International Scholars Journals

African Journal of Geography and Regional Planning ISSN 2736-1586 Vol. 10 (2), pp. 001-013, February, 2023. Available online at www.internationalscholarsjournals.org © International Scholars Journals

Full Length Research Paper

New Model Details Internal Electromagnetic Mechanism That Allows Ball Lightning to Self-Stabilize

Tim G. Waterman and Urs W. Batzel*

Affiliations—Timothy G. Waterman consults through TIPSLLC. His current address and email are 303 Quail Dr., Eldersburg MD 21784, USA and Twater1@comcast.net. Urs Batzel is unaffiliated and the Corresponding author. His current address and email are 430 Stratton Ln, Pittsburgh PA 15206, USA and urs@batzel.net.

Accepted 13 January, 2023

Abstract

The strange natural phenomena, ball lightning, is rich in mythology, but remains a mystery after centuries of scientific effort. Detailed eyewitness accounts describe luminous bubbles with diameters of a few centimeters to several meters that have been observed alongside lightning, typically moving horizontally, sometimes passing through windows and aircraft walls, and dissipating sometimes silently or violently after a lifetime of a few seconds. Using an electromagnetic model for ball lightning, this paper provides an analysis of the internally generated forces that can hold the ball lightning sphere together, specifically how three orthogonal electromagnetic waves propagating inside of a conducting "bubble" of free-floating charge are capable of providing the forces necessary to counteract the expanding forces generated by the bubble of charge itself. The spherical boundary conditions will be described including how they determine the allowable field shapes of the trapped propagating waves and that the forces acting on the sphere's boundary are uniform.

Keywords: Ball-Lightning, Cavity Mode, Orthogonal Electric Fields, Trapped Propagating Wave, Whispering Gallery Mode.

1. A BRIEF HISTORY

MANY papers have been written over the years that postulate Ball Lightning, BL, as intimately tied to electromagnetics. Recently, Shmatov[1] outlined the history of various potential BL models and in particular models involving resonant electromagnetic structures. We add only that in 1973 Jennison[2] added that BL may be a stable EM phase-locked loop in a standing wave that externally exhibits a spherical configuration and in 1975 Handel[3] proposed a mechanism that could create BL, specifically, that a localized electric field, a soliton, is formed by an atmospheric maser. These lead to Wu[4,5] which extend the maser concept to microwave frequencies, detailing the formation of the BL bubble and the generation of microwaves in thunderstorms. Because these references, as well as others, are readily available, this paper will not elaborate on past electromagnetic models.

2. INTRODUCTION

Let us first consider the parameters and EM properties associated with a typical lightning bolt. These parameters as well as those from Wu[4,5] outlined in the next section will be used throughout this paper.

A typical lightning bolt length, L_B, is 5 km with a diameter of about 2 to 3 cm[6]. It is reasonable to assume a uniform distribution of free electrons in the lightning bolt and a roughly spherical region of free charge at the tip of the bolt with a radius, r_B, equal to 1.27 cm. Its speed, v_B, is 120000meters/second[7]. Whereas the charge of a single electron, q_E, is 1.6×10^{-19}coulombs[8], a lightning bolt contains q_B = 15 coulombs[9] of free electrons heading from the clouds down toward the surface of the earth. On average a gigajoule of energy is available with about 30000amps[10].

When moving, like charges traveling in the same direction attract one another as shown in Fig 1. However, when the leading tip of the bolt suddenly stops, the magnetic field that is holding the moving electrons together in the tip is thrown into disorder.

The next sections pertain to the number of free electrons liberated from the tip of the lightning bolt only. That is the number of electrons that comprise Ball Lightning, not all of the electrons in the entire bolt. The forces pushing outward due to all of the newly liberated free electrons in this region can be calculated using an estimate of the number of electrons liberated. The spherical volume of liberated charge (V_C) and the volume of the lightning bolt (V_B) are respectively.

$$V_C = 4\pi r_B^3/3 = 8.58 \times 10^{-6}\text{meters}^3 \quad (1)$$

$$V_B = L_B \cdot \pi r_B^2 = 2.53\text{meters}^3 \quad (2)$$

The number of electrons in the spherical volume of liberated charge can be estimated as shown.

$$N_E = q_B \cdot V_C/V_B \cdot 1/q_E = 3.18 \times 10^{14} \quad (3)$$

This number of expanding electrons is similar to the number expressed by Wu[5].

Coulomb's Law, shows the relationship between the electrostatic force, F, in Newtons that is pushing outward relative to the radius, for the expanding bubble of charge. This relationship is displayed in Fig 2 and by

$$F = K_e\, q_1 q_2/r^2, \quad (4)$$

where the constant K_e equals 9×10^9 Newton meters^2/coulomb^2, $q_1 = q_2$ is the total charge of the free electrons pushing against one another, $q_1 = q_2 = N_E \cdot q_E = 5.08 \times 10^{-5}$ coulombs, and r is the average radius of the expanding bubble using a centroid as shown in Fig 3.

Fig 3 shows the spherical shape of BL's conducting wall and how the density of the cloud of charge is concentrated near the sphere's perimeter.

Wu[5] shows how free electrons and ionized air molecules form spherically shaped "bubbles" of free charge, of both positive and negative varieties. This can occur when the lightning bolt tip impacts a boundary such as a conductor or the earth. The lower mass electron cloud pushes itself apart more quickly than the heavier ions into the shape of a spherical shell. A spherical shape naturally occurs because of the way charge interacts with itself. Each electron sees the force from "all" of the remaining electrons as coming from their combined charge center. In addition, locally in the shell that is forming, nearby electrons push one another apart. Charge moving into a region of lower charge density is caused by ponderomotive force.

The time lapsed graphs that are included in Wu[5] as Figure 3 therein show the positions of the expanding electron cloud and put the radial velocity of the electrons at approximately $v_E = v_r = 0.625\, c_0$. We estimate an expansion of 0.375 meters per 2×10^{-9} seconds from those figures. The repulsive force of the electrons pushes them apart at close to the speed of light. A careful examination of Figure 4 in Wu[5] reveals the diameter of the steady state electron cloud's centroid to be approximately 0.458 meters or a radius of $r_W = 0.229$ meters. This size is associated with the resonant frequency of the evaluated sphere, 625 MHz. Similarly, the graphs demonstrate that the electrons, based on their speed, would take approximately $t_{expansion}$ = 1.22 x 10^{-9} seconds to travel to the steady state bubble diameter.

There is sufficient electric field strength (see Fig 12) in the microwave frequency band generated by the expanding charge to ionize the air molecules of the sphere.

3. MAGNETIC FIELDS AND SPIN FORCES

Moving charges generate magnetic fields and magnetic fields can move charges around. Three sources of strong magnetic fields and their spin forces have been identified: 1) the spin on the bolt due to the earth, 2) the spin on the expanding charge bubble due to the earth, and 3) the spin on the expanding charge bubble due to the bolt. The force exerted, F, can be quantified using the Lorentz Magnetic Force Equation,

$$F = \left|-q_E\left(\vec{v} \times \vec{B}\right)\right|, \quad (5)$$

which, because of the relationship between $\vec{v}$ and $\vec{B}$ in the considered cases can be simplified to

$$F = |-q_E vB \sin\theta|, \quad (6)$$

and the corresponding tangential spin velocity, v_T, can be found using

$$v_T = \sqrt{F \times r_B/M_E}. \quad (7)$$

It is well known that plummeting free charges will spiral around the earth's magnetic field lines as they rain down.

The force and spin velocity due to the earth's magnetic field can be calculated to be $\mathrm{F} = 9.6 \times 10^{-19}$ Newtons and $v_T = \sqrt{F \times r_B/M_E} = 116000$ meters/second = $3.9 \times 10^{-4} c_0$ respectively, using:

- the earth's magnetic field, B, equal to 5×10^{-5} Tesla[11],
- the mass of an electron, M_E, equal to 9.1×10^{-31}kg[8],
- the previously defined lightning bolt velocity, v_B,
- the lightning bolt radius,r_B,
- the fact that the worst-case angle, where the force is strongest, between the plummeting electrons and the Earth magnetic field occurs at θ equals 90 degrees,
- (6), and
- (7).

Fig 4 shows the force and subsequent spin direction of the expanding bubble of charge due to the earth's magnetic field. This force on the expanding electron cloud is also only a function of ϕ.

The force and spin velocity due to the spin of the charge bubble due to the earth are calculated to be $\mathrm{F} = 1.06 \times 10^{-15}$ Newtons and $v_T = 0.0128\ c_0$ respectively, using the values above and

- the speed of expansion $v_E = v_r = 0.625\, c_0$,
- the angle θ from $\vec{v} \times \vec{B}$= 45 degrees,
- (6), and
- (7).

Finally, Fig 5 shows the force and subsequent spin direction of the expanding bubble of charge due to the magnetic field

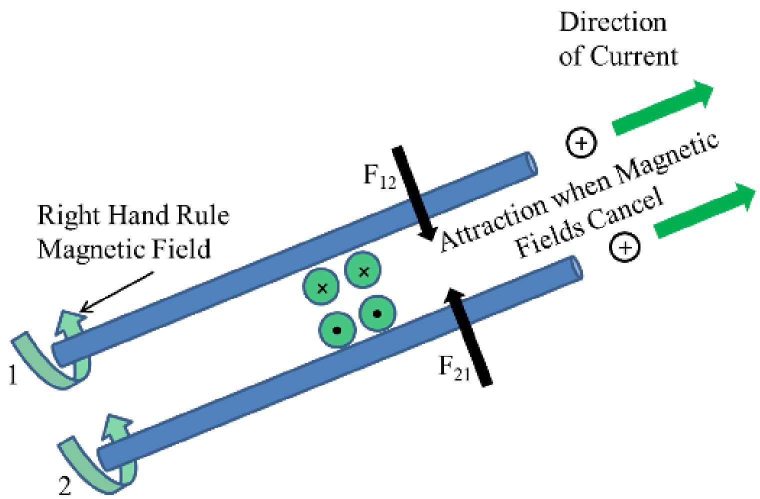

Figure 1: The magnetic fields of like charges moving in the same direction attract one another.

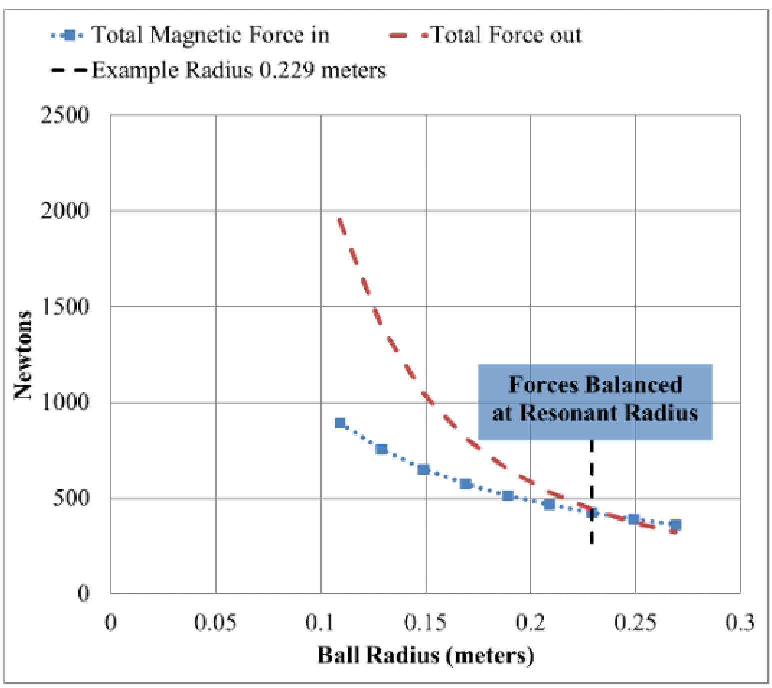

Figure 2: The forces acting on an expanding spherical bubble of charge.

generated by the current in the bolt of lightning itself. The force and spin velocity due to the bolt are found to be $\mathrm{F} = 5.52 \times 10^{-13}$ Newtons and v_T ~0.29 c_0 respectively, using the values above,

- the angle θ from $\vec{v} \times \vec{B}$ = 45 degrees,
- the bolt's magnetic field $B = 0.026$ Tesla (which was found using the radius $r_{wgm} = 0.229$ and (17)),
- (6), and
- (7).

This force on the expanding electron cloud is only a function of θ. Ultimately, this force is weaker than and counteracted by the ponderomotive force and contributes no additional net spin.

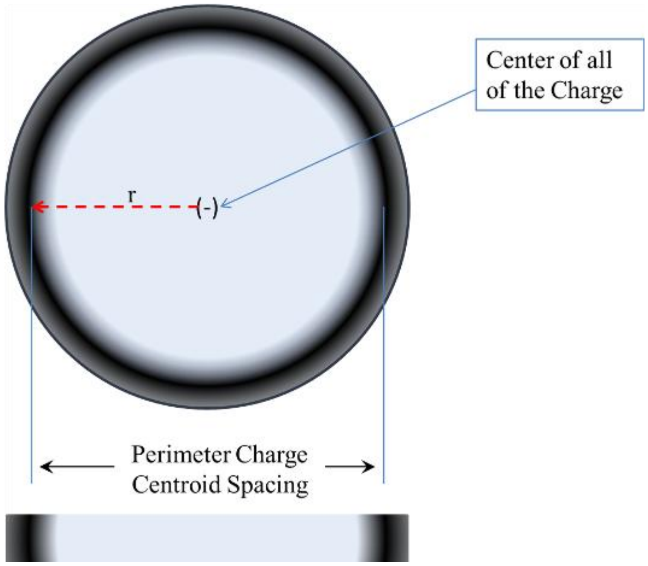

Figure 3: Clouds of charge near the perimeter of the spherical bubble of charge have a centroid location where the force of their local cloud appears to come from. The forces act on the centers of charge.

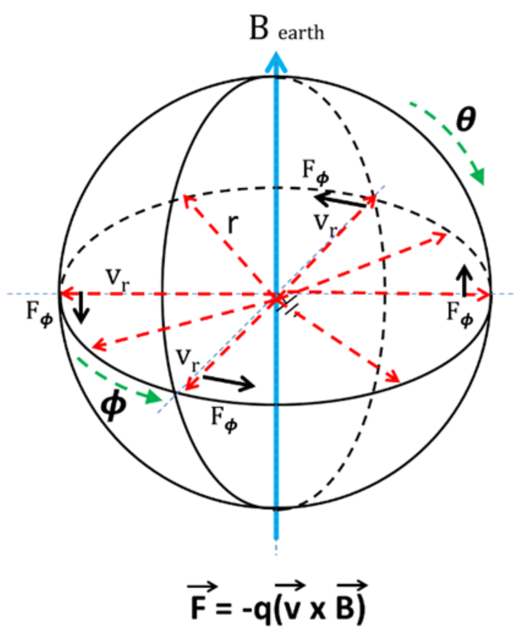

Figure 4: The force on the expanding electron cloud due to the earth's magnetic field causes the electrons to rotate around the charge center in the direction of Phi(***ϕ***).

None of the forces causing spin are capable of compressing the sphere of charge. The forces generated are all tangential to the bubble surface.

To restate, all previously described interactions of the expanding sphere of electrons with locally induced magnetic fields cause the electrons to spin around the sphere's axes and do not generate forces that oppose expansion. ***The boundary conditions of the ball lightning sphere do allow electromagnetic field shapes inside a sphere of conducting free electrons. A mode that supports***

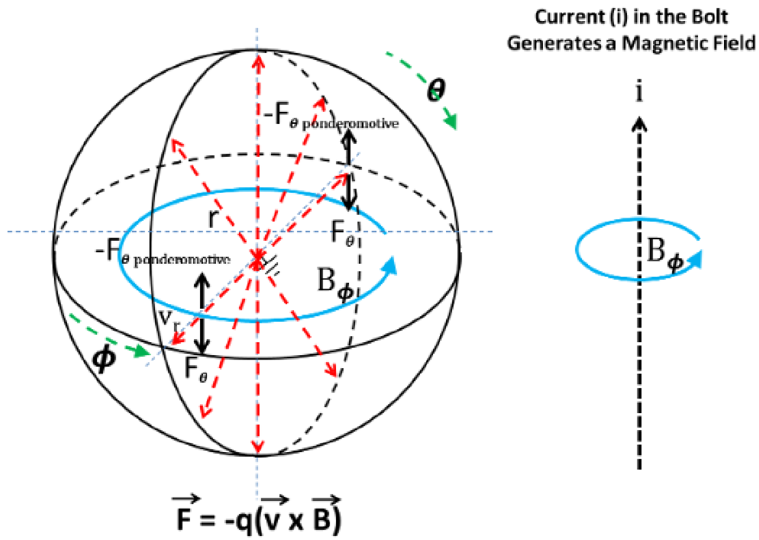

Figure 5: The Force on the expanding electron cloud due to the current of the lightning bolt causes the electrons to rotate around the charge center in the direction of theta.

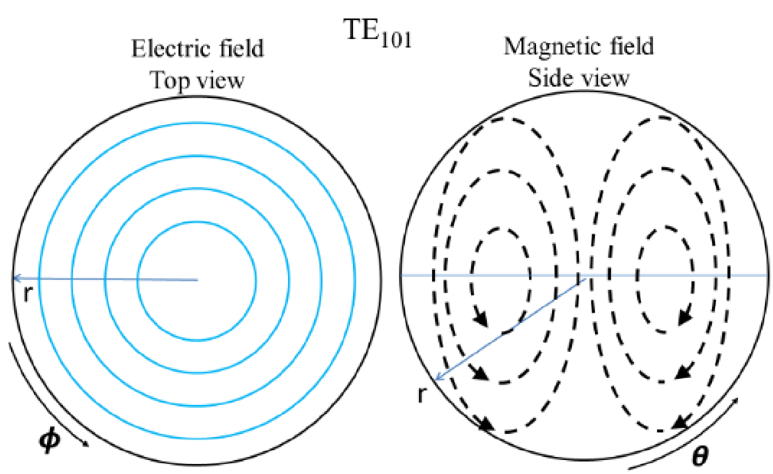

Figure 6: These cross sections of the TE_{101} mode show the orientation of its electric and magnetic fields.

electromagnetic fields which can generate inward forces and stop the expansion and stabilize the ball of electrons was identified and is discussed next.

It is well known that a spherically shaped conductive shell can support internal resonant EM waves. Their resonant frequencies as well as the allowable transverse electric, TE, or transverse magnetic, TM, mode shapes can be calculated. The lowest order, electrically smallest, and simplest modes will be discussed here, as well as how they might influence the behavior of isolated clouds of “free” charge.

Of course, in order for a ball of charge to reach a steady state, there must be an inward directed EM force ignited by the expanding charge bubble that is capable of counteracting the direct-current-like force pushing outward. But it is precisely this aspect that researchers have not solved.

Because of the spherical shape of the conducting wall there are only a few EM rules that will influence the "steady state" shape of the trapped waves. The electric field, E, vector must be oriented perpendicular, normal, to the wall. All parallel electric fields go to zero at the wall. Away from the wall, parallel E vectors can exist and can reach a maximum ½ wavelengths away from the conductor.

The behavior of the magnetic field, H, is opposite that of the E field. At the conductive boundary, the H fields are only parallel. The normal component is zero. Likewise, away from the wall, normal H fields can exist and reach a maximum at ½ wavelengths away from the conductor.

Lastly, because of the constraints listed above, the spherical cavity's size plays a role in the allowable stable resonant frequencies that can exist inside. The smallest cavity needs to be approximately a wavelength in diameter or larger; otherwise, the walls will be too close and will short out the E field.

We will briefly review two standard spherical cavity modes, TM_{101} and TE_{101}, that result in the smallest sphere at any resonant frequency. They are similar in size as a function of wavelength but do not provide the necessary uniform forces on the bubble of charge to stop its expansion to create a stable ball of lightning.

4. COMMON CAVITY MODES

Figs 6 and 7 show the TE_{101} and TM_{101} modes respectively. Solid lines depict the orientation of the electric fields whereas the dashed lines show the magnetic fields shape and orientation.

The TE_{101} mode has a solution to the spherical wave equations of:

$$(2\pi/\lambda) \cdot r \approx 4.49 \quad (8)$$

[12]

where r is the radius of the sphere.

At a resonant frequency of 625 MHz, would correspond to a radius of 0.343 meters. This is significantly larger than Wu[5]'s results show. In addition, the polarities of both the electric and magnetic fields will tend to push outward on the bubble (see Fig 6) and so this trapped mode is ruled out as a stabilizing mode.

The TM_{101} mode has a solution to the spherical wave equations of:

$$(2\pi/\lambda) \cdot r \approx 2.74 \quad (9)$$

[12,13]

where r is the radius of the sphere.

At a resonant frequency of 625 MHz, would correspond to a radius of 0.209 meters. This is somewhat smaller than what Wu's results show. In this mode which is a non-propagating oscillating wave, the electric field is perpendicular to the spherical boundary. The oscillating charge, q, is moving in the direction of and parallel to the electric field with velocity, $\vec{v}$. The magnetic field $\mu_0 \vec{H} = \vec{B}$ runs parallel to phi, ϕ. Equation (5) suggests because it is a cross product, that any forces generated by this mode will run parallel to the surface of the sphere and not inward. Therefore, this trapped mode, shown in Fig 7, is also ruled out as a stabilizing mode.

5. WHISPERING GALLERY MODE VARIATION

This last spherical cavity mode, that is close to the same size as the bubble of free charge being introduced in this paper, is a "whispering gallery mode[14]," WGM, variation. The mode described meets the outlined spherical boundary conditions of a stable trapped wave and is shown below to have sufficient force to hold the bubble together. The particular mode described here is the smallest allowable size of this mode for any given frequency.

The WGM shown in Fig 8 is different than the previous two modes described earlier. The circumference of the sphere is 3 wavelengths which corresponds to a radius of

$$r = 3\lambda/(2\pi) \quad (10)$$

where r is the radius of the sphere.

At a resonant frequency of 625 MHz, the radius, r_{wgm}, equals 0.229 meters, which lines up almost exactly with the centroid of Wu's modelled charge bubble.

Each of 3 orthogonal propagating waves in the WGM is a transverse electromagnetic, TEM**,** wave which is dictated by the internal and external boundary conditions. At every point on the sphere both the electric and magnetic fields are orthogonal to their directions of propagation. All of the electric fields are radially polarized and have a toroidal shape in amplitude because the effective electric "short" along the spin axis. Each of the three TEM waves has its own unique and orthogonal spin axis. Fig 8 shows a cross section of one of those waves which is propagating out of the page at the top and into the page at the bottom.

Because the propagating wave is a plane wave with a semi-circular cross section, the magnetic field can be thought of as related to the electric field by the impedance of 176 ohms (see Fig 9).

Magnetic field density, B, the electric field density, D, and impedance, Ω, equal:

$$B = E \cdot \cos\theta / c_0 \quad (11)$$

$$D = H \cdot \cos\theta / c_0 \quad (12)$$

$$\Omega = B/D \quad (13)$$

Such that the

$$\Omega_{wgm} = 377 \sum_{n=1}^{6} (H_n/W_n) = 176 \text{ Ohm.} \quad (14)$$

Fig 10 shows that the wave velocity, v, is a function of the angle between the centerline of the spin axis and any path away from that centerline. The wave velocity is

$$v = c_0 \cdot \cos\theta \quad (15)$$

Along the centerline, $\theta = 0$, the wave velocity of the TEM wave is c_0, but it slows down for any angle $\theta > 0$. This is an important fact that explains why the sum of all the forces pushing inward is a constant. Constant force pushing in on the surface is necessary for stability.

Fig 8 and Fig 11 show cross-sections of the internal electric and magnetic fields' orientations of one of the TEM waves. The perspective of Fig 11 is from the negative x axis Fig 8. These opposing magnetic fields provide the attractive force necessary to push back on the expanding charge force. Unlike

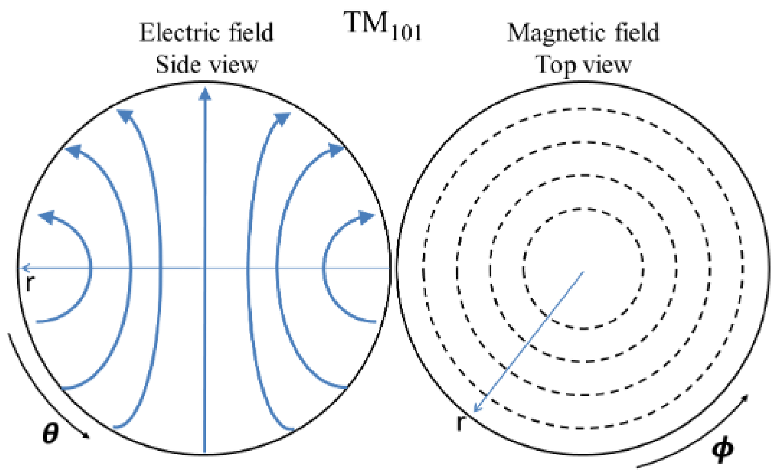

Figure 7: These cross sections of the TM_{101} mode show the orientation of its electric and magnetic fields.

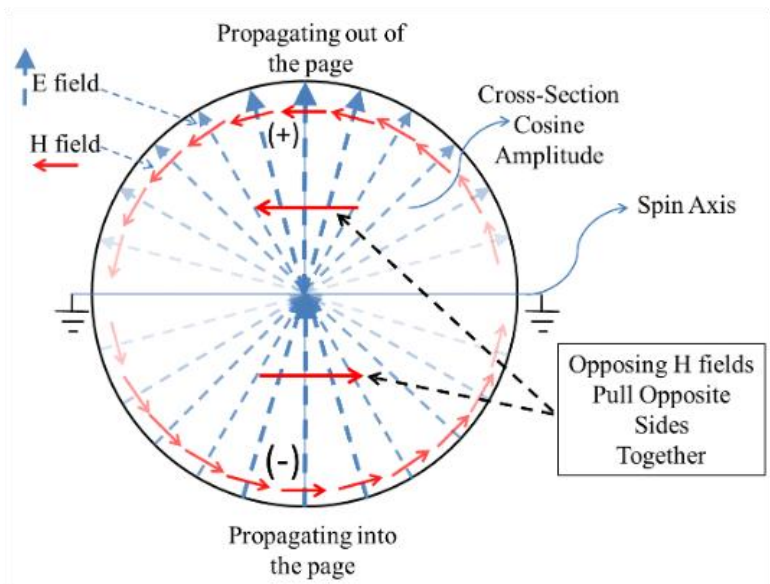

Figure 8: This cross section of the WGM variation shows the orientation of the electric and magnetic fields for one of the three orthogonal propagating EM waves. The opposing H-fields on opposite sides of the sphere pull the sphere together.

the TE_{101} and TM_{101} modes described earlier, three orthogonal propagating TEM waves trapped in a sphere with a 3-wavelength circumference have a direction of charge and a proper phasing around the sphere to provide a uniform stable force pushing inward against the outward force of the expanding charge. The expanding charge moving at a velocity of v_E, along with a tangential magnetic field density, $B = E/c_0$, has enough force to initiate the electrons to move tangentially at very close to the speed of light. This gets the ball rolling so-to-speak. Because of the 180-degree phase difference and opposite direction of propagation on the other side of the sphere, the induced TEM travelling waves now have enough charge moving in the right direction to provide an inward pushing force. At a specific frequency the forces will equalize

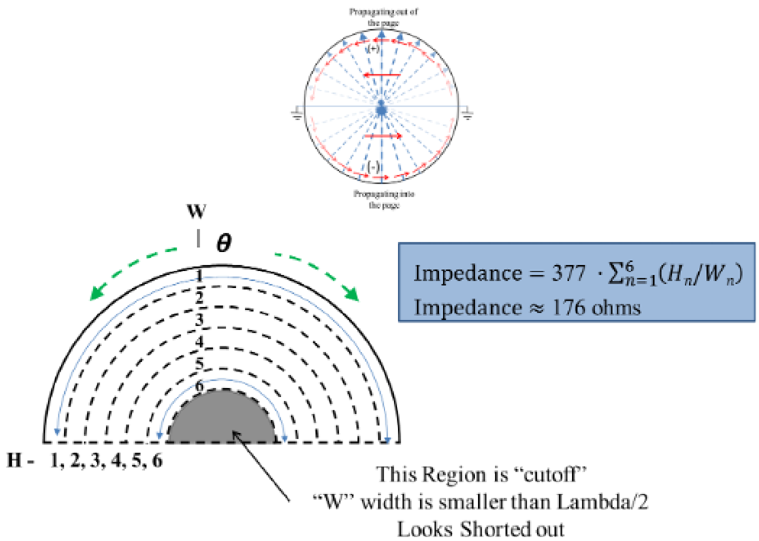

Figure 9: TEM wave-front impedance calculation. There is a fixed amount of energy, charge, and therefore voltage in the expanding volume. The electric and magnetic fields are related by the free space impedance of 377 ohms per unit area.

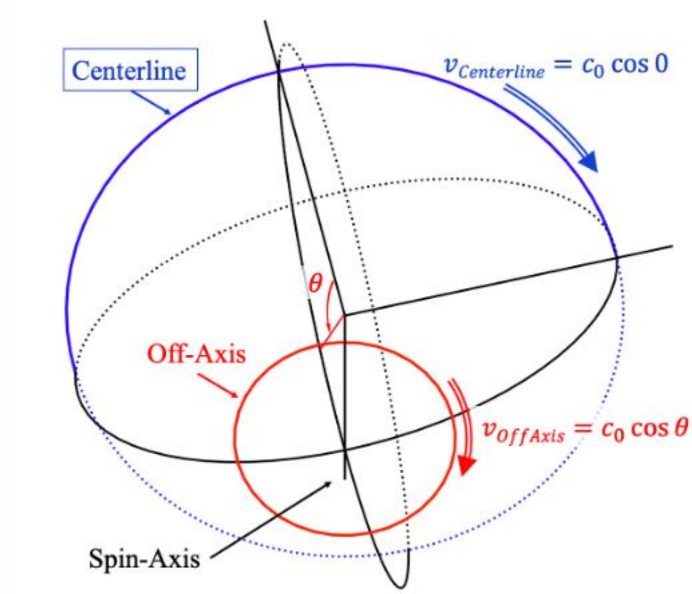

Figure 10: A plane wave propagating around its spin axis has a wave velocity that is a function of theta (***θ***). Theta is the angle between the wave centerline and any off-axis component.

and expansion will stop. That frequency will depend on the initial conditions of charge, energy etc. and in turn determine the sphere's size.

The strength of the EM force that is pushing in opposition to the expanding charge bubble can now be calculated using the parameters described earlier.

Assuming each of the three WGM's TEM waves consist of 1/3 of the expanding charge bubble's total charge, the charge of each of the three wave is $q_{wgm} = q_1/3 = 1.69 \times 10^{-5}$Coulombs.

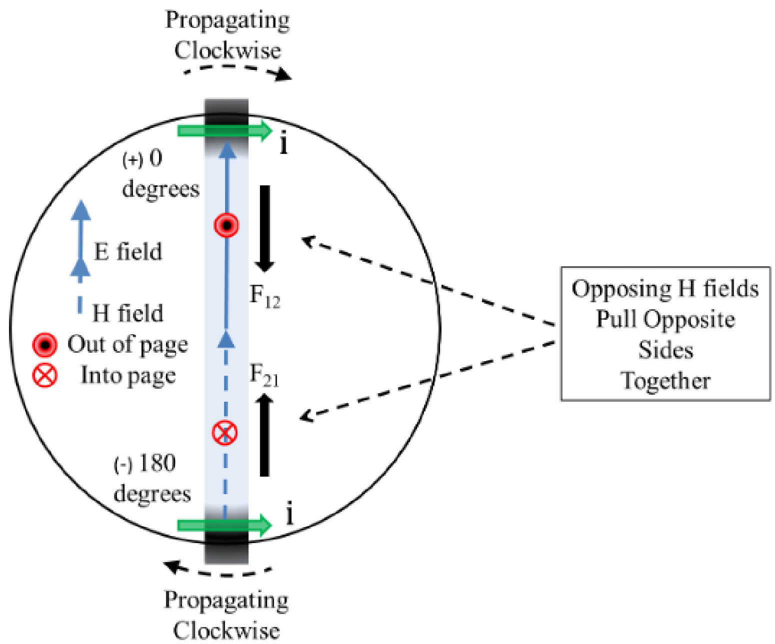

Figure 11: Side view of a single TEM wave propagating around its spin axis showing the force generated from the opposing H-fields pulling the sphere together.

In turn the average current during the expansion is $i_{ave} = q_{wgm}/(t_{expansion} \cdot 2) = 6940$Amps. Integrating over the cosine distribution on the toroid surface from –π/2 to π/2 will double the current.

The voltage of the waves generated by the expanding charge can be found by Ohm's Law: $V_{wgm} = i_{ave}\Omega_{wgm} = 1.22 \times 10^6$Volts.

Fig 12 shows the electric field strength of the EM wave as the bubble expands

$$E_{wgm}(r) = V_{wgm}/r \quad (16)$$

The resulting electric field strength is very high relative to the breakdown in air at standard temperature and pressure, STP.

The magnetic force equation, can be used to calculate the force pushing in on the sphere of charge using 1/3 of the total charge, q_{wgm}, and $\|\vec{v}\|$ is equal to the speed of light. An estimate of the magnetic field density, $\vec{B}$, as it appears on the opposite side of the sphere is required. Fig 13 shows how B varies around a single conductor,

$$B = \mu_0 i/2\pi r, \quad (17)$$

vs. a uniform wall of conductors,

$$B = \mu_0 H = E/c_0. \quad (18)$$

For the latter, it is evident that B is uniform and does not vary with distance, d. In addition, if L is the length of the planar arrangement of conductors, $H = i/L$, so that both H and B are constant at any distance d from the wall of conductors. Fig 14 depicts what the magnetic field density would look like on the opposite side of the sphere. Because it more resembles the uniform current sheet, (18) is a better estimate. The curvature of the sphere might make the field a little stronger than the calculation that follows by focusing the field. $E_{wgm} = 5.33 \times 10^6$ V/m, and $B = \mathrm{E}_{wgm}/c_0 = 0.0178$ Tesla are calculated using (16) and r_{wgm}.

The inward pushing force for each of the three WGM can then be found from (5) and an adjustment made for the integral of cosine[2] from $-\pi/2$ to $\pi/2$ that increases the force by $\pi/2$.

$$|\vec{F}_{wgm}| = q_{wgm} \cdot v \cdot B \cdot \pi/2 = 142\text{Newtons} \quad (19)$$

The combined force from all three WGMs is thereby $|\vec{F_T}| = 3 \times |\vec{F}| = 426$ Newtons.

6. WGM Uniformity

Fig 15 describes perhaps the most important feature of the three propagating TEM waves that allows for the forces that each wave generates to add up uniformly around the surface of the sphere. (5) is adjusted to contain a cosine[2] term such that $F = q(v \cdot cos\theta \times B \cdot cos\theta)$, because of how the wave velocity and the magnetic field density vary across the toroid. A, B, and C are three orthogonal spin axes. At all points on the sphere's surface the squared terms, one from each toroid, will add up to a constant. Specifically,

$$(cos\theta_A)^2 = y^2 + z^2, \quad (20)$$
$$(cos\theta_B)^2 = x^2 + z^2, \quad (21)$$
$$(cos\theta_C)^2 = x^2 + y^2, \quad (22)$$

and the sum of those cosine squared terms

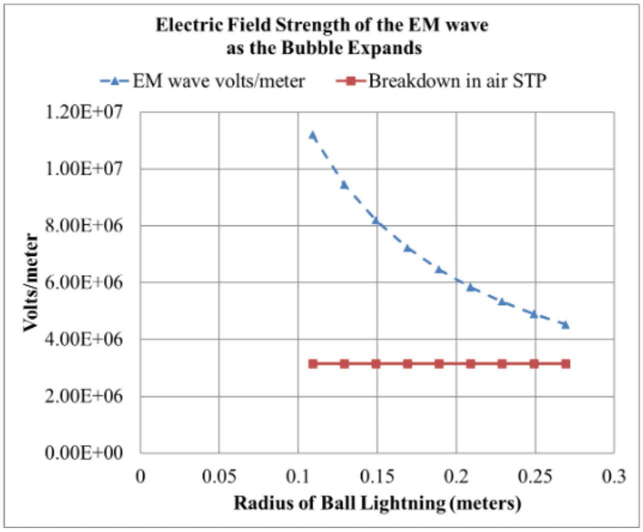

Figure 12: There is sufficient electric field strength to ionize air molecules in the bubble of expanding charge.

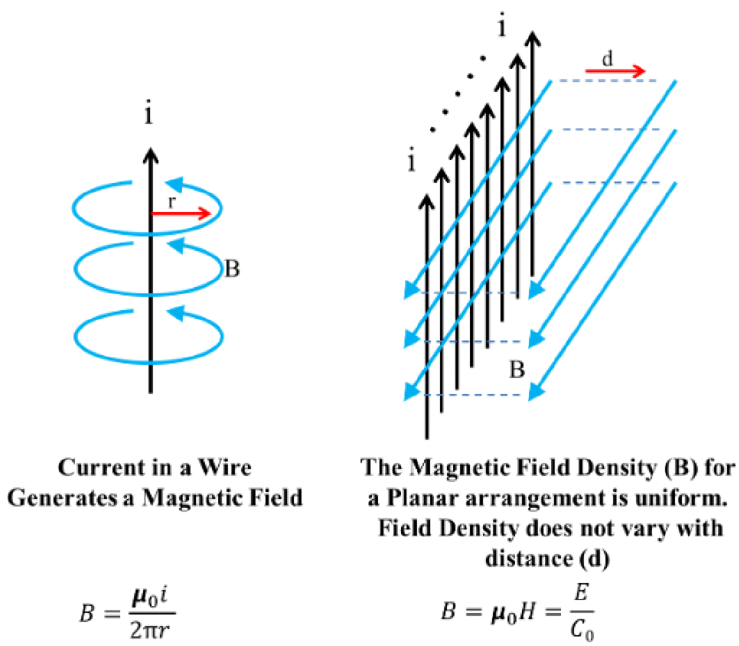

Figure 13: The strength of the magnetic field density $B$for a single conductor vs. a planar wall of conductors. The planar wall has a uniform magnetic field density.

$$= 2(x^2 + y^2 + z^2) = \text{Constant.}(23)$$

Consequently, the total Force from the three tori pushing inward on the surface of the sphere is uniform. This is critical because the charge bubble pushing outward is also uniform everywhere on the surface.

7. WGM Force Balance

Referring to Fig 2 again, with a uniform force pushing outward and a uniform force pushing inward these forces balance and support a stable spherical bubble of charge at a resonant

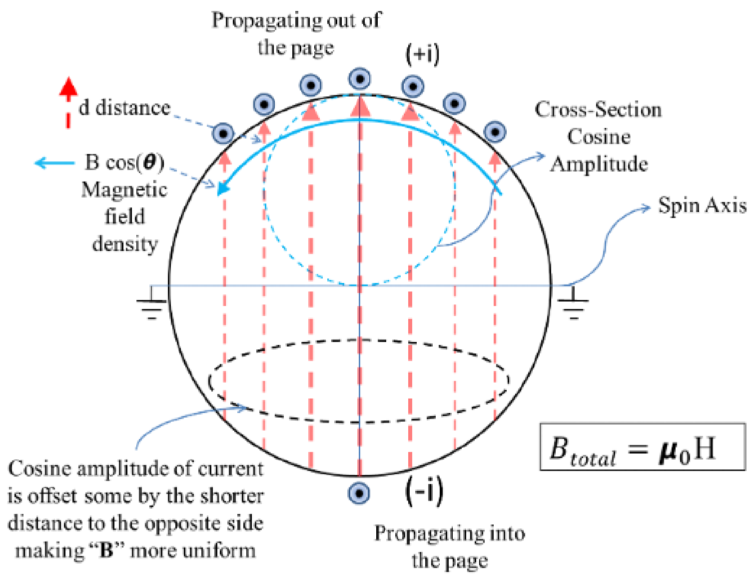

Figure 14: The strength of the magnetic field density B at the opposite point on the surface of the sphere is fairly uniform like that of a planar current sheet.

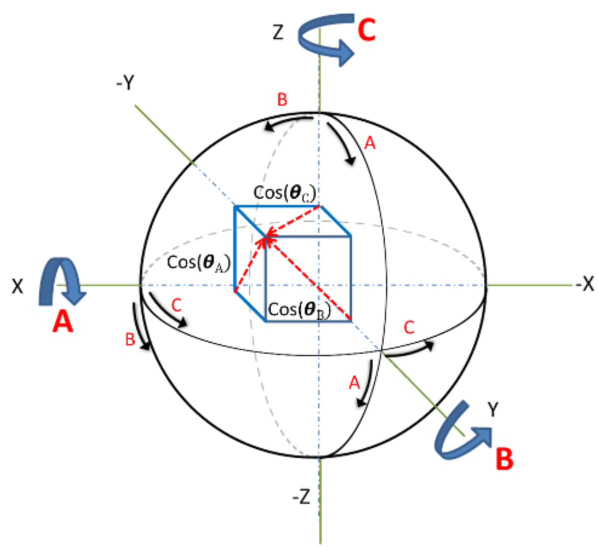

Figure 15: The Force each wave provides at any point on the sphere is proportional to the cosine^2 of the off-axis angle of its plane wave. Consequently, the total force from the three tori pushing inward on the surface of the sphere is uniform.

radius almost exactly equal to 0.229 meters. This corresponds to Wu[5]'s data and is consistent with the resonant radius predicted by the WGM cavity described in this paper.

8. CONCLUSION

"Ball Lightning" is not common and may comprise different phenomena grouped together under one name, a straightforward EM analysis of the energy, charge and initial conditions applied to an expanding ball of free spinning electrons using the parameters of a typical lightning bolt shows that self-generated trapped TEM waves contained inside the ball are capable of providing the compressing force necessary to keep the ball ionized and of a stable size. The size is dependent on frequency. Of Shmatov's[1] eight characteristics of BL, the proposed theory matches six. The two not addressed, "can decay loudly or quietly" and "has the characteristics of arcing, noise and smell," may also be true.

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

REFERENCES

[1] M.L. Shmatov, K.D. Stephan, "Advances in ball lightning research,"Journal of Atmospheric and Solar-Terrestrial Physics, col. 195, Nov. 2019, DOI.10.1016/j.jastp.2019.105115.

[2]R. C. Jennison, "Can ball lightning exist in a vacuum?" Nature, vol. 245, pp. 95, Sept.1973.

[3]P.H. Handel, "Maser theory of ball lightning" in Bulletin of the American Physical Society Series II, vol. 20, no. 26, 1975.

[4]H.C.Wu. (2015, Dec).Theory of ball lightning presented at 1st International Symposium on Lightning and Storm. Available: arxiv.org/pdf/1411.4784.

[5]H.C.Wu, "Relativistic-microwave theory of ball lightning," Scientific Reports, vol. 6, no. 28263,pp. 1-7, Jun., 2016, DOI. 10.1038/srep28263.

[6] M. A. Uman, "How long and how wide is the lightning channel?" in All About Lightning. New York, USA, Dover Publications 1986, pp. 81-92.

[7] L. M. Grenci and J. M. Nese, "Thunderstorms," in A World of Weather, 3rd ed. Dubuque, Iowa, USA: Kendall/Hunt Pub. Co., 2001, ch.8, pp. 202.

[8] E. Tiesinga, P. J. Mohr, D. B. Newell, and B. N. Taylor, "CODATA recommended values of the fundamental physical constants: 2018," Rev. Mod. Phys.,vol.93,Jun., 2021, DOI:10.1103/RevModPhys.93.025010.

[9] R. Hasbrouck,"Mitigating Lightning Hazards," Science & Technology Review, May, 1996.

[10] V. A. Rakov, "Lightning Statistics," in IX Int. Symposium onLightning Protection. Foz do Iguaça, Brazil, 2007.

[11] P. W. Zitzewitz, R. F. Neff, and M. Davids. "Magnetic fields," in *Physics: Principles and Problems*. New York, USA: Glencoe/McGraw-Hill, 1995, ch.24, sec. 2, pp. 503.

[12] S. J. Lai, B. Z. Wang and Y. Duan, "Eigenvalue analysis of spherical resonant cavity using radial basis functions," Progress In Electromagnetics Research Letters, vol. 24, pp. 69-76, 2011.

[13] J. A. Kong, "Spherical Cavities," in Theory of Electromagnetic Waves. New York, USA: A Wiley-Interscience publication, 1975, ch.5, sec. 3, pp. 170–173.

[14] M. L. Gorodetsky and A. E. Fomin, "Geometrical theory of whispering-gallery modes," in IEEE Journal of Selected Topics in Quantum Electronics, vol. 12, no. 1, pp. 33-39, Jan.-Feb. 2006, doi: 10.1109/JSTQE.2005.862954.

Tim G. Waterman received a Bachelor's degree in Electrical Engineering from the University of Michigan, Ann Arbor, Michigan, USA, 1976 in electromagnetic field theory. In addition, he received a Bachelor's degree in Environmental Engineering from the same university, Ann Arbor, Michigan, USA, 1976, majoring in water quality.

From 1978 to 2012, as a Senior Consultant and Advisory Engineer at the Northrop Grumman Corporation (previously Westinghouse) located in Baltimore Maryland, he played a key role in the concept, design and development of antenna arrays used for military and commercial applications. He has made significant contributions to programs with high national security importance such as the TPS-63 LSA, TPS-43 ULSA, TPS-70, METS, STAR ULSA, ARSR-4, the Australian AEW (Wedgetail), and horizontally polarized UHF wing array Sensorcraft systems. He has received over 20 patents in the area of electromagnetic design and has compiled more than 100 invention disclosures. He has authored two books detailing a new theoretical model for the construction of matter; *Matter with Electromagnetic Resonance* (Maple Creek Media 2015) and *How Nature Made Matter* (Kindle 2020).

Mr. Waterman is a consultant for corporations focusing on radar and other antenna systems, provides mentoring for young engineers, and speaks to audiences of varying technical understanding on the electromagnetic resonant cavity theory of matter and how it relates to a potential unified field theory.

Urs W. Batzel received the B.S. and M.S. degrees from Carnegie Mellon University, Pittsburgh, PA, USA, in electrical and computer engineering, in 1998 and 1999 respectively, and an additional M.S. degree from Johns Hopkins University, Baltimore, MD, USA, in applied and computational mathematics in 2008.

He has more than two decades of experience in antenna systems design, mathematics, and electromagnetics. Prior to his current research, he was employed by defense contractor companies including 12 years at Northrop Grumman Corporation. At Northrop Grumman Corp. he contributed to programs of national and international significance by leading, advising, and performing antenna system analysis, design, and test, and developing analysis software, test software, and antenna optimization algorithms.