Lightning by cavity quantum electrodynamics?

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Abstract Thunderstorms are generally thought electrified by the static electricity produced in the collision of rising particles of supercooled water in the updraft and falling particles in the all-ice downdraft. Today, the collision charging mechanism is not understood despite over a half century of extensive research. Collision charging is proposed to be the dissociation of water molecules into hydronium H^3O^+ and hydroxyl OH^- ions by electromagnetic (EM) radiation induced by cavity quantum electrodynamics (QED). Collision of particles assures that at a prior instant, a submicron gap momentarily existed between particle surfaces. The gap is treated as a 1-D QED cavity having an EM resonant frequency beyond the vacuum ultraviolet (VUV) while the water molecules in the particle surfaces emit infrared (IR) radiation. By cavity QED, the low frequency IR radiation from the water molecules within the penetration depth of the VUV radiation standing across the QED cavity is suppressed. Conservation of EM energy in a QED cavity requires the energy loss by the suppressed IR radiation be gained at the VUV resonance of the QED cavity, the process called cavity QED induced EM radiation. Thus, VUV radiation is produced having sufficient Planck energy to photodissociate water molecules in the particle surfaces. Because of the acidic pH of the moisture in the updraft, the particles carry a positive charge that separates the QED induced ions; the hydronium ions repulsed from and the hydroxyl ions attracted to the particles. The hydronium ions combine with water molecules to form proton hydrate (PH) clusters while the hydroxyl ions combine with nitrogen oxides to form negative non-proton hydrate (NPH) charged clusters. The ionic clusters separate by gravity: the light PH clusters are carried aloft to form buoyant positive charged PH clouds while the heavier NPH clusters form negative charged clouds that tend to fall to the earth. During the storm before lightning is observed, the NPH clusters as an electronegative gas increase the electrical conductivity of the atmosphere. The PH and NPH clouds carry ionic charge at high electrostatic potentials, but are absent free electrons. But free electrons are produced in cloud-to-cloud lightning as atmospheric air undergoes electrical breakdown between PH and NPH clouds. Cloud-to-ground lightning is then the runaway of free electrons through the electronegative NPH clouds to the earth along the path of least electrical resistance.

Keywords: cavity QED; atmospheric electricity; lightning; hydronium and hydroxyl ions.

1. Introduction

Thunderstorms are thought electrified in the collision of rising supercooled water particles and falling all-ice particles (Hallett, 2004). But absent EM radiation, electrification is not likely. It is sometimes stated that electrons are knocked-off the rising particles to carry positive charge to the top of the cloud while the electrons gather at the bottom. However, collisions are likely to only produce neutral particles because the binding energy of the electron to the atom is far greater than that binding the atoms to each other (Prevenslik, 2002a). Similarly, particle collisions absent EM radiation are unlikely to produce ionic charge by the separation of the water molecule into hydronium and hydroxyl ions.

Depending on pH, the equilibrium concentration of hydronium and hydroxyl ions is naturally available in colliding particle surfaces without a source of EM radiation. Because of this, hypotheses have been made about the role of the equilibrium pH concentration of hydronium and hydroxyl ions in thunderstorm electrification. One such hypothesis is the melting of the sharper falling ice crystal particles on the flatter rising supercooled particles (Baker and Dash, 1994; Baker and Nelson, 2002). Under electric fields within the ice crystals, the hydronium ions are assumed to migrate to sharp points that upon collision melt, the hydronium charged melt transferred to the supercooled particle. But the migration of hydronium ions cannot proceed without hydroxyl ions in close proximity otherwise pH equilibrium is violated. Since the particles have the same pH before collision, and since collision does not change the pH, it is unlikely that net charge is transferred from the ice crystal to the supercooled particle.

Other hypotheses have similar difficulty because of pH equilibrium. Hydronium and hydroxyl ions are assumed concentrated at the particle surfaces by the growth of the particle itself (Takahashi, 1970; Dash, et al., 2001). But this theory is considered limited to the vapor growth of both colliding particles without wet growth (Yair, 2004). The thermoelectric effect relies on the mobility of hydronium ions being an order of magnitude larger than the hydroxyl ion, the warmer end acquiring a negative charge due to the diffusion of H^+ away from that end (Latham and Williams, 1961). Beyond pH equilibrium, the process is considered too slow to be effective to account for observed charge (Yair, 2004). The Workman-Reynolds effect relies on the double layer across the ice-liquid interface leading to a negative charge on the ice and positive charge on the water droplets (Workman and Reynolds, 1950). Similarly, the mechanism is thought to only operate at altitudes where the temperature is close to the melting point of ice, and therefore cannot explain charging at temperatures colder than -16 C. (Yair, 2004).

In this paper, cavity QED induced EM radiation in the gap at the collision between rising supercooled particles and falling ice particles promptly photodissociates water molecules on the particle surfaces into hydronium and hydroxyl ions. Unlike the transfer of hydronium ions between the same equilibrium pH concentrations, cavity QED provides an external source of hydronium and hydroxyl ions to the equilibrium pH concentration. Thus, the acidic pH concentration in the moisture of the updraft provides the positive background charge by which the cavity QED ions separate – the hydronium ions repulsed from the gap to the atmosphere and the hydroxyl ions attracted to the particle surfaces. Lightning is shown to be upper bound by ~ 20 collisions of rising supercooled particles and falling ice particles. But cavity QED induced EM radiation is also produced in nanovoids that form in the volume expansion of supercooled particles, the EM radiation by photodissociation of water molecules in the void surfaces providing initial ionic charge for the subsequent collision with all-ice particles, thereby reducing the ~ 20 collisions necessary to electrify the thunderstorm for lightning.

1.1 Electrification mechanism

Since Einstein's explanation of the photoelectric effect, EM radiation at VUV frequencies is required to free electrons from atoms or dissociate water molecules. Only IR radiation is available at ambient temperature, but EM radiation at VUV levels may be produced from the IR radiation by the theory of cavity QED induced EM radiation.

By this theory, QED cavities comprising voids at the nanoscale in the liquid or solid state suppress long wavelength radiation (Harouche and Raimond, 1993). Thus, IR radiation from atoms within the penetration depth of the VUV waves standing across the voids is suppressed. To conserve the EM energy loss by the suppression of IR radiation, an equivalent gain in EM energy is required at the resonant frequency of the QED cavity, and therefore IR radiation is frequency up-converted to the VUV.

Indeed, cavity QED induced EM radiation was proposed as the source of atmospheric electricity by voids - water vapor bubbles - that form in the volume expansion of graupel (Prevenslik, 2002b and 2003a) and is presented in Appendix A.

But voids are not necessary as nanoscale gaps between surfaces also produce EM radiation. In fact, early applications of cavity QED induced EM radiation explain static electricity (Prevenslik, 2002a) by the suppression of IR radiation from a microscopic particles confined between closed surfaces, say by a person stepping on a micron sized dust particle between the sole of their shoe and the floor.

Although the suppression of IR radiation from a particle confined in a QED cavity was the first and obvious way to induce VUV radiation, cavity QED induced EM radiation was later extended to the suppression of IR radiation from atoms and molecules in the penetration depth of the VUV wave standing across the QED cavity. Thus, the generality of cavity QED induced EM radiation was extended to voids and gaps absent particles. Indeed, thermophotovoltaic devices comprising a near IR photocell in close proximity to a heated surface emitting far IR radiation is used to produce electricity by the frequency up-conversion of far to near IR radiation (Prevenslik, 2003b). Cavity QED induced EM radiation has shown (Prevenslik, 2004b) that the attractive force between neutral metal plates is electrostatic and not neutral as envisioned by Casimir.

In the following, the atmosphere is proposed electrified by hydronium and hydroxyl ions from the dissociation of water molecules by cavity QED induced EM radiation produced in the collision between rising supercooled particles and falling all-ice particles. Collision charging is enhanced by additional hydronium and hydroxyl ions produced by cavity QED induced EM radiation in voids formed by the expansion of the supercooled particles *before* collision with the all-ice particles.

2. Theoretical Background

The electrification of the thunderstorm by the collision of rising supercooled particles in the updraft and falling all-ice particles in the downdraft is depicted in Fig. 1.

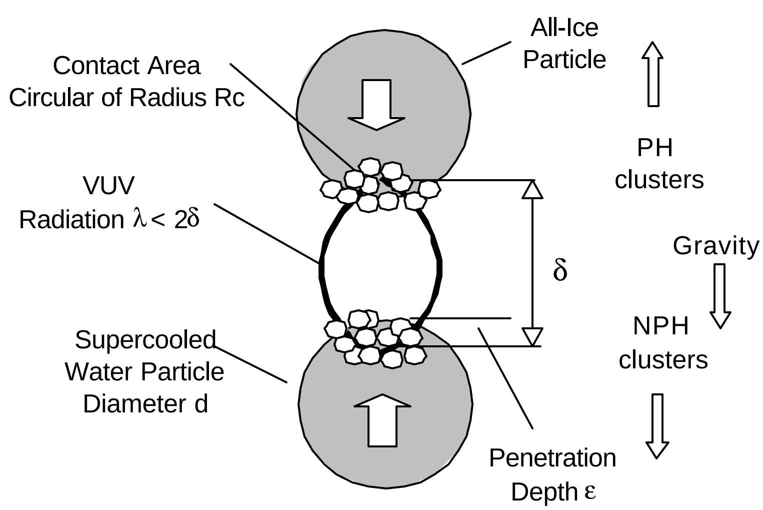

Fig. 1 Thunderstorm electrification - Collision of Particles

Upon collision, the contact deformation between the supercooled water and all-ice particles is insignificant because of the low impact velocities, i.e., the particles only glance off each other. The EM radiation is produced in the sub-micron gaps δ that are very small compared to the particle diameters d of order 100 μm, and therefore for clarity the gap δ is enlarged in Fig. 1. Cavity QED induced EM radiation is depicted by VUV radiation standing across the gap δ acting over a radius R_c of circular contact area, the VUV radiation having a penetration depth ε in the particle surfaces. The EM energy U_{IR} of the of the IR radiation suppressed depends on the thermal kT energy of the number $2\pi R_c^2 \varepsilon / \Delta^3$ of water molecules in *both* particles,

$$U_{IR} = \left(\frac{2\pi R_c^2 \varepsilon}{\Delta^3} \right) N_{dof} \frac{1}{2} kT \tag{1}$$

where, $N_{dof} = 6$ is the number of degrees of freedom of the water molecule, Δ is the spacing between water molecules at liquid (or ice) density, k is Boltzmann's constant, and T is absolute temperature. Conservation of EM energy gives the number N_{VUV} of VUV photons standing in the gap δ having Planck energy E_{VUV},

$$N_{VUV} = \frac{U_{IR}}{E_{VUV}} = 6\pi \frac{R_c^2 \varepsilon}{\Delta^3} \left(\frac{kT}{E_{VUV}} \right) = 6\pi \frac{R_c^2 \varepsilon}{\Delta^3} \left(\frac{2\delta kT}{hc} \right) \tag{2}$$

where, $E_{VUV} = h\upsilon$, $\upsilon = c / 2\delta$, and c is the speed of light. The ionic charge Q_{ions} produced by the dissociation of the water molecule into hydronium and hydroxyl ions is,

$$Q_{ions} = N_{VUV} Y e \tag{3}$$

where, Y is the photodissociation yield of hydronium and hydroxyl ions per VUV photon and e is the electronic charge.

Since the gap δ is decreasing as the particles approach contact, the optical spectrum of the standing photons is broadband from the IR through the visible to the VUV. Of the total N_{total} emitted, the number $N_{IR+visible}$ photons,

$$N_{IR+visible} = N_{total} - N_{VUV} \tag{4}$$

Separation of hydronium and hydroxyl ions in the gap follows from a proposal (Loeb, 1958) that ionic charge may be separated if the charge of one sign collects in the vapor state while the charge of the opposite sign collects in the liquid state. In the gap between contact surfaces, this condition is nicely satisfied as the particles having an acid pH carry a background positive charge, and therefore the hydronium ions are repulsed from the gap into the atmosphere while the hydroxyl ions attach to the particles.

The hydronium ions combine with water to form positive charged $H_3O^+ \bullet (H_2O)_n$ proton hydrate (PH) clusters while the hydroxyl ions combine with nitrogen oxides to form nitric acid which react with water to form negative charged $NO_3^- \bullet (HNO_3)_m(H_2O)_n$ non-proton hydrate (NPH) clusters (Swider, 1985).

The light PH and heavy NPH clusters form clouds that separate by gravity in the atmosphere as depicted in Fig. 1. The falling NPH clouds form an electronegative gas in the lower atmosphere in which the lightning stroke can propagate. The PH and NPH clouds are formed by ions, but otherwise are absent the free electrons necessary for current to flow along a path to the earth. But the PH and NPH clouds have high electrostatic potentials that breakdown air in the cloud-to-cloud lightning at the PH/NPH cloud interface to supply the current for the pilot streamer, stepped leader, and lightning stroke. Once the current reaches stepped leader levels, lightning currents occur as electron collisions ionize atmospheric gases along the path to produce a cascade of runaway electrons.

Even with a supply of free electrons at the PH/NPH interface, the path by which the pilot, leader, and stroke follow to the earth is complicated by the fact that the NPH clusters from the thunderstorm are not uniformly dispersed in the atmosphere. Indeed, convection and turbulence produce random distributions of electrical conductivity that are constantly changing in time. Despite this difficulty, the pilot streamer initiated at the PH/NPH interface always chooses the usual zig-zag path of least electrical resistance to the earth's surface. Provided the time between the pilot and stoke is not long so as to alter the path conductivity, the stepped leader and the lightning stroke successively follow the path formed by the pilot streamer.

3. Analysis

The path followed by the pilot streamer, stepped leader, and lightning stoke in an electronegative gas (e.g. NPH clusters) is generally thought (Niemayer, 1986) caused by the random process of local breakdown of space charge close the leader tip, the leader tip acting as a continuous pulse of positive voltage. On this basis, stepped leader simulations have found analogy with switching surge breakdown (Farouk, 1989) in long air gaps. Indeed, the electric field associated with the space charge of the positive surge pulse has been confirmed for the breakdown of air in about 10 meter lengths. Because stepped leaders are observed to follow the pilot streamer in comparable steps, the argument (Kumar and Nagabhushana, 2000) is made that the surface pulse experiment extended by continuous inception and breakdown is applicable to the propagation of stepped leaders over thousands of meters in the atmosphere.

However, surge pulses are not necessary to produce lightning. Electrons are continually being produced by the breakdown of air in the cloud-to-cloud lightning at the PH/NPH cloud interface. Once the free electrons are available, the pilot streamer, stepped leader, and lightning stroke may indeed propagate thousands of meters to the earth, but only if the NPH clusters have increased the electrical conductivity of the atmosphere to sustain the respective currents along the path of least resistance.

Consider a thunderstorm as a dipole of positive PH and negative NPH clouds having charge $\pm Q_o$ as shown for the early and later stages of the thunderstorm in Fig. 2.

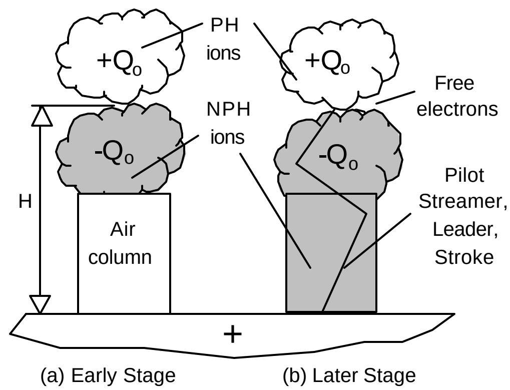

Fig. 2 Thunderstorm Stages. During fair weather, the global electrical circuit charges the earth negative. But at the early and later stages of the storm, the earth is charged positive.

3.1 Early Stage of the Thunderstorm

In the early stage of the thunderstorm, the NPH cloud is separated from the ground by an otherwise neutral column of air of height H shown in Fig. 2(a). Treating the PH/NPH cloud interface and earth surface as the plates of an air capacitor, the capacitance C_o is,

$$C_o = \frac{\varepsilon_o A}{H} \tag{5}$$

where, ε_o is the permittivity of free space and A is the area of the air column. The potential V_o of the positive charged PH cloud above the earth is, $V_o = Q_o / C_o$.

The thunderstorm is treated (Kumar and Nagabhushana, 2000) as a dipole having charge $Q_o \sim \pm 30$ C located $H \sim 2500$ m above the earth. The volume V_c of the PH and NPH clouds is taken as 20 million cubic kilometers (Wahlin, 1989). Taking an air column area $A = V_c^{2/3} \sim 7.35\text{x}10^6$ m^2 gives $C_o \sim 2.6\text{x}10^{-8}$ F and $V_o \sim 1.15\text{x}10^9$ V.

Leakage Current to Earth

Even though under high voltage V_o from the PH cloud, breakdown of the air column does not occur because the average electric field $E_f = V_o / H \sim 4.6\text{x}10^5$ $V \cdot m^{-1}$ is less than the breakdown strength E_{BD} of air, $E_{BD} \sim 2.6\text{x}10^6$ $V \cdot m^{-1}$. But the electrons produced in cloud-to-cloud lightning leak a small current I_o to the earth. The resistance R of the air column of area A and length H is given in terms of the electrical conductivity σ,

$$R = \frac{H}{\sigma A} = \frac{V_o}{I_o} \tag{6}$$

where, I_o is the current flowing form the PH/NPH cloud interface to earth. For atmospheric air (Swider, 1985) in the initial stage of the storm, the conductivity $\sigma \sim 10^{-14}$ $(\Omega \cdot m)^{-1}$ gives $R \sim 3.4\text{x}10^{10}$ Ω and current $I_o \sim 34$ mA.

3.2 Later Stage of the Thunderstorm

In the later stages of the thunderstorm, the NPH clusters have migrated to the earth to increase the electrical conductivity of the air column as depicted in Fig. 2(b). Electrons are continuously being produced in the breakdown of air in cloud-to-cloud lightning to initiate and supply the runaway currents, but the pilot streamer does not form until the electrical conductivity reaches a critical value. The NPH clusters move in the average electric field E_f at velocity V_{NPH},

$$V_{NPH} = \mu E_f \tag{7}$$

where, μ is the mobility of the NPH cluster in air, $\mu \sim 1.6\text{x}10^{-4}\ \text{m}^2\cdot(\text{V}\cdot\text{s})^{-1}$ (Swider, 1985). For $E_f \sim 4.6\text{x}10^5\ \text{V}\cdot\text{m}^{-1}$, $V_{NPH} \sim 74\ \text{m}\cdot\text{s}^{-1}$. Since the time H / V_{NPH} ~ 33 s, any potential build-up in the PH cloud is promptly compensated by an increase in the conductivity of the air column while electrons are being produced at the PH/NPH cloud interface.

Number Density of NPH Clusters

Stepped leaders are brought down at currents I_o from 600 to 2600 A (Kumar and Nagabhushana, 2000). Taking I_o ~ 860 A, Eqn. 6 gives the air column resistance R ~ $1.33\text{x}10^6\ \Omega$ and conductivity $\sigma \sim 2.5\text{x}10^{-10}\ (\Omega\cdot\text{m})^{-1}$. By the time lightning is observed, the NPH clusters have increased the conductivity of the atmosphere by a factor of 25,000. The stepped leader resistance R/H ~ 532 $\Omega\cdot\text{m}^{-1}$ is less, but consistent with 1000 $\Omega\cdot\text{m}^{-1}$ for the preliminary leader (Kumar and Nagabhushana, 2000). Absent the NPH clusters, the stepped leader cannot propagate thousands of meters to the earth.

The number density N_{NPH} of NPH clusters necessary to sustain the stepped leader current,

$$N_{NPH} = \frac{\sigma}{e\mu} \tag{8}$$

Thus, $N_{NPH} \sim 9.7\text{x}10^{12}\ \text{m}^{-3}$. That the thunderstorm can provide the necessary NPH clusters is shown as follows.

Particle Charge

In the thunderstorm, moisture is converted to supercooled water particles. Taking an ice particle of diameter d = 100 μm, collisions at a velocity of 8 $\text{m}\cdot\text{s}^{-1}$ produce charge Q_{ions} ~ 4 fC and number $N_{photons} \sim 3.6\text{x}10^4$ of photons, i.e., see Fig. 1 and 2 of (Keith and Saunders, 1988). At a Planck energy E ~ 8.3 eV having wavelength 150 nm, water has a photodissociation yield Y ~ 0.75 (Mozumder, 2002). For an ionic charge Q_{ions} ~ 4 fC, Eqn 3 gives $N_{VUV} \sim 3.3\text{x}10^4$ VUV photons. For water, the spacing between water molecules at liquid density is Δ ~ 0.3 nm while the VUV radiation is absorbed at penetration depths ε ~ 30 nm. Hence, Eqn 2 gives the contact radius R_c ~ 22 nm. But the total number of photons N_{total} exceeds the number N_{VUV} of VUV photons necessary to produce the measured ionic charge Q_{ions}. This consistent with photons from the IR to the visible produced by cavity QED induced EM radiation lack the Planck energy to dissociate the water molecule, specifically $N_{IR+visible} = N_{meas} – N_{VUV} \sim 300$ photons.

Number of Particles in the Cloud

Considering the collision of 100 μm supercooled and all-ice particles, the mass m_p,

$$m_p = \frac{4}{3}\pi\rho r^3 \tag{9}$$

where, ρ is the density of water and r is the particle radius. For r = 50 μm and ρ = 1000 $kg \cdot m^{-3}$, $m_p \sim 5.23x10^{-10}$ kg. The mass M_c of water vapor in the cloud is,

$$M_c = \rho_c V_c \tag{10}$$

where, ρ_c ~ is the density of water in the cloud. For cumulonimbus clouds, $\rho_c \sim 0.005$ to 0.015 $kg \cdot m^{-3}$ (Wahlin, 1989). Taking an average $\rho_c \sim 0.010$ $kg \cdot m^{-3}$, the water mass of the cloud is, $M_c \sim 2x10^8$ kg. The number $N_{particles}$ of particles in the cloud is,

$$N_{particles} = \frac{M_c}{m_p} \tag{11}$$

Thus, $N_{particles} \sim 3.8x10^{17}$.

Total Available Charge in Cloud and Number Density of NPH Ions

The total available charge Q_{total} in the cloud is,

$$Q_{total} = N_{particles} Q_{ions} \tag{12}$$

and the number N_{ions} density of NPH ions,

$$N_{ions} \sim \frac{Q_{total}}{AHe} \tag{13}$$

Thus, $Q_{total} \sim 1530$ C and $N_{ions} \sim 5.2x10^{11}$ m^{-3}, and therefore the particle collisions are sufficient to sustain a cloud with a charge of 30 C. But $N_{ions} < N_{NPH}$, and therefore a single particle collision is not sufficient to produce the necessary electrical conductivity for the pilot streamer to reach the earth. However, if each particle collides ~ 20 times – a reasonable occurrence - the necessary electrical conductivity is achieved.

Stepped Leader Charge and Current

Consider cloud-to-cloud lightning producing charge Q_o at the PH/NPH cloud interface. The stepped leader charge Q brought down in time t is,

$$Q = Q_o\left[1 - \exp\left(\frac{-t}{\tau}\right)\right] \quad (14)$$

where, τ is the relation time constant for the simple RC_o circuit,

$$\tau = RC_o = \frac{\varepsilon_o}{\sigma} \quad (15)$$

Thus, τ ~ 14 ms. The runaway current I_o brought down,

$$I_o = \frac{dQ}{dt} = \frac{Q_o}{\tau}\exp\left(\frac{-t}{\tau}\right) \quad (16)$$

For Q_o ~ 30 C, the currents I_o vary from 600 to 2600 A. Stepped leader response for relaxation times τ of 11, 35, and 50 ms corresponding to electrical conductivity σ ~ 8, 2.5, and 1.75x10 $(\Omega \cdot m)^{-1}$ are shown in Fig. 3.

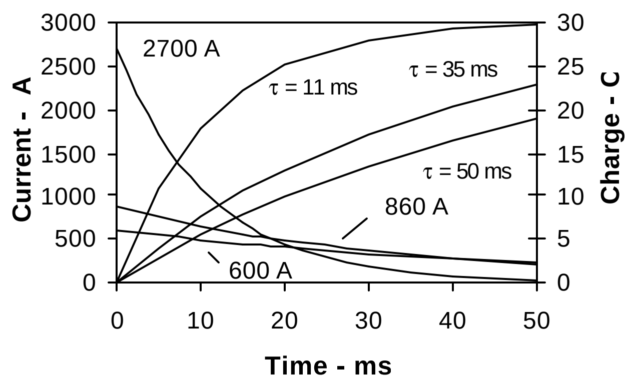

Fig. 3 Stepped Leader Current and Charge

The stepped leader relaxation time (τ ~11 ms) corresponds to the full electron charge Q_o ~ 30 C brought down in time t ~ 50 ms and gives the highest current I ~ 2700 A. The lowest current I ~ 600 A (τ ~ 50 ms) brings down about 20 C in ~ 50 ms. The response for relaxation time (τ ~ 35 ms) corresponds to Fig. 4 of (Kumar and Nagabhushana, 2000) that shows about 1.5 C of charge brought down in 1.8 ms.

Stroke Current

Currents in the lightning stroke average 25 kA and may even reach 400 kA (Wahlin, 1989). Higher electrical conductivity is required to sustain the stroke than the stepped leader, but the path after the stepped leader is highly ionized and no longer needs to rely on the NPH clusters for conductivity.

4. Discussion and Conclusion

Thunderstorms are shown electrified by the collision of rising supercooled water particles and falling all-ice particles. Water molecules in the contact surfaces between colliding particles dissociate into hydronium and hydroxyl ions by VUV radiation induced from IR radiation by cavity QED. But the magnitude of the ionic charge requires that each particle collide at least ~ 20 times to produce the ionic charge necessary to increase the electrical conductivity of the atmosphere and allow the electrons produced by cloud-to-cloud lightning to undergo runaway discharge to the earth as the pilot, stepped leader, or lightning stroke.

The ionic charge transfer in the collision of particles in thunderstorm electrification was based on the conversion of cloud moisture to 100 μm diameter particles, although greater charge transfer occurs for larger particles more representative of those in the thunderstorms (Keith and Saunders, 1988). An improvement in charge transfer efficiency is expected with larger particles, and therefore the ~ 20 collisions of each particle is an upper bound estimate of thunderstorm charging.

However, cavity QED induced EM radiation produces ionic charge in the rising supercooled water particles *before* they collide with the falling all-ice particles. It has been known for some time that the supercooling of a water particle produces a cloud of positive charged ice crystals leaving the supercooled particle with a negative charge (Cheng, 1973). The charging of ice crystals and supercooled particles is proposed explained by treating the voids formed in the volume expansion of the supercooled particle as QED cavities producing EM radiation as depicted in Fig. 4.

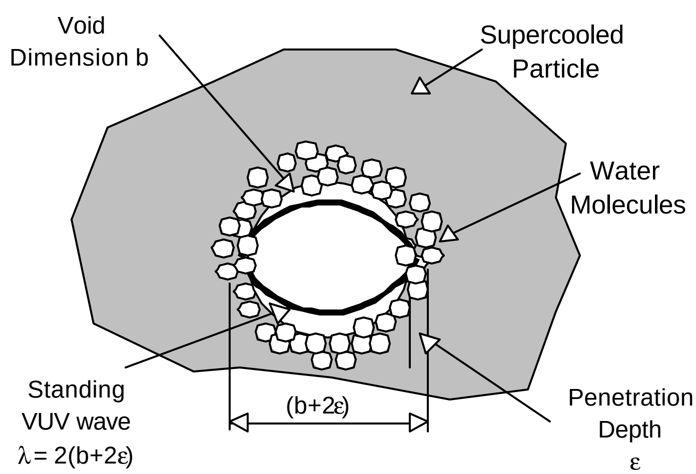

Fig. 4 Void Formation in Supercooled Particle

For clarity only a single enlarged QED cavity of dimension b is shown in the supercooled particle. The IR radiation from the water molecules having wavelength λ_{IR} in the penetration depth ε is suppressed by VUV waves having wavelength $\lambda = 2(b+2\varepsilon) < \lambda_{IR}$ standing across the void as a QED cavity, but for clarity only a single standing VUV wave is shown in Fig. 4. The VUV radiation then photodissociates the water molecules in the QED cavity surface into hydronium and hydroxyl ions.

Because of the acidic pH of the supercooled particle, the hydronium ions are repulsed into the QED cavity while the hydroxyl ions are attracted to its walls. After the formation of PH and NPH clusters, the supercooled particle contracts upon solidification and expulses microdroplets of entrained air and PH clusters to the atmosphere. The microdroplets upon freezing produce positive charged all-ice particles while the NPH clusters remain with supercooled water particles and fall to the earth (Cheng, 1973).

Unlike charging by the collision of particles that occurs many times with each collision producing ionic charge, voids formed in the supercooled water particles produce ionic charge only once. Even so, the ionic charge produced in void formation provides the thunderstorm with a significant initial charge that is transferred in subsequent collisions between supercooled water particles and all-ice particles.

The combination of ionic charge produced both *before* and *after* collisions between rising supercooled water and falling all-ice particles supports the conclusion that lightning is produced by thunderstorms that electrify by the dissociation of water molecules by cavity QED induced EM radiation.

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Appendix A
Cavity QED induced EM radiation

Generally, the laws of thermodynamics preclude the spontaneous transformation of thermal kT energy from IR to VUV levels. But this is not true for IR radiation from the surface of a VUV resonant QED cavity. To the contrary, IR radiation from QED cavity surfaces is indeed spontaneously frequency up-converted to VUV levels, the process called cavity QED induced EM radiation.

Cavity QED induced EM radiation follows from the most basic laws of physics – that low frequency EM radiation is suppressed in a high frequency QED cavity - the generality of the law applicable to QED cavities in both the solid and liquid state. Typically, IR radiation from QED cavity surfaces at ambient temperature is suppressed from atoms within the penetration depth of the resonant VUV radiation standing across the QED cavities. But in a VUV resonant QED cavity the EM energy loss from the suppression of IR radiation can only be conserved by an equivalent gain at its VUV resonant frequency, the significance of which is the QED cavity surface is spontaneously excited by VUV radiation having Planck energy to photodissociate water molecules.

Consider a spherical void of radius R in a solid or liquid as a QED cavity having an EM resonance emitting a VUV photon hυ shown in Fig. A-1.

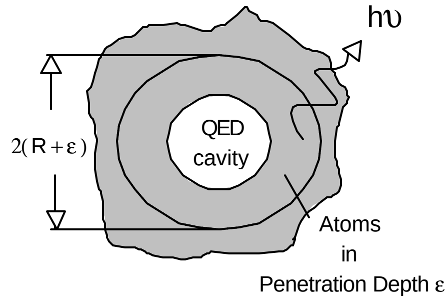

Fig. A-1 – Spherical Void in the Solid or Liquid State

The QED cavity extends beyond the surface of the void to include the penetration depth ε of the resonant standing EM wave. Initially for ε = 0, there are no atoms in the penetration depth of the standing EM wave for the respective IR radiation to be suppressed, and therefore the standing EM wave having an EM resonant wavelength λ = 4R is absent EM energy. But for ε > 0, the EM wave gains energy by conserving the loss from the IR radiation suppressed from the atoms. The EM wave has resonant wavelength λ and includes the depth ε necessary to assure absorptive (or reflective) boundary condition,

$$\lambda = 4(R + \varepsilon) \tag{A1}$$

The Beer-Lambert law gives the depth ε by the absorption coefficient α of the cavity wall at the EM resonant wavelength λ = 4R of the QED cavity. The EM radiation intensity I at depth ε is related to the intensity I_o at the QED cavity surface by,

$$I / I_o = \exp(-\alpha\varepsilon) \tag{A2}$$

For αε = 5.15, over 99 % of the surface intensity is absorbed.

At ambient temperature, the thermal kT energy of atoms in depth ε is emitted as EM radiation at IR frequencies (Christy and Pytte, 1965) given by the harmonic oscillator shown in Fig. A2.

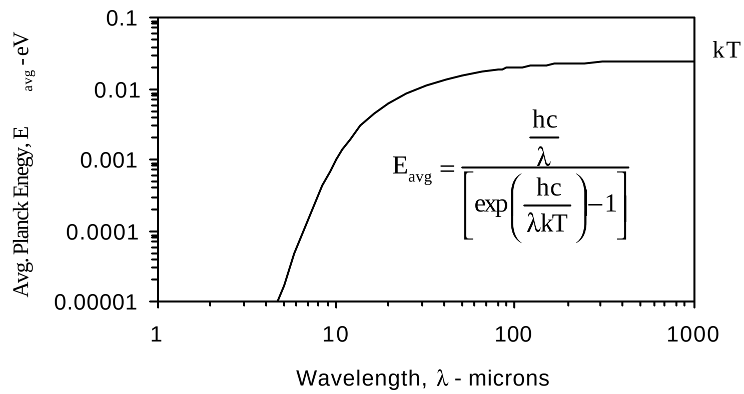

Fig. A-2 – Harmonic Oscillator at 300 K. In the inset, k is Boltzmann's constant, T is absolute temperature, h is Planck's constant, and c is the speed of light.

The suppression of IR radiation by cavity QED depends on the dimensions (Harouche and Raimond, 1993) of the voids in the liquid and solid state. For IR radiation having wavelength λ_{IR}, the IR radiation is suppressed in the void if $\lambda_{IR} > \lambda = 4(R + \varepsilon)$. To conserve the suppressed EM energy, it might be stated that the temperature of the atoms must approach absolute zero. But this does not occur.

Instead, ambient temperature T may be maintained while the kinetic energy of the atoms in the penetration depth vanishes. For example, consider a QED cavity having a resonant wavelength $\lambda \sim 4\ \mu m$ producing a VUV photon. Fig. A-2 shows that after suppression of the IR radiation, the fraction of Planck energy remaining is $E_{avg} < 10\ \mu eV$, but the temperature is still ambient. Thus, the production of the VUV photon is conserved at ambient temperature with the loss of kinetic energy of the atoms. Rather than conserving the suppressed IR radiation by emitting a VUV photon, the kinetic energy of the atoms might approach zero, but this takes time. Thus, the preferred path for EM energy conservation is by the spontaneous frequency up-conversion of the suppressed IR radiation to the VUV resonant frequency of the QED cavity. Indeed, frequency up-conversion is the consequence of conserving EM energy in QED cavity.

Since the EM resonance of the QED cavity here is considered from the near IR to the VUV, the low frequency IR radiation of the atoms in the depth ε is suppressed. The total IR energy U_{IR} suppressed,

$$U_{IR} = \frac{4\pi}{3}\Psi\left[(R+\varepsilon)^3 - R^3\right] \quad \text{(A3)}$$

where, Ψ is the EM energy density, $\Psi \sim N_{dof}$ x ½ kT / Δ^3, and Δ is the cubical spacing between atoms at solid or liquid density. N_{dof} is the number of degrees of freedom of the atoms and molecules. Typically, for solids and liquids, $N_{dof} = 3$ and 6, respectively.

Suppressed IR is a loss of EM energy that in a QED cavity may only be conserved by an equivalent gain in Planck energy at its resonant frequency. For QED cavities having EM resonance from the near IR to VUV, the conservation of EM energy may be expressed by,

$$NE = U_{IR} \tag{A4}$$

where, N is the number of photons having average Planck energy E over the depth ε,

$$E = \frac{hc}{4(R + 0.5\varepsilon)} \tag{A5}$$

and if the leakage through the void surfaces is neglected, then NE = $N_{near\ IR}\ E_{near\ IR}$ = $N_{visible}\ E_{visible}$ = $N_{VUV}\ E_{VUV}$. Otherwise, the conservation of EM energy requires an appropriate reduction in the number N of photons produced. Combining, the number N of photons having Planck energy E produced in the penetration depth ε,

$$N = \frac{8}{3}\pi\frac{kT}{hc} N_{dof}\left(R + 0.5\varepsilon\right)\left[\frac{(R+\varepsilon)^3 - R^3}{\Delta^3}\right] \tag{A6}$$

Generally, cavity QED induced EM radiation is produced at VUV frequencies *anytime* voids at the nanoscale are formed in solids and liquids thereby explaining why electrons by the photoelectric effect and photons by photoluminescence are observed at ambient temperature. Although the IR radiation from the atoms in the penetration depth is incoherent, the VUV radiation *becomes* coherent (van Zee, 2002) by the selective feedback of the QED cavity as an optical resonator. After emission of the VUV photon, the recovery of ambient temperature for the subsequent VUV emission depends on the liquid or solid state.

In the liquid state, the nanovoids form under hydrostatic tension, say by the volume expansion in supercooling. But the most notable is sonoluminescence (SL) - the production of light under ultrasound - whereby the thermal kT energy of the molecules in the penetration depth is recovered every cycle by the flow of liquid at ambient temperature. Although the number of SL photons produced by cavity QED induced EM radiation is discrete every cycle, at ultrasonic frequencies SL appears as steady light.

The voids are nanogaps in the solid state. Solids absent fluid flow recover thermal kT energy in the penetration depth by conductive heat flow at ambient temperature across the boundary of the penetration depth. Thus, visible light is produced from cavity QED induced EM radiation by photoluminescence. The suppression of IR radiation does not reduce the temperature of the atoms in the penetration depth to absolute zero, but rather leaves the atoms in a non-equilibrium state at ambient temperature with a vanishing kinetic energy. Thus, there is no temperature difference by which heat may be transferred. Instead, conductive heat flow occurs by the equivalent transfer of kinetic energy by collisions from atomic vibrations of atoms across the boundary of the penetration depth, the cavity QED induced EM radiation at VUV frequencies is conserved with the loss of kinetic energy of the atoms in the penetration depth.

In both liquid and solid states, the source of cavity QED induced EM radiation is *always* the thermal kT energy of the atoms at ambient temperature.