Ball Lightning: Bubbles of Electronic Plasma Oscillations

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Abstract: *We present a theory that explains all known properties of ball lightning (BL) in terms of collective oscillations of free electrons*[*]*. The simplest case corresponds to radial oscillations in a spherical plasma membrane. These oscillations are sustained by parametric amplification, resulting from regular "inhalation" of charged particles that are present at lower densities in the ambient air. BL vanishes thus by silent extinction when the available density of charged particles is too low, while it disappears with a loud and sometimes very violent explosion when this density is too high. Electronic oscillations are also possible as stationary waves in a plasma ball or thick plasma membrane. This yields concentric luminous bubbles. Ball lightning is a remarkable example of dissipative and self-organizing open systems, depending on non-linear processes.*

1. Introduction

Ball lightning is a very peculiar natural phenomenon, since it usually appears during thunderstorms as *a spherical, freely moving luminous entity*. Its scientific study began during the first decades of the 19th century, when Arago [1] gathered about 30 witness accounts. He was motivated by what happened for meteorites, where stories about "stones that fell from the sky" were attributed to unreliable witnesses. "Balls of fire", assumed to be a particular form of lightning, were also treated with skepticism. Even today, the preconception that BL can't be real has not yet completely disappeared. It was suggested, indeed, that ordinary lightning could create round afterimages [2] or that its strong transient magnetic field could stimulate the brain and produce phosphenes [3]. This is rather astonishing, since several thousand witness reports were gathered in the meantime. Arago preferred already to get a better knowledge of the phenomenon, before any attempt to explain it.

Sauter [4], a German high school teacher, collected and analyzed a selection of 213 witness accounts from before 1895. About 15 years later, the Belgian scientist De Jans [5] provided a larger repertoire of characteristic properties of BL and noted two tendencies in trying to understand these facts. Several authors had proposed a *chemical* interpretation in terms of some yet unknown "fulminate matter", while De Jans was convinced that "BL is essentially an *electrical* phenomenon". He mentioned, but rejected the proposition that BL could be a spherical condenser [6], since a *static* charge separation in atmospheric air is not plausible. However, we will show that a condenser-like charge separation can be achieved in a dynamical way.

Brand [7], another German high-school science teacher, published in 1923 a very remarkable study, based on a collection of about 600 written reports. He selected 215 cases and provided a full copy of the corresponding data. His careful analysis confirmed not only the existence of BL, but extended also the repertoire of its amazing properties. Nevertheless, no plausible theoretical proposition emerged until 1955, when the famous Russian physicist Kapitsa [8] compared BL to the initial, very bright luminous spheroid generated by nuclear explosions. It has a diameter of about 150 m and contains

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totally ionized air that radiates all its energy in less than 10 s. If the initial state of BL were similar, the energy dissipation would also be proportional to its surface, but the diameter of BL is only of the order of 10 cm. The lifetime of BL should thus not exceed $(0.1/150)^2.10$ s = 5.10^{-6} s, while the real lifetime of BL is of the order of a few seconds and can even reach some minutes. Kapitza concluded that *BL requires a constant energy input.* He suggested that this plasma could perhaps absorb energy from an EM radiation that is present in the terrestrial atmosphere under thunderstorm weather conditions. This hypothesis was not confirmed, but his rational approach and insistence on possible research arose much interest.

Further milestones of BL research were the books of Singer [9], Barry [10] and Stenhoff [11], as well as review articles of Smirnov [12] and Turner [13]. Since microwaves can ionize air and set free electrons in oscillation, they are able to create *luminous plasmoids,* similar to BL [14], but in general, they have more irregular boundaries and natural BL is not created that way. Many reports about other BL observations, their analysis and new theoretical propositions continued to appear. The International Symposium on Ball Lightning [15], organized every 2 years, played a major role in fostering progress.

The present article is divided in 3 parts. We start with an analysis of phenomenological data, in order to detect clues for the construction of a theory and to be aware of the wealth of data that has to be explained. Then, we present a theory of electronic plasma oscillations, developed at first for a relatively thin plasma membrane. It can be generalized, but we get always collective oscillations of free electrons, sustained by the same mechanism. Finally, we consider various applications and verifications. They show that the proposed theoretical model seems to account for all known facts. We also propose an experimental test.

2. Analysis of phenomenological data

Occurrence and Appearance of BL

Observations of BL are by far the most frequent during thunderstorm activity, especially towards its end [7]. This suggests that BL contains charged particles, resulting from increased ionization of atmospheric air. Moreover, BL appears nearly always a short time after a lightning stroke and relatively close to its impact. Since linear lightning produces a strong magnetic field of short duration, we have to expect that this field contributes somehow to the natural production of BL. Witnesses tell us that it suddenly appeared in font of their eyes, as if a light bulb had been switched-on. Before this happened, they saw nothing special at this place, but it is reasonable to assume that a “virtual BL” was already present, without being visible.

An essential property of BL is that, once it reaches its light emitting state, it usually preserves the same size, colour and luminosity during its whole lifetime. This constancy implies an internal mechanism that combines three functions: (1) It confers a long lifetime to the locally excited state of atmospheric air, in spite of unavoidable energy losses. (2) It allows for constant renewal of charged particles, to compensate for recombination processes. (3) It insures plasma confinement, although a gas of charged particles should expand by diffusion. The central difficulty of the BL problem is therefore that we have to discover a yet unknown mechanism to create entities that are *dissipative and self-ordering open systems*. They contain charged particles and are able to stay for some time in a thermodynamically improbable state, by extracting matter and energy from their environment. According to Prigogine, such systems are governed by a set of nonlinear equations.

Nikitin expressed the same idea [16], but its implementation for BL remained an unsolved problem. Nevertheless, we know that living beings provide examples of this kind of systems and that our own beating heart is a rather autonomous system that can cope with a wide range of changing conditions.

Silberg [17] considered already in 1978 a nonlinear current-voltage relation for the generation of BL in submarines. Sanduloviciu et al. [18] presented experimental evidence for spatial structuring of low-pressure plasmas, associated with nonlinear current-voltage characteristics. Dimitriu et al. extended this work [19] and showed that different nonlinear responses of electrons and positive ions to electric fields can create luminous dipole layers. However, BL does not result from a constantly applied electric field and does not require a low pressure atmosphere. The Russian plasma physicist Kadomtsev [20] tried also to relate BL to a nonlinear current-voltage relation. Even the unaltered propagation of nerve-impulses depends on nonlinear effects that regulate the conductivity of biological membranes for different types of ions. However, we can only prove that BL results from nonlinear actions of an electric field on free electrons when we explain also how this field is generated.

Motions, Disappearance and Apparent Energy Content

BL is moving in an erratic way, but it can enter a house and move inside a room as if it wanted to explore it. It is more reasonable to consider that BL is somehow "searching" for charged particles. They are present in atmospheric air, especially during thunderstorm activity, and their density could be greater in a house than in open air. The idea of inhomogeneous distributions of charged particles is confirmed by the fact that BL can move against the wind. Sometimes, it squeezes itself through key-holes or narrow slits. It could be attracted to the other side, if there were more charged particles?

BL can even pass through windowpanes [21], while the glass remains intact. We are thus forced to abandon the idea that BL contains special types of atoms or molecules. It should rather be *an excited state of atmospheric air,* since it can be ionized and charged particles can be set in oscillation. Motions of BL would then be similar to the propagation of a wave, although it requires charged particles. Other plasma phenomena and the word "fire ball" may suggest that thermal agitation is essential to ionize the air, but when freely moving BL passed near witnesses, they didn't notice any heat radiation. BL is thus no hot plasma, but it could allow for coordinated oscillations of charged particles that are superposed on relatively modest thermal agitation. These *plasma oscillations* would be comparable to sound waves, but they do only involve charged particles and have to be orchestrated in such a way that they insure plasma confinement. BL would then prove that this can be achieved without sophisticated technical means, as for controlled nuclear fusion.

Since we are trying to analyze available data, in order to locate essential problems and to envision possible solutions, we must be astonished by the paradoxical modes of disappearance of BL. It can vanish through silent and peaceful "extinction", as if a light bulb had been switched-off, but it can also end its existence with a loud and often very violent "explosion". According to some statistics [12], the probabilities are nearly equal. This suggests a random cause, but it is customary to assume that the liberated energy had to be stored somehow inside the luminous entity and was simply released by the explosion. This idea seems to result from the fact that BL can't acquire energy from the outside in the form of EM radiation, but we mentioned already that BL could have the ability to collect charged particles that are present in the ambient medium. This would be equivalent to an energy input, since the creation of free electron and positive ion pairs required some energy. Peaceful extinction or violent explosion would then depend on the density of charged particles in the partially ionized surrounding air. It has often been observed that BL exploded when it entered another room or open chimney. The air could there contain more charged particles than necessary for survival of the moving BL. Extinction would result, on the contrary, from "starving" when the ambient medium is too poorly ionized.

In some cases, it was possible to evaluate the *liberated energy.* The observation of Morris in 1936 provides an instructive example [9, 10, 11]. He saw a luminous red ball that had only the size of an orange, but it entered a barrel that contained about 18 liters of water and heated this water up to boiling temperature. Analysis of this observation led to the conclusion that this BL contained an energy density of about 6.10^3 J/cm^3. Some 30 workers of a Hungarian factory observed in 1972 a BL of a football's size that entered a water pit. This led to the complete evaporation of about 120 liters of water [22]. If the required energy had already been stored in this BL when it entered the water, the energy density would have been about 3.10^4 J/cm^3. Many other evaluations were made [10]. They included also interactions with wood that could contain moisture. We have thus to ask ourselves if BL did not extract energy from the water, instead of releasing stored energy.

Statistics for Diameter, Lifetime and Luminosity

Much effort was devoted to establish statistical data by collecting and analyzing witness reports. It appeared that different collections displayed no systematic differences and that the *probability distribution* P(X) is very similar for different observables X. This can be the estimated diameter of BL, its lifetime, luminosity or velocity of displacement. There is always a most probable value for X, but the distribution is skewed, so that larger values of X are more frequent than smaller ones. The most probable diameter falls between 10 and 50 cm (for 63% of 4587 cases), while the diameter was smaller than 2 cm or larger than 1 m in about 2 % of this ensemble [23]. The size of BL was often compared to that of an orange, a child's head or a football, for instance, but BL can be as small as a pea and in exceptional cases, it is very big [24].

Dijkhuis [25] has proven in 1992 that all existing data collections are compatible with the same probability distribution P(X), which is the *log-normal distribution*. This means that one gets a normal, bell-shaped distribution when logX is considered as the random variable instead of X. To optimize the comparison with empirical data, he used the cumulative probability distribution, renormalized in terms of the corresponding average value and standard deviation [11]. The most probable values are then nearly 19 cm for the diameter, 8 s for the lifetime, 70 W for the luminosity and 1 m/s for the velocity of displacement. The arithmetically calculated average values would be greater, of course. This summarizes a century of data collection on three continents and is the only quantitative law in this field. Although this is a statistical law, applying to a large ensemble of observations, it is very important, since it should be possible to explain this remarkable fact.

Grigorjev et al. noted already that bigger BL tends to have a longer lifetime and a greater luminosity [26]. Amirov and Bychkov [27] confirmed that lifetime and diameter increase together, but they noted a special feature. The correlation depends on the mode of disappearance, since the lifetime decreases beyond a certain value of the diameter for exploding BL, while this is not true for extinctions. This fact could indicate that a structural difference existed already before this event. In our view, bigger BL requires a greater number of charged particles, and this number has still to be increased to achieve explosions, while extinctions simply follow from a lack of available charged particles.

Structure and other Observable Effects

It would be very helpful to know more about the internal structure of BL, but in general, we ignore if light is only generated near the surface of BL or also in its volume. We will thus consider both hypotheses, but the following observations are in favor of the first one. In 1904, a German engineer and his wife were walking in stormy weather. There was rain, hail, snow and strong wind. Nevertheless, they saw a luminous ball that had a diameter of about 4 m. It sank to the ground and for a short while, it enveloped the couple [28]. They were not harmed, but were isolated from the outside wind and stood in a thick white sea of light. They could only see the nearby pebbles on the road [9]. They had no sensation of heat and didn't smell any odor, but were surrounded by a luminous membrane. During a violent electrical storm in 1895, there appeared a distinctly outlined yellow-red sphere that had the apparent size of the moon. "Its outer rim appeared to be a fine, bright ring, *as if the sphere had a skin"*. It disappeared with a mighty detonation when it collided with a cottage and destroyed it [29].

Grigorjev et al. found that in 226 cases among 2082 observations (11%), the witnesses mentioned that BL had a semi-transparent shell [26]. Perhaps, the intensity of the emitted light is usually too high to recognize a luminous membrane. It should also be noted that the outer surface is not always sharply defined. A floating luminous ball with a diameter of about 15 cm had the appearance of a soap bubble, but it was covered or made up of a 2.5 cm thick semi-transparent furry coat. The witness could see through this coat the inner face of the opposite side, which was smooth [30]. The external surface carried even here and there some spikes, which had a length of about 5 cm, but their positions changed all the time. This bubble disappeared with a loud pop and left a smell as for electrical discharges. BL can thus produce ozone and have a fuzzy outline. Spherical BL can even display quite long radial protrusions. It also happens that a moving BL has a tail, and after the disappearance of BL there can remain a mist that is blue in reflected light and brown in transmitted light [7]. These colors indicate the presence of very small particles, responsible for Rayleigh scattering of incident light. Moreover, the mist is white in moist air, which is expected for larger particles.

"Hollow balls" were also reported [7], but some witnesses saw a "luminous core with a halo" or even *several concentric luminous shells.* The Russian chemist Dmitriev made in 1967 a very remarkable observation of this type [31]. He saw a BL that appeared after an intense flash of ordinary lightning and passed then over the observer, who was camping at the Onega River [9] It had an average diameter of 13 cm, but was slightly ellipsoidal, with a vertical major axis of about 14 cm. It had a very bright central part of yellow-white color, surrounded by *two* luminous shells. They were easily discernable, since the middle shell was dark violet and the outer one light blue. They had a thickness of about 2 cm, while the core had a diameter of 6 to 8 cm. This BL appeared above the river and approached the witness by following the curved path of assembled wood floats. Over the shore, its motion became erratic and disappeared after contact with a tree. Although it was not very great, its lifetime amounted to about 80 s, which could result from a high ionization level of the ambient air.

The chemist was equipped with evacuated 200 cm^3 glass bulbs, to collect air samples for later analysis. He did this at intervals of 5 seconds by holding the tubes over his head in the immediate neighborhood of the passing BL. He had the impression that "energy was continually generated in the lightning ball", since he heard a continuous noise and some crackling. His transistor receiver detected also a "continuous rumble". There was "a visible trail of bluish mist with an acrid odor". Later analysis of the gas samples disclosed that the concentrations of all air components were normal, except for a strong increase of O_3 and NO_2 molecules between his taking of the first and second sample. The third sample indicated a slower decrease, but the concentrations where nearly normal again for the fourth sample. The peak was higher for nitrogen oxide than for ozone, but the essential point is that these molecules are also formed in electric discharge processes. Moreover, the observation of a layered structure was detailed and trustable.

BL is frequently moving at a height of about 1 or 2 m above the ground, at a velocity that is similar to that of a walking man, but there is no strict rule. Even fast motions from clouds towards the ground have been observed. The path can be oblique with respect to the wind and BL can even remain motionless for some time, as if it were attached to somehing [7]. It can roll along wire fences, rain gutters, telephone wires, power lines or the extension cord of a table lamp. This indicates that it is attracted by metallic conductors. Although free-floating BL radiates no heat, it can melt these wires on contact. A gold wedding ring got very hot. BL is attracted by water and we mentioned already that its penetration in water results in heating. On contact with moist ground, BL can even dig a furrow, like an excavator [32]. It is often soundless, but can produce hissing, buzzing or crackling noises.

The emitted light can have various colors. For more than 4000 events [12], the most frequent colors were orange (23%), white (21%) and yellow (20%), followed by red and pink (18%), blue or violet (11%). Green was rare (1%), but patches of different colors were also possible (6%). The surface can even display wormlike structures (GLB13[33]), which are continually forming and breaking up. Changes of color and size were sometimes observed immediately before silent or explosive disappearance [10].

We interpret this fact as resulting from the beginning of an important decrease or increase of the global content of charged particles. The intensity of the emitted light can fluctuate during the apparently erratic motions of BL, even so much that this leads to momentary extinctions [34]. This confirms the concept of optically invisible BL that can survive and emit light again under more favorable conditions. Regular *pulsations* of the light intensity were documented on still photographs [10]. Since these pulsations were not visually detected, their frequency was higher than about 20 Hz.

When BL results from plasma confinement, there has to be some *surface tension,* but BL is more unusual than soap bubbles. It is more resistant, since it can bounce on the ground like a rubber ball. Its surface tends to be as small as possible, but it can be enlarged by radial protrusions. Rod-shaped and snake-like BL were also observed [33]. Over a tree or a church tower, spherical BL can fall apart in many smaller globes, and fusion of two globes, forming a bigger spherical entity is also possible. Even a flat rectangle has been reported [35]. The central difficulty of the BL problem does thus not result from a lack of information, but from *a wealth of data of bewildering complexity and undisputable originality.* Nature "tells" us something, but to understand it, we have to crack the code. We have to make this phenomenon mentally transparent. For an excellent review that includes also recent attempts to explain the BL phenomenon, we refer to Donoso et al. [36]. Let's now try to construct a theory that combines observed facts with known physical laws and concepts of plasma physics.

3. Electronic plasma oscillations

Natural Production of BL

It occurs under stormy weather conditions, where stronger electric fields accelerate free electrons. This leads to a sequence of ionization processes, since the secondary and primary electron can be accelerated again. We can thus get a local cloud of charged particles. That's the first step towards the creation of BL (figure 1). The second step is initiated by a nearby lightning stroke. Its horizontal transient magnetic field acts in combination with the vertical electric field, to push all free electrons in the same direction. Since the much heavier ions remain practically motionless inside the local cloud of charged particles, this yields positive and negative surface charges. This is the ignition process of electronic plasma oscillations, resulting from cooperating effects.

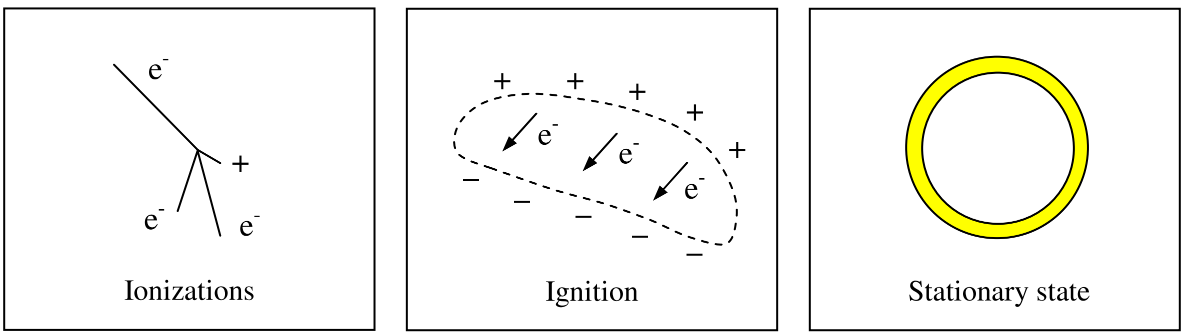

Figure 1: Three steps towards the natural production of BL

The surface charges create an electric field that slows down the electrons and reverses their motion. By overshooting their equilibrium positions, they create surface charges of opposite sign. The motions of the free electrons are then reversed again. The collective displacement of all free electrons inside the local cloud of charged particles corresponds to the onset of *plasma oscillations.* Moreover, the surface charges will attract one another. This flattens the cloud of charged particles until we get a relatively thin plasma membrane. We can now expect and will prove that it is able to close itself, while the collective oscillations of free electrons continue. When they are sufficiently powerful to excite air molecules, the plasma membrane becomes luminous. Moreover, we should get a stationary state, lasting until the BL disappears.

Justification of the Log-normal Distribution

During the ionization process, the total number Z of free electrons was exponentially increasing, so that $Z(t) = Z(0)\exp(\gamma t)$. To avoid arbitrariness, we chose the instant $t = 0$ in such a way that the initial value $Z(0) = 1$ for the local cloud of charged particles. The lightning stroke appeared at some particular instant t with a bell-shaped distribution around a given average value $\bar{t}$. Thus, we can express the probability distribution in two different ways:

$$P(t) = C\exp\left[\frac{-(t-\bar{t})^2}{2\sigma^2}\right] \qquad \text{or} \qquad P(Z) = C\exp\left[\frac{-(lnZ-ln\bar{Z})^2}{2(\gamma\sigma)^2}\right]$$

$\bar{Z} = Z(\bar{t})$. When we consider average values for γ, σ, $\bar{t}$ and $\bar{Z}$ that apply to the ensemble of BL events, we get a *log-normal distribution* for the number Z of free electrons, accumulated at the instant t where a particular BL was created. Taking into account the fact that BL has a strong tendency to preserve its initial properties, the number Z becomes a characteristic property of any particular BL during its whole lifetime. This will be justified later on, but for empirical reasons, we can already accept that Z remains constant and that all observable properties X are proportional to Z for optically visible BL. It follows therefore that $\ln Z - \ln\bar{Z} = \ln X - \ln\bar{X}$ for any particular observable X. This justifies the empirical law of Geert Dijkhuis. It transcends the enormous variability of particular situations and indicates that the natural production of BL is usually achieved in the same way.

Collective Oscillations in a Plasma Membrane

A small piece of the membrane of a plasma bubble can be treated as if it were flat. Inside this membrane, the charge carriers are homogeneously distributed, because of thermal agitation. The strong tendency to preserve electrical neutrality of BL implies that the density n of free electrons is equal to the density of positive ions or to the excess of positive charges when there are also negative ions.

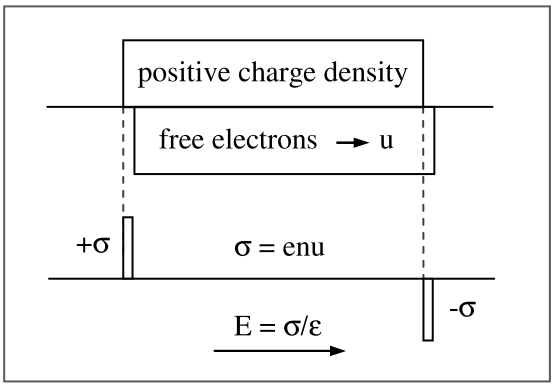

Figure 2: Charge distributions in the membrane

Because of their much greater mass, the ions remain practically motionless, while all free electrons are displaced at a given instant t by the same distance u with respect to their equilibrium positions.

These electrons obey quantum-mechanical laws, but we can consider their average motions, which are independent classical motions. They are synchronous and generate positive and negative surface-charge densities of magnitude $\sigma = enu$ (figure 2). As for an electric condenser, the resulting transverse electric field $E = \sigma/\varepsilon$.

ε is the dielectric constant inside the plasma memrane. When both distributions of surface charges are considered as delta functions, we can assert that every free electron inside the plasma membrane the situation is subjected to the same force $-eE = -(ne^2/\varepsilon)u$. It is proportional to u, but has thge opposite sign. It is thus *an elastic restoring force,* so that evedry free electron inside the plasma membrane will behave like a harmonic oscillators. Its average motion is described by Newton's law, which yields the following equation when all terms are divided by the electron mass m:

$$\ddot{u} + \nu \dot{u} + \omega_p^2 u = 0 \qquad \text{where} \qquad \omega_p^2 = ne^2/\varepsilon m \qquad (1)$$

Every dot corresponds to a derivation with respect to the time variable t. The square of the plasma frequency ω_p is proportional to the electron density n. Since we are considering electronic oscillations in air at normal atmospheric pressure, we have also to take into account the effects of viscous friction. As in the Drude theory for conduction electrons inside a metal, ν is the *collision frequency* for electron scattering and $\tau = 1/\nu$ is the relaxation time. In partially ionized atmospheric air, the electrons encounter individual molecules, atoms and ions. They are quite transparent to the electronic wave function, because of the quantum-mechanical Ramsauer effect, but the collision frequency is not negligible!

Although electronic plasma oscillations may be started by an adequate impulse through the ignition process, a stationary state would not be possible.

Collective oscillations of conduction electrons in very thin metal films or very small metal islands, formed by condensation on a transparent substrate are possible and known to exist [37]. The appearance of surface charges leads then to a resonance when the electrons are subjected to an oscillating electric field of adequate frequency, but this implies optical absorption, since the electrons transfer energy to the lattice. Until this effect was clarified, it was simply called an "anomalous optical absorption". Excitation of surface plasmons accounts also for "characteristic energy losses" of electrons passing through very thin metal foils [38] and for specific absorption of EM waves [39]. These effects depend on the type of material and show that collective oscillation of conduction electrons would be damped if they were not constantly re-excited by a flux of incident electrons or incident EM waves. The collision frequency ν determines then the width of the absorption band. The excitation of collective oscillations of free electrons at single metal surfaces has become an important tool in material science and biology [40] and can be applied for telecommunications [41].

BL raises more intricate problems. Collective oscillations of free electrons are really possible, but it is not sufficient to excite these oscillations at some particular instant. They have also to be sustained by another mechanism that compensates the effects of friction. Trying to find out how this might be achieved, we remembered a childhood experience. Sitting on a swing, we could sustain and even amplify its oscillations without external help, by simply changing our position in a particular way. We solved this problem by trial and error, but it is instructive to understand the underlying physics. Actually, we provided the required energy, but did this in a peculiar way. Can this method be transposed to account for the mysterious stationary state of BL?

BL is a Parametric Amplifier

A swing is equivalent to a pendulum and obeys equation (1) with $\omega_p^2 = g/L$. When we change the length L during every oscillation in such a way that the mass is raised near the extreme positions, we increase its potential energy at instants where it is predominant. We can reproduce this effect, by pulling on the string at two times its oscillation frequency, to get a variation of L that corresponds to $L = L_o(1 + 2\alpha \sin 2\omega t)$, while $u(t) \approx A \sin\omega t$ (figure 3).

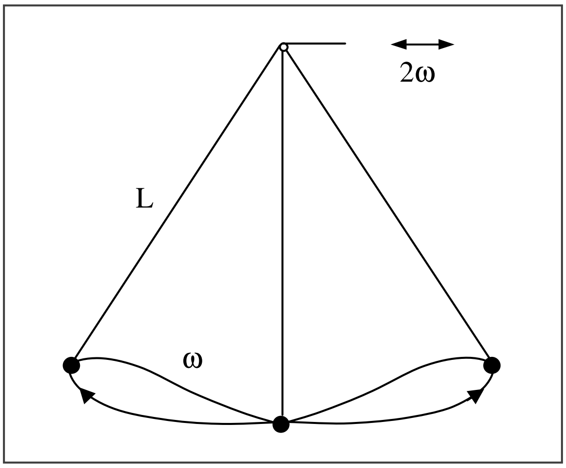

Figure 3: A pendulum can be a parametric amplifier

When $\alpha \ll 1$, the last terms of equation (1) will be replaced by

$$\omega_p^2\, u = A\omega_o^2(1 - 2\alpha \sin 2\omega t)\, sin\omega t \qquad (2)$$

where $\omega_o^2 = g/L_o$. Since 2sin2ωtsinωt = cosωt - cos3ωt, it appears that the modulation of the length L is equivalent to the introduction of two additional forces. The force which varies like cosωt compensates exactly the frictional force, when $\omega = \omega_o$ and when α is adjusted so that ν = αω. The other force is off-resonance and produces only a small anharmonic perturbation that can be neglected. In general, we get u(t) = A exp(μt) sinωt, where

$$\omega^2 = \omega_o^2 + \mu^2 + \mu\nu \qquad \text{and} \qquad \alpha\omega_o^2 = \omega\nu + 2\omega\mu \qquad (3)$$

A stationary state is thus achieved when μ = 0, which requires that $\omega = \omega_o$ and α = ν/ω. Larger values of α lead to exponential amplification, while smaller values, still close to the critical value ν/ω, yield moderate damping. A pendulum shows thus that frictional energy losses can be compensated by modulating a single parameter in a certain way. It becomes a “parametric amplifier”. Since this depends on a product of two oscillating functions, it is *a nonlinear effect.* BL could also be a parametric amplifier, if the electron density n did vary in such a way that

$$n = n_o(1 - 2\alpha \sin 2\omega t) \qquad \text{while} \qquad \omega_o^2 = n_o e^2/\varepsilon m \qquad (4)$$

This can be achieved, because of another remarkable process. Let us consider a piece of the plasma membrane at an instant where the external surface is positive and where the total charge Q of the spherical BL is zero. The potential energy for free electrons varies then in the radial direction as indicated in figure 4a. The discontinuities result from the surface charge densities. Inside the membrane, there exists a constant electric field E, creating a potential well near the external surface of the bubble. Free electrons coming from the outside medium will there be trapped, but the added negative charge will be uniformly distributed on the external surface of spherical BL. There appears a Coulomb potential outside the sphere, so that the potential energy for positive ions becomes attractive (figure 4b). When the total charge Q is again zero or even positive, electrons and negative ions can be trapped. BL will thus alternatively extract positive and negative particles from moderately ionized surrounding air.

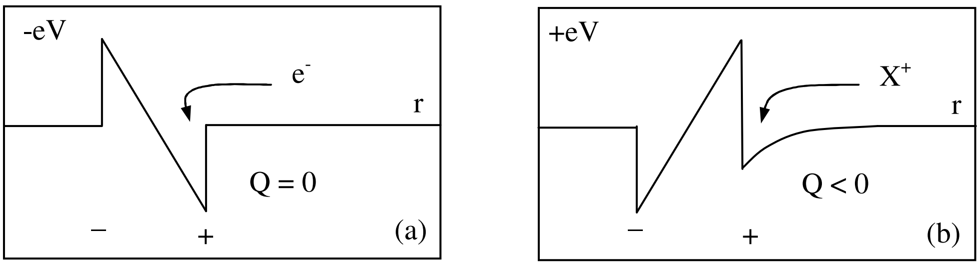

Figure 4: Potential energy across the membrane for electrons (a) and positive ions (b).

The intake of charged particles occurs constantly in an alternative, but somewhat random way. It is more efficient for high values of $|u|$, since the absolute value of the electronic displacement u determines the value of the surface charge σ. It vanishes when u = 0, while a sign reversal for u changes only the order of capture of positive and negative particles. These processes are not necessarily symmetric, but the swing experiment proves that this is of secondary importance. The essential point is that charged particles are imported and that this will automatically occur at the frequency 2ω, when the electrons oscillate at the frequency ω.

Since this process is analogous to the respiration of living systems, extracting oxygen and nitrogen molecules from the ambient air, we will call it "inhalation". Fishes extract oxygen from water, but animals need special respiratory organs, while BL uses simple electrical means. We have still to prove, however, that the electron density n inside the plasma membrane varies as required by (4). Does the electron density really increase and decrease at the adequate instants? This depends not only on the inhalation process, but also on a set of interrelated processes inside the membrane. The density n of free electrons is there mainly decreased by *attachment* to neutral particles, but also by *recombination* with positive ions. When N is the instantaneous density of negative ions, the corresponding density of positive ions is N+n, since there is a strong tendency to maintain always electrical neutrality for energetic reasons. It is thus sufficient to consider the possible variations of n and N.

$$\dot{n} = -an - \hat{a}nv^2 - rn(n+N) + \hat{B}n|u| \tag{5}$$

$$\dot{N} = an + \hat{a}nv^2 - \rho N(n+N) + \hat{b}n|u| \tag{6}$$

The coefficient *a* defines the probability of attachment of an electron to neutral particles par unit time, but attachment of free electrons can be enhanced by increasing their kinetic energy [42], especially for the dissociation of oxygen molecules ($O_2 + e^- \rightarrow O + O^-$). The probabilities of recombination of free electrons and negative ions with positive ions are specified by r and ρ. The density n of free electrons can only be increased by the inhalation process, modulated according to the magnitude of the surface charge σ or the absolute value of *nu*. Negative ions can be imported in the same way, but this is less efficient because of their greater inertia. For light emission it is sufficient to excite air molecules, atoms or ions inside the membrane. The oscillating electrons don't thus have to reach the high energies that would be required for ionization (12.1 eV for O_2 and 15.5 eV for N_2). These processes are disregarded inside the relatively thin membrane. Excitation processes result from inelastic scattering that increases the effective collision frequency ν, since they have to be added to elastic scattering. We would thus surely get damped oscillations, if there were no parametric amplification. Equations (5) and (6) can be solved, by setting

$$n(t) = n_o \exp(f) \qquad and \qquad N(t) = N_o exp(g) \tag{7}$$

n_o and N_o are constants, while f and g are functions of the time variable t. To find out if a stationary state is possible or not, we set u = A sin(ωt). This yields

$$\dot{f} = -a - a'(1 + cos2\omega t) - r(n+N) + B(1 - cos2\omega t) \tag{8}$$

$$\dot{g}N = an + a'n(1 + cos2\omega t) - \rho N(n+N) + bn(1 - cos2\omega t) \tag{9}$$

$a' = \hat{a}\omega^2 A^2/2$, $B = \hat{B}A/2$ and $b = \hat{b}A/2$. Since f and g are usually small compared to 1, the expressions (7) reduce to $n = n_o(1+f)$ and $N = N_o(1+g)$, so that the electron and ion densities fluctuate around their constant average values. Condition (4) would thus be satisfied if we could get f = -2αsin2ωt. Actually, we can solve (8) and (9) by a perturbation calculation when n_o and N_o are great enough. Separating constant and non constant terms, we get then

$$n_o = \frac{\rho(B-a-a')^2}{r[r(a+a'+b)+\rho(B-a-a')]} \qquad \text{and} \qquad N_o = \frac{(B-a-a')(a+a'+b)}{r(a+a'+b)+\rho(B-a-a')}$$

$$\dot{f} = -(B + a')\cos 2\omega t \qquad \text{and} \qquad \dot{g}N_o = (a' - b)n_o \cos 2\omega t$$

This yields the required expression (4) when $4\alpha\omega = B + a'$. *A stationary state is thus possible* when $\alpha = \nu/\omega$ or $B + a' = 4\nu$. The inhalation has to be sufficiently efficient to compensate friction. Energy dependent attachment is also helpful. Anyway, B has to be larger than $a + a'$ to get positive values for n_o and N_o.

We can also describe what happened when the values of n and N were still much smaller than n_o and N_o. According to (8), we can then consider the average variation of f, by disregarding the superposed oscillations. This yields $\dot{f}$ = B-a-a' = F, as long as r(n+N) is negligible. Thus, f = Ft - C, where C is constant. This means that n(t) = n(0)exp(Ft), where the *initial value* n(0) = $n_o$exp(-C). These results are confirmed by numerical integration of (8) and (9). Figure 5 was obtained by setting A = a = ω = n(0) = N(0) = 1, B = 2, a' = b = 10^{-1} and r = ρ = 10^{-4}. We see that the inhalation process leads to an accumulation of charged particles inside the plasma membrane and that a stationary state is possible, even with large oscillations of n with respect to its average value.

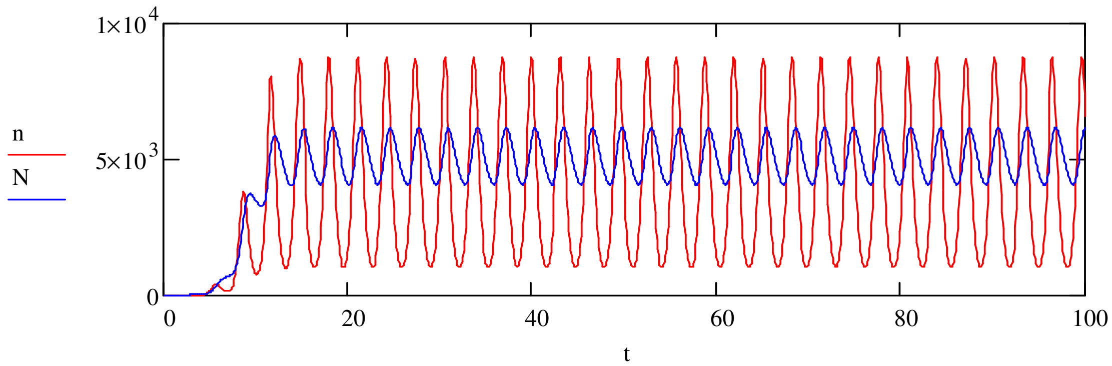

Figure 5. Calculated variations of the densities of free electrons and negative ions.

We used arbitrary units for time and particle densities, but the numerical solutions are quite robust with respect to changes of the chosen values of the parameters that appear in (8) and (9). Since we assumed here that u(t) = A sinωt, the initial condensation of charged particles inside the plasma membrane will be more progressive, but the essential result is that *a stationary state is possible.*

Stationary Waves for Radial Plasma Oscillations

To account for the occasional observation of concentric bubbles, it is sufficient to consider radial electronic oscillations inside a *plasma ball*. The average density n of free electrons is there constant and insures electrical neutrality with respect to motionless ions, but the actual electron density at a given point **r** and a given instant t is $n_e(\mathbf{r},t) = n + n'(\boldsymbol{r},t)$. The function $n'(\boldsymbol{r},t)$ defines small departures from the average neutrality, because of oscillations of free electrons with respect to their equilibrium position. Since n' is small compared to n and since the local velocity $\mathbf{v}(\mathbf{r},t) = \partial_t\mathbf{u}(\mathbf{r},t)$, where ∂_t stands for partial derivation with respect to t, the continuity equation reduces to

$$\partial_t n' = -n\,\nabla.\partial_t \boldsymbol{u} \qquad \text{or} \qquad n' = -n\,\nabla.\boldsymbol{u} \tag{10}$$

A disturbance of the electrical neutrality creates an electric field **E**, where

$$\boldsymbol{\nabla}.\boldsymbol{E} = -en'/\varepsilon \qquad \text{or} \qquad \boldsymbol{E} = ne\boldsymbol{u}/\varepsilon \tag{11}$$

The electrons are subjected to the force **F** = -e**E**, which is an *elastic restoring force*. Newton's law of motion for any particular electron inside the plasma ball allows thus for oscillations, but we get propagating waves, since we have also to take into account the effects of pressure gradients, acting on the electronic fluid.

$$\partial_t^2 \boldsymbol{u} + \nu\, \partial_t \boldsymbol{u} + \omega_p^2 \boldsymbol{u} = -\frac{\nabla p}{nm} = \upsilon^2\, \nabla(\nabla . \mathbf{u}) \tag{12}$$

This result is obtained by noting that $n \approx n_o$, while $\nabla p \approx (\partial p/\partial n)\nabla n'$. But $(p/p_o) = (n/n_o)^\gamma$, where $\gamma = 3$ when there is only one degree of freedom [43]. The parameter υ has the dimensions of a velocity. Because of (11), the oscillations are longitudinal with respect to the electric field. Thus, $\partial p/\partial n \approx 3p_o/n_o = m\upsilon^2$. For spherical symmetry and radial displacements,

$$\nabla(\nabla . \mathbf{u}) = \frac{\partial}{\partial r}\left[\frac{1}{r^2}\frac{\partial}{\partial r}(r^2 \mathbf{u})\right] = -k^2 \mathbf{u}$$

If the collisions were negligible, we could get *stationary waves* with

$$u(r,t) = A\, sin\omega t\, \frac{sinkr - kr\, coskr}{r^2} \qquad \text{with} \qquad \omega^2 = \omega_p^2 + \upsilon^2 k^2 \tag{13}$$

$$n' = -\frac{n}{r^2}\frac{\partial}{\partial r}(r^2 u) = -Ank^2 sin\omega t \frac{sinkr}{r} \tag{14}$$

The electric field **E** has only a radial component that varies in space and time like the radial displacement u. The average electron density is n, but there are superposed variations, oscillating in synchrony with the electronic displacements, while the spatial variations are different. The value of k is determined by the chosen boundary condition for r = R (figure 6). Since the collision frequency ν is not negligible, it is necessary to compensate friction by means of *parametric amplification,* achieved through regular inhalation of charged particles. This requires that the electric potential V = V(r,t) reaches maximal or minimal values at the surface. Since $E = -\partial_r V$, this happens when E = 0 and u = 0. We have chosen a value for kR that allows for *three concentric luminous bubbles,* corresponding to three maxima of u(r,t). This accounts for Dmitriev's observation [31]. Light emission requires, indeed, that the electronic velocity is sufficiently great to excite air molecules, but the stationary state (13) yields only large velocities at those places where the spatial variation of u(r,t) reaches maximal values.

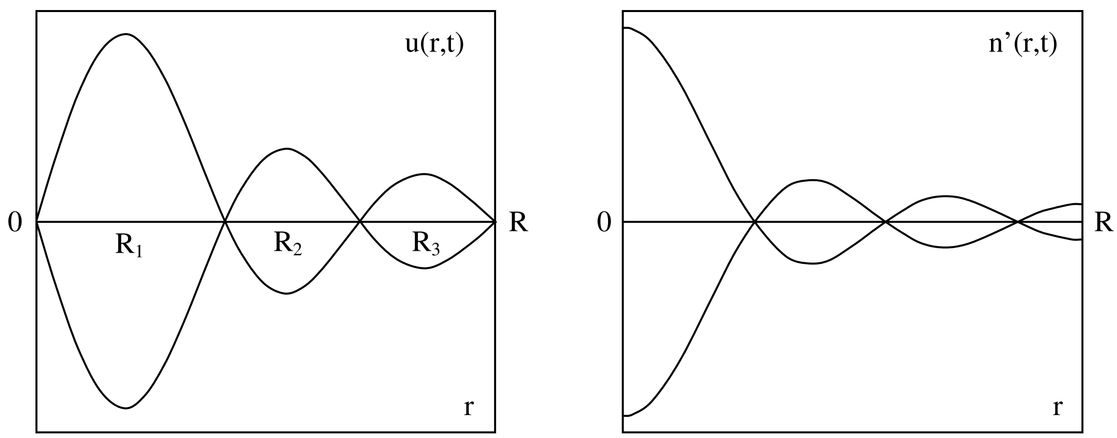

Figure 6: Extreme values of the displacement and density variation of free electrons in a plasma ball

The luminosity and color of the emitted light will depend on the ensemble of excited states that are populated by means of electronic impacts. Dmitriev saw a very luminous white core, surrounded by a blue external halo and an intermediate purple layer. Other witnesses saw only a core, surrounded by a separate halo. This could correspond to a plasma ball with two maxima R_1 and R_2 or to a hollow ball, with a thick membrane. The model of electronic plasma oscillations is thus quite flexible, but parametric amplification and inhalation of charged particles are always required.

4. Applications and verifications

Light Emission, Motions and Disappearance

Light emission results from inelastic collisions at those instants where the kinetic energy of the oscillating electrons is high enough to excite air molecules. Thus, it is pulsed, and this accounts for many BL photographs, taken with an open shutter [10, 11]. In BL with a relatively thin plasma membrane, light emission occurs everywhere inside this membrane. In plasma balls it occurs only near those places where the oscillation amplitude reaches a maximal value for stationary radial plasma waves. This yields concentric luminous bubbles. The color of the emitted light depends on the ensemble of excited states that can be populated by the available kinetic energy of the oscillating electrons. The color can thus be different for concentric bubbles. The fact that BL can eventually display "mixed colors" confirms that the electronic oscillations are transverse with respect to the external surface. Even small local differences are sufficient to get significant differences for the electronic velocities, since they depend on the amplitude and the frequency of the electronic oscillations. Worm-like structures appear when bubbles become deformable tubes.

In general, BL tends to preserve the stationary state for collective oscillations of free electrons by *adapting its local velocity and direction of motion* to the inhomogeneous density distribution of charged particles in the ambient medium. Figure 5 shows, indeed, that once a stationary state has been reached, it can be maintained. As required for the statistical law of Geert Dijkhuis, the total number of free electrons is then practically constant for any particular BL. Even the color and brilliance of the emitted light remains usually constant. In some cases, BL was seen to be surrounded by a corona-like glow or diffuse structures. This can be explained by excitation of neutral molecules that survive in a metastable state, since that allows for diffusion beyond the external surface of BL and even for retarded light emission in a luminous trail. Dmitriev detected ozone and nitrogen oxides outside BL [31].

The presence of ozone is typical for electric discharges, but the dissociation of oxygen molecules ($e^- + O_2 \rightarrow O + O^* + h\nu$) requires electron energies of about 6.5 eV. The exited oxygen atom allows then for ozone production ($O^* + O_2 \rightarrow O_3$), which is facilitated at normal atmospheric pressure by catalytic interactions with O_2 and N_2 molecules [42]. We can even understand why BL *suddenly appears,* as if a light bulb had been switched on. The plasma bubble or plasma ball was already there, but optically invisible, since the amplitude and frequency of the electronic oscillations had to become large enough to allow for excitations that result in the emission of visible light. Moreover, an extinction of BL can be followed by its reappearance, since the electronic oscillations are only slightly dampened when the density of charged particles in the ambient medium is nearly sufficient for adequate inhalation. The oscillation can be amplified again when inhaling becomes more efficient.

We understand also the erratic or apparently explorative motions of BL. It attracts charged particles, but is also attracted itself by charged particles. BL will thus automatically move in the direction where the density of charged particles in the ambient medium is greater, which favors longer survival for adequate external conditions. Sometimes, BL stays motionless at a given place, but this does not require that there are two types of BL, as suggested by Brand [7]. It is sufficient to assume that BL is sometimes surrounded by equal densities of charged particles. This can happen for instance above a flame or a pointed object.

The most important argument in favor of parametric amplification and the associated inhalation of charged particles is that *it accounts as well for peaceful extinction as for violent explosion.* When BL does not find enough charged particles in the ambient medium, the electronic oscillations are damped. This doesn't matter too much, when more charged particles can be found sufficiently soon. Otherwise, the oscillations are definitively extinguished. BL will explode, on the contrary, when the ambient medium contains more charged particles than required to preserve its stationary state. The oscillations are then exponentially amplified. Since the oscillation frequency is proportional to the average value of the density of free electrons, it is also increased. This leads to positive feedback and explosions.

BL is a Purely Electrical Phenomenon

Electronic plasma oscillations imply the existence of electric currents, but we know that the current density $\mathbf{J} = -en\partial_t\mathbf{u}$, while the electric field $\mathbf{E} = ne\mathbf{u}/\varepsilon$.Thus, curl$\mathbf{B} = \mathbf{J}+\varepsilon\partial_t\mathbf{E} = 0$. There is no magnetic field, although there are currents inside BL, and no EM radiation is emitted at the plasma frequency. This applies even to the *average* currents outside BL, since a spherical ball or bubble that carries an electric charge Q at a given instant t creates in the outside medium a radial electric field of magnitude $E = Q/4\pi\varepsilon r^2$. The average radial current density varies in such a way that $4\pi r^2 J(r) = -dQ/dt$ when the current density is directed towards the outside. It follows that $\mathbf{J} + \varepsilon\partial_t\mathbf{E} = 0$. Nevertheless, transistor and car radios can eventually detect *EM noise,* since individual motions of electrons and ions are partially random. Moreover, one can eventually hear *acoustic noise,* because of the entrainment of neutral particles by colliding positive ions in the ambient air. Both effects were observed by Dmitriev [31].

The instantaneous value Q of the total electric charge of spherical BL fluctuates around the average value $\overline{Q} = 0$. When the centre of a spherical charge distribution is situated at a distance r from a semi-infinite conductor or dielectric medium, there will appear an image charge -Q on the other side of the interface. The resulting *image force* is always attractive and proportional to $Q^2/(2r)^2$. Its average value is thus not zero. Conducting wires and roof gutters, for instance, are also known to attract BL.

A remarkable experiment [44] has proven that sudden dispersion of an aerosol by a unipolar discharge can lead to the formation of a sphere, composed of *long chains of very small particles.* We propose that these particles were polarized by the radial electric field. The mutual attraction of positive and negative poles of neighboring particles led then to the formation of chains. Once the particles are in contact, they stick together when the field is shut down. This results from Van der Waals forces, which are due to the reduction of oscillation frequencies and zero point energy of coupled dipole oscillations for decreasing separations of neighboring particles. Zaitsev [45] considered chains of particles and Bychkov [46] developed an ingenious BL model, based on the concept of a fractal structure of inter-knitted thin polymer fibers. They were assumed to result from an aggregation of aerosol particles of vegetal origin that could naturally be present in air. Lightning impact can also produce aerosol particles by soil erosion, but this cannot provide a general mechanism for the natural creation of BL, since it would not account for the appearance of BL inside houses and airplanes. This is also contradicted by the possible passage of BL through intact windowpanes. However, electronic plasma oscillations are associated with an electric field that could produce chains of particles.

It may seem strange that "fire balls" can appear and subsist when it is raining, but a higher density of water molecules can even be favorable, since positive and negative ions will then be surrounded by polarized water molecules. The resulting heavy ions are thus more protected from recombination. Stakhanov [47] proposed that the long lifetime of BL could be attributed to this effect, but it is not sufficient. Inhalation of charged particles is needed to provide sufficient energy and to renew the reserve of oscillating electrons.

Collective Proton Oscillations

BL is attracted by liquid water, because of the image force, but why can it survive there and heat the water up to boiling temperature? As we suspected at the outset, the liberated energy can be extracted from the water, instead of being stored inside BL, but it is then necessary to generalize the previous concepts. Water cannot provide free electrons like partially ionized air. However, it is well known that every water molecule has a certain probability to be dissociated ($H_2O \leftrightarrow H^+ + OH^-$). There are thus free protons, but protons behave like electrons, since quantum mechanics confers a special role to small masses. Not only "hydrogen bonds" are possible, but also collective oscillations of free *protons* with respect to the heavier ions of opposite charge (OH^-) or results of proton attachment (H_3O^+). BL should thus also be possible when free electrons are replaced by protons.

The density of free protons in water is low, but at normal temperature, water tends to maintain a constant proton density. The inhalation process, extracting protons and OH^- ions from ordinary water, will thus automatically lead to their replacement by other ones. Since water is a dense medium that is heated by proton collisions, the dissociation process and parametric amplification will be stimulated. Collective proton oscillations in minute structures that are similar to BL can also generate heat inside solid materials that can be partially filled with hydrogen, like palladium in cold fusion experiments.

Surface Tension of BL

Spherical plasma bubbles imply surface tension, like soap bubbles, but the physical origin of this surface tension is different. In liquid membranes, it results from the fact that molecules that are close to its surface are attracted towards the inside of the liquid. This is not true inside a plasma membrane, since all free electrons have there the same status. Surface tension of BL is thus a volume effect, instead of a surface effect. The total energy of the plasma membrane is $U_m = U_o + u_m S\delta$, where U_o corresponds to ordinary air, while u_m is *the energy density inside a plasma membrane* of external surface S and thickness δ. It results from three different processes, so that $u_m = u_1 + u_2 + u_3$.

The component u_1 results from the presence of positively and negatively charged particles, since the formation of every pair required a certain energy. When n is the density of free electrons and N the density of negative ions inside the membrane, there are n+N positive ions per unit volume. Thus, $u_1 = (n+N)E_i$, where E_i is the average ionization energy per pair. All free electrons behave like harmonic oscillators. For a stationary state, $u = A\sin\omega t$, where $\omega^2 = ne^2/\varepsilon m$ and A is constant. The corresponding energy density is $u_2 = n(m\omega^2A^2/2) = (neA)^2/2\varepsilon$. The same expression would be obtained by considering the energy density of the oscillating electric field, when one adds the kinetic energy of the oscillating electrons. The third component of u_m results from the fact that all charged particles interact with one another. They are randomly distributed with an average separation r, but statistically, every charged particle tends to be surrounded by particles of opposite charge. Since the density of charged particles is 2(N+n), we get $u_3 = -2(N+n)Ce^2/4\pi\varepsilon r$, where C is the Madelung constant. As for ionic crystals, it is of the order of 1.7.

By analogy with soap bubbles, we define the surface tension τ of a plasma bubble by setting $U_m = U_o + 2\tau S$, where $2\tau = u_m\delta$. This requires that the thickness δ of the plasma membrane has a finite value. Assuming that the inhalation process keeps the surface S and the total number of charged particles per unit membrane surface at constant levels for a given stationary state, we get constant values for Nδ and nδ. The energy density u_1 is thus proportional to 1/δ, while u_2 is proportional to A^2/δ^2 and u_3 is proportional to 1/rδ. The average separation r determines the volume per particle, so that δ/r^3 is constant. Thus, r is proportional to $\delta^{1/3}$, and $2\tau = c_1\delta^{-1} + c_2A^2\delta^{-2} - c_3\delta^{-4/3}$ where the coefficients c_i are constants. The two first terms are positive and increase when δ tends towards zero. The third term is negative and insures *cohesion,* but its absolute value increases more slowly than the second term when δ decreases. We get thus a *minimum* for the energy per unit external membrane for a finite value of the membrane thickness δ. Since its value depends on the amplitude A of the electronic oscillations, its adaptation to variable external condition could also contribute to the stability of the stationary state and constancy of the external appearance of BL.

As for soap bubbles of radius R, the effects of surface tension have to be compensated for spherical BL by an overpressure p of the imprisoned air with respect to the outside air. For a volume V, the total energy is then $U = U_o + 2\tau S - pV$, where $S = 4\pi R^2$ and $V = 4\pi R^3/3$. Equilibrium will be achieved when $R = 4\tau/p$. A larger radius requires a lower overpressure, but the total number Z of free electrons has then to be greater. These arguments can be generalized for plasma balls, since surface tension of BL corresponds always to a capacity of confinement, resulting from the mutual attraction of positive and negative particles.

Freely floating plasma bubbles and soap bubbles allow for *elastic deformations,* but plasma bubbles are usually more resistant to contact with solid objects. They can bounce on the ground or a wall. BL can even undergo impressive transformations, since it can squeeze itself though keyholes or narrow slits. As we suspected at the outset, BL is then attracted towards the other side, where the air is more ionized. This implies not only strong deformations, but also excellent resilience. BL can even undergo *fission or fusion,* as well as enormous elongations to become *a luminous stick.* It is also possible that a cylindrical plasma membrane with hemispherical extremities is created at the outset for a very elongated local cloud of charged particles. It is even possible to create stationary oscillations of free electrons in Cartesian coordinates for a flat box-like structure. Anyone of these particular shapes corresponds to a potential well, while form changes require the overcoming of a potential barrier.

Even tube-like *radial protrusions* of quasi spherical BL have been observed. We propose to attribute these unusual structures to an incorporation of small particles that have an affinity for charges of a particular sign. Since such localized charges repel one another, their separation has to be maximized, although the external surface of BL should be minimized. The actual shape is a compromise. When the extra charge Q is relatively small, an ellipsoidal deformation may be sufficient, but the membrane could also contain heavier molecules or dust particles that are inhomogeneously distributed. This allows for pear-shaped BL that was occasionally observed and corresponds to a possible potential distribution. Black or smoky BL (GLB11) [33] can also be attributed to inclusions or products of particular chemical reactions. Since tube like BL is possible, we can even account for the special case where a "ring detached itself" from spherical BL and formed a Saturn-like structure (GLB1, X220) [33]. A luminous halo or tail (GLB16) [33] can simply be attributed to diffusion of electrically neutral, metastable excited molecules, as we mentioned already.

Passage through Windowpanes

When BL comes close to a windowpane, it is attracted towards the glass by polarizing it, which yields an image force. It enters thus in contact with the glass and is even partially deformed, but it attracts also charged particles that are contained in atmospheric air on the other side of the windowpane. The density of charged particles will increase there and the plasma bubble or plasma ball will reconstitute its previous size and shape, as this happens normally for a moving BL. It can thus pass through a windowpane and leave it unharmed [26]. It is only necessary to adapt the over-pressure inside both parts of the progressing BL, but this is possible through inflow of air on one side and outflow of compressed air on the other side along the rim where the plasma membrane contacts the glass.

In a lower number of cases (26 instead of 42 for 3515 observations), the passage of BL through window panes left circular holes [21]. Rings were cut out, but they were not due to fusion of the glass.

They resulted from strong thermal stresses. This is possible, since the oscillating surface charges of a plasma membrane on both sides of the window pane will produce strong oscillating electric fields inside the glass, since the induced charges have opposite signs. The glass will then be heated because of its ionic conductivity, but heating increases this conductivity. This positive feedback can produce very strong thermal tensions, breaking the glass. Since the heating period is longer when the window pane is in the middle of sperical BL, the expected diameter of the hole is equal to the diameter of the plasma bubble.

4. Conclusions

BL is a natural phenomenon that remained shrouded in mystery. Research was intensified during the last decades and several ingenuous theories were advanced [36], but they were mainly devised to explain particular effects. The concept of *electronic plasma oscillations* opens a new way to approach this baffling problem. The basic principles are simple and physically secure, since they have already been applied and tested for free electrons in thin metals films and small metal particles [37]. However, they had to be transposed and adapted to allow for a stationary state of electronic plasma oscillations. This is possible for air at normal atmospheric pressure, because of *parametric amplification,* resulting from regular "inhalation" of charged particles that are present at lower densities in the ambient medium. The functioning of BL depends on nonlinear processes and provides a new example of *dissipative, but self-organizing open systems.*

The ensemble of observed facts is surprisingly complex, but the analysis of phenomenological data provided some important clues for the construction of the proposed theory. It was necessary to add other ideas, since theories try to make reality mentally transparent by imagining what is hidden and by considering the consequences of the proposed hypotheses. They have to be logically consistent and to explain all known facts by revealing the underlying mechanism. This is true in particular for the disappearance of BL by peaceful extinction or violent explosion.The theory should also be confirmed by further observations or specific experiments.

It was useful to begin with the more intuitive model of a "plasma bubble", where free electrons and ions are concentrated in a relatively thin membrane. Their average density is there homogeneous, and all electrons are oscillating in synchrony. The required elastic restoring force results from the creation of surface charges. This model was generalized, to account for a "plasma ball", but the density of the oscillating free electrons varies in space. We get radial electronic plasma waves that are reflected at the external surface to produce *stationary waves* with one or several maxima for the wave amplitude and light emission. This yields concentric bubbles, but the essential point is that frictional effects have always to be compensated by *parametric amplification.*

Usually, BL adapts its motions to variations of the local density of charged particles in the ambient air, in order to maintain the same stationary state for electronic plasma oscillations in light emitting BL. It appeared also that collective oscillations of free electrons are possible in such a way that their highest kinetic energy is not sufficient to excite molecules. This accounts for *virtual or invisible BL.* Moreover, we could explain why BL can penetrate in water and heat it up. It extracts energy from the water, instead of simply liberating stored energy. This implies, however, that the survival of BL in water is achieved by switching from electronic oscillations to proton oscillations.

We proposed a mechanism for the natural creation of BL, by considering a sufficiently strong electric field to create a local cloud of charged particles and a very strong transient magnetic field. Their combination displaces all free electrons in the same direction, while the ions remain practically motionless. The proposed theory is thus *experimentally verifiable,* by reproducing similar conditions.

Other methods of production of BL, especially in water where charged particles are naturally present, require very sudden electrical impulses for particular electrode configurations, but the survival of BL in atmospheric air requires always that it contains a sufficient amount of charged particles.

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