as long as a second or a minute, because the transition is in fact one of the many well-known strongly forbidden transitions between pairs of nearly coincident rotational energy levels of the H_2O molecule. It is becoming only weakly allowed under the influence of perturbing fields. We also included an effective pumping rate R_e. It describes the rate by which, in some cases, the population inversion is replenished by various processes (such as, e.g., a circulation of inverted air through a barn, or recuperation of a hole burned into an inhomogeneously widened gain profile in the frequency domain). De-excitation from the upper maser level E_2 is mainly to a lower level E_1 with a population that has been assumed negligible. Otherwise N_2 symbolizes the population difference N_2-N_1.

In the quasi-stationary regime the time-derivatives are zero in Eqs. (1)-(2). We can then eliminate N_2 and solve the resulting quadratic equation for n, with the result

$$n = (p/2)\{ r-1 + [(r-1)^2 + 4r/p]^{1/2}\}, \qquad (4)$$

where $p = 1/K\tau_2$, $r = R_e/R_t$ is the reduced pump rate, $R_t = 1/\tau_2 K\tau$ is the threshold pump rate, and $\tau^{-1}=\tau_c^{-1}+\tau_l^{-1}$. Since p is a very large number of the order of 10^{20}, Eq. (4) describes a large increase of the number of photons n as a function of r, whenever r exceeds unity. Precisely this is what happens at the demise of a BL discharge. The BL demise causes τ_l to become suddenly infinite, and therefore r to exceed unity considerably. A similar spike exists also at the creation of the BL discharge, when the original population inversion is caused by the initial field pulse.

After the creation of the population inversion by the large initial electric field pulse, the initial population inversion N_2 decays very fast due to strong maser action. However, it continues for a much longer period of the order of τ_2, because the population inversion remains unaffected in the nodes of the standing electromagnetic maser wave, being depleted only at the antinodes. This can lead to continuous regeneration of the population inversion (equivalent to an effective pumping rate R_e) through the migration of new groups of Doppler shifted atoms into the spectral resonance window, and due to the gradual motion of the air from nodes to antinodes. Thus a quasi-stationary, slowly decaying, maser action can sustain a BL over a considerable interval of time.

Let us consider in detail what happens qualitatively after the sudden creation of an initial population inversion $N_2 >> N_{2th}$, i.e., much larger than the threshold level required by Eqs. (2)-(3) for oscillation. The photon number n builds up very rapidly from noise to a value considerably higher than the level appropriate for the quasi-stationary operation appropriate for R_t. This causes a local depletion (hole) to values well below the threshold value in the inhomogeneously broadened line profile, which in turn stops the maser action. This ends the first spike, which ignites the BL by causing ionization in a point of resonance (Handel and Schneider, 1985). The population inversion regenerates itself, because other groups of excited molecules from within the inhomogeneously broadened line profile move into the active window, and again a spike of maser action takes place. These spikes are repeating themselves with gradually decreasing amplitude, until the ball is destroyed prematurely, or until it dies out. In the first case, but also sometimes in the second case, spiking resumes because t_l suddenly becomes infinite, as the load (which was the BL) disappears. This final act of spiking in the absence of the BL load can be very destructive, because both the electric field amplitude and n increase explosively to very high levels, tearing apart electrostatically various dielectrics which happen to be in the vicinity of the former BL.

The spiking process also provides the explanation for the much lower temperature of BL, compared to the arc discharge that is normally obtained at atmospheric pressure in the laboratory. Indeed, the BL continuously tries to extinguish, due to the absence of free electrons at the low temperatures at which BL is observed, and that often are only slightly higher the surrounding temperature, particularly in the case of orange-colored BL. When the discharge attempts to end, however, the vanishing load generates the next spike. The spike consists of photons identical to the ones in the previous spike, because it is generated through stimulated emission initiated by photons still present in the standing wave. These new photons have a large maximum of their wave function, i.e., electric field, in exactly the same anti-nodal place in which the BL was located. This is why there is no buoyancy, even in the considerably hotter white form of BL, which resembles the H-discharge in Babat's 1947 terminology.

That avalanche of photons instantaneously causes cold emission of electrons from molecules of air. This occurs with an extremely short rise time, almost instantaneously, as shown in Sec. 4 below, thereby restoring the discharge in the same place. The observed natural BL is therefore characterized by a continuous series of deaths and rebirths, which dynamically stabilizes the soliton in a fixed position. The movement of BL is determined mainly by de-phasing of the component waves coming from the higher excitation region, with respect to those from the lower excitation region, as shown in our companion article presented here. The frequency of these re-ignitions is close both to the spiking frequency and to the life time of the carriers. This frequency is sometimes noticed by BL observers as a humming tone.

A linearized approximate form of Eqs. (2)-(3) for the limit of small spiking oscillations is

$$d\Delta n/dt = (r-1)\Delta N/\tau_2; \quad (5)$$

$$d\Delta N/dt = - \Delta n/\tau_c - r\Delta N/\tau_2. \quad (6)$$

The solution is an exponential function of time

$$\Delta n = \Delta n(t=0)e^{st} \quad (7)$$

$$\Delta N = \Delta N(t=0)e^{st}. \quad (8)$$

Here,

$$s = -r/2\tau_2 \pm i[(r-1)/\tau_2\tau_c - (r/2\tau_2)^2]^{1/2} = -\gamma_s \pm i\omega_s. \quad (9)$$

This determines both the attenuation of the spikes γ_s and their repetition frequency ω_s as a function of the reduced pumping rate $r = R_e/R_t$ defined above. The relaxation time τ_2 of the upper maser level ($>>\tau_c$) of the upper maser level, can be as long as a second or a minute, because the transition is in fact one of the many well-known strongly forbidden transitions between pairs of nearly coincident rotational energy levels of the H_2O molecule. It is becoming only weakly allowed under the influence of the large foul weather field.

2. Perceived Energy of Ball Lightning

The energy of BL spikes can be considerable in open air. On the other hand, in the case of BL confined to a conducting enclosure, the total energy of the final spike is too small to produce any damage, or even to be noticed. Indeed, assuming for instance an enclosure of 10m 5m 3m = 150m^3, we find with an absolute humidity of 20g/m^3 and a BL frequency of 2 10^8 Hz, a water content of 9kg = 495 mol H_2O and a maximal BL energy of 165 6 10^{23} 6.6 10^{-27}erg 2 10^8/s = 13.2 J. In practice, however, we do not expect every water molecule to contribute a photon, so we expect a ten times smaller result, 1.3 J, which is harmless. In open air, the maser volume may be 2km 5km 5km = 50km^3, and the corresponding energy about 2.2 10^6 kJ for total inversion, and 2.2 10^5kJ if only 10% of the water molecules contribute a photon. This is in general agreement with the experimental observations.

3. Calculation of the Ponderomotive Forces in Open-Air Ball Lightning Explosions

The classical equation of motion for matter of density ρ, dielectric permittivity ε, and magnetic in an electromagnetic field is given by

$$\mathbf{f}_i = \rho dv_i/dt = (\partial/\partial x_j)[\varepsilon E_i E_j + \mu H_i H_j - \delta_{ij}(\varepsilon E^2 + \mu H^2)/2] - \varepsilon\mu(\partial/\partial t)(\mathbf{E}\times\mathbf{H})_i \quad (10)$$

This can be seen as the conservation law for the component i of momentum per unit volume, both mechanical $\rho\mathbf{v}$ and electromagnetic $\varepsilon\mu\mathbf{E}\times\mathbf{H}$. The mechanical stress tensor term $(\partial/\partial x_i)T_{ij}$ is neglected. We are also neglecting also the electromagnetic momentum term. To evaluate the pressure exerted by the electromagnetic field spike of an exploding open air BL on a surface of separation between two media, we integrate the term with δ_{ij}. We integrate perpendicular to the surface of separation from a point close to the surface on one side to a point close to the surface on the other side, and obtain

$$F = \int f\, dx \approx \langle E^2 \rangle \Delta\varepsilon = w\Delta\varepsilon/\varepsilon. \tag{11}$$

Here w is the energy density of the spike at the BL location. For various materials, the differences $\Delta\varepsilon$ are of the order of the unity, because no metallic screening has time to develop. The energy density, however, is obtained by dividing the total 2.2 10^5 KJ energy of the spike through the volume of devastation, which is of the order of 100 m^3. This yields a pressure of

$$P \approx 2{,}000{,}000 N/m^2 \approx 200{,}000 Kg\ force/m^2 \approx 20\ Kg\ force/cm^2 \approx 20\ Atm. \tag{12}$$

Such a pressure can displace and damage objects. Often, electric conductors and conduits are ripped from behind the plaster and thrown on the street by open-air BL "explosions", without a sign of heating or burning. The pressure caused by these ponderomotive forces can also damage tissues of different ε-values in the human body, or even displace heavy objects, such as cars.

4. Rise Time of the Field Spike

Spiking has a very short rise time when the volume of the atmospheric maser feeding the BL is large. Indeed, the characteristic time of the photonic avalanche is given by Eq. (2) in first approximation for large n, through

$$dn/dt = (KN_2^* - 1/\tau_c)n; \qquad n = n_o \exp[(KN_2^* - 1/\tau_c)t] = n_o \exp[St] = n_o \exp[t/t_o].. \tag{13}$$

Here

$$K = pK_o = 1/\tau_{rad} \approx 10^{-2}\ s^{-1}, \quad N_2^* \approx 10^{29}, \tag{14}$$

for example. Indeed, considering the concentration of H_2O molecules in saturated vapor at 20^oC to be $6\cdot 10^{17} cm^{-3}$, the inversion volume 2x5x5 km = $5\cdot 10^{16}$ cm^3, we obtain $N_1+N_2 \approx 3\ 10^{34}$. The degree of inversion can be considered about $(N_2-N_1)/N_1 \approx 10^{-5}$, because in thermal equilibrium it is about $e^{-kT/hf}-1 \approx -kT/hf \approx -10^{-5}$. The electromagnetic pulse generated by lightning may almost reverse this population difference, therefore justifying our choice for the fractional population inversion. We obtain from Eq. (13)-(14)

$$S = K N_2^* \approx 10^{27}/s \qquad t_o = 10^{-27} \text{ s.} \tag{15}$$

This is indeed a very short time, that precludes dielectric screening of the destructive field. The large values of the rate S and of n also cause strong line-narrowing. This conclusion of a very short rise time is also applicable to smaller maser volumes, e.g., 500 m^3, therefore explaining the instantaneous re-ignition process for indoor BL with $t_o = 10^{-19}$ s in smaller volumes, e.g., airplanes or living rooms. We conclude that low frequency atmospheric masers can generate a completely new type of discharge at atmospheric pressure, in the form of BL.

5. Conclusions

The maser-soliton theory of BL provides a reasonable explanation of the explosive demise possibility of open-air BL. It interprets it as a maser spiking phenomenon, and evaluated its energy in reasonable agreement with the observations. The theory also explains the forces that are observed at BL explosions, as well as the character of the destruction. Finally, the theory explains the nature of the discharge, its low temperature, its lack of buoyancy, based on the unusual load response of the atmospheric maser, and based on the extremely short rise time calculated for the photon avalanche in a spike.

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