BALL LIGHTNING AS A SELF-ORGANIZING PROCESS OF A PLASMA-PLASMA INTERFACE – A THEORETICAL APPROACH

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Using the scale relativity theory, within the framework of a new self-organizing physical scenario suggested by laboratory investigation of formation and stability of self-consistent extended macroscopic space charge configurations, some properties of a ball lightning are established: the oscillation regimes, the hysteresis, the distributions of the electric potential, field and charge.

Key words: ball lightning, Scale Relativity Theory, self-organizing process, plasma-plasma interface.

1. INTRODUCTION

Ball lightning (BL) appears as haphazard phenomena, usually associated with thunderstorms, in the form of free-floating, relatively long living flaming globes having different dimensions and colors. Because of their random appearances, a direct experimental investigation was not possible up to now. Consequently, information concerning their visual image and behavior is mainly based on qualitative reports of eyewitnesses and on rare photographs. There are two different opinions on the generation of a BL. One of these starts from the hypothesis that the generation and lifetime of BL can be explained by considering the energy accumulated during its generation by a lightning stroke [1, 2]. The other opinion relates the appearance and lifetime of BL with a local concentration of the radio frequency (RF) electric field energy, possible after interference of electromagnetic waves produced by atmospheric electricity [3, 4].

In a recent paper [5], the genesis and characteristics of BL are explained within the framework of a new self-organizing physical scenario suggested by laboratory investigation of formation and stability of self-consistent extended macroscopic space charge configurations. These are known as fireballs in dc gas discharges and as plasmoids in gas discharges sustained by a radio frequency electric field. The paper justify the proposed explanation with a test experiment able to simulate step by step, under controllable laboratory conditions, the succession of physical processes whose final product is a gaseous stable flaming globe revealing characteristics usually attributed to BL. Although involving energies much lower than that developed in the Earth's atmosphere during thunderstorms, the described experimental simulation evidences that self-organization is – very probably, the most suitable natural phenomenon able to explain the BL appearance.

According to this phenomenological scenario, in the present paper, a mathematical model on the BL generation by means of the self-organizing of a plasma-plasma interface is given.

2. THEORY AND EXPERIMENTAL ASPECTS

2.1. THE BALL LIGHTNING BY MEANS OF THE SCALE RELATIVITY THEORY

The self organization of the plasma–plasma interface as a BL is a fractal process (for details see [6, 7]) and consequently the Scale Relativity Theory (SRT) [6] can be applied. Then, the interface dynamics is described by the coupled equations set:

$$2im\mathcal{D}\partial_t\Psi_1 = T_1\Psi_1 + \Gamma\Psi_2, \quad 2im\mathcal{D}\partial_t\Psi_2 = T_2\Psi_2 + \Gamma\Psi_1, \qquad \text{(1a,b)}$$

with Ψ_1, Ψ_2 the wave functions of the plasmas, T_1, T_2 the "Hamiltonians" of the plasmas, Γ a coupling constant, $\mathcal{D}$ the Nottale's coefficient and m the effective mass of the electron – positive ion pair. Explaining the wave functions by the relations $\psi_1 = \sqrt{\rho_1}e^{i\theta_1}$, $\psi_2 = \sqrt{\rho_2}e^{i\theta_2}$ and separating in (1a, b) the real parts from the imaginary ones, we obtain:

$$\begin{aligned}
&\partial_t\rho_1 = -\partial_t\rho_2 = \Gamma / m\mathcal{D}\sqrt{\rho_1\rho_2}\sin(\theta_2-\theta_1)\\
&\partial_t\theta_1 = -T_1/2m\mathcal{D} - \Gamma/2m\mathcal{D}(\rho_2/\rho_1)^{1/2}\cos(\theta_2-\theta_1)\\
&\partial_t\theta_2 = -T_2/2m\mathcal{D} - \Gamma/2m\mathcal{D}(\rho_2/\rho_1)^{1/2}\cos(\theta_2-\theta_1)
\end{aligned} \qquad \text{(2a-c)}$$

From here, with $T_1 = qV$, $T_2 = -qV$, $\rho_1 = \rho_2 = \rho$, $\theta = \theta_2 - \theta_1$ it results the current:

$$I = q(\partial_t\rho_1 - \partial_t\rho_2) = I_M \sin\theta \qquad (3)$$

of amplitude $I_M = 2q\rho\Gamma / m\mathcal{D}$ and phase difference θ:

$$\theta = \theta_0 + (q/m\mathcal{D})\int V dt, \ \ \theta_0 = const. \qquad \text{(4a, b)}$$

with q the effective charge of the pair. The relation (4a, b) reproduces immediately a d.c. Josephson fractal type effect if $V = 0$, and an a.c. Josephson fractal type effect, oscillations of current with the pulsation $\omega = qV/mD$ assuming that a nonzero voltage, $V \neq 0$, is applied to the interface. Choosing the dependency $V = V_0 + v_0 \cos(\Omega t + \varphi_0)$ (3) becomes:

$$I = I_M \sin\left[\theta_0 + qV_0 t/m\mathcal{D} + (qv_0/m\mathcal{D}\Omega)\sin\left(\Omega t + \varphi_0\right)\right] = \\ = I_M \sum_{n=-\infty}^{+\infty} J_n(qv_0/m\mathcal{D}\Omega)\sin\left[\left(n\Omega + (qV_0/m\mathcal{D})\right)t + n\varphi_0 + \theta_0\right] \tag{5}$$

where J_n is the n-order Bessel function. For $\Omega_0 = n\Omega$, $\Omega_0 = qV/mD$ the temporal average of $I(t)$ differs from zero, *i.e.* exists a continuous component of the current of the form:

$$I_c = (-1)^n I_M J_n(qv_0/m\mathcal{D}\Omega)\sin(n\varphi_0 + \theta_0). \tag{6}$$

We notice that any time-dependent signal admits locally a Fourier discrete decomposition [8]. This means that the previous results are of maximum generality. From (6) it results peaks of the continuous current for $\Omega_0 = n\Omega$, and consequently a negative differential resistance. So, the negative differential resistance is a self-structuring condition of the two plasmas interface as a BL. This result is in good agreement with the experimental observations from [9, 10]. Moreover, the pulsation of the BL is proportional to the potential applied on it. This last result is directly verified in the experiment [9, 11].

2.2. THE BALL LIGHTNING EQUIVALENT CIRCUIT. OSCILLATION REGIMES AND HYSTERESIS

It will be instructive to analyze the BL in the terms of the equivalent circuit shown in Fig. 1 which contains the current supply $I_M \sin\theta$ of the BL, a capacitor to represent the displacement current and a conductance to account for the electron-positive ion pairs and capacitor leakage currents. We assume that the dc current supply $I = I(V)$, shown on the left drives the BL circuit. The differential equation for the current flow I in the equivalent circuit is:

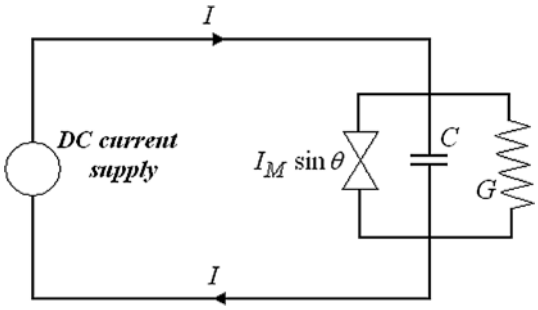


Fig. 1 – The equivalent circuit of the BL.

$$I = I_M \sin\theta + GV + C\ dV/dt \tag{7}$$

where G is assumed to be constant, although in a more general analysis it can be taken as voltage dependent. Relations (3) and (4a, b) can be used to eliminate the voltage and write the circuit equation in terms of the phase $\theta(t)$:

$$I/I_M = \beta_M \mathrm{d}_{\tau\tau}\theta + \mathrm{d}_\tau\theta + \sin\theta \tag{8}$$

where $\Omega_M = qV_M/m\mathcal{D}$; $V_M = I_M/G$; $\beta_M = \Omega_M C/G$; $\tau = \Omega_M t$. If the BL can be considered to a quasi-autonomous structure [7], the equation (8) becomes:

$$\mathrm{d}_{\tau\tau}\theta + \Omega_0^2 \sin\theta = 0; \qquad \Omega_0^2 = (1/\beta_M) \tag{9a, b}$$

3. RESULTS AND DISCUSSION

We discern the following situations:

i) For $\left(\dot{\theta}_0/2\Omega_0\right)^2 + \sin^2\left(\theta_0/2\right) > 1$, the solution becomes:

$$\theta = \pm sn\left[k^{-1}\Omega_0(\tau - \tau_0)\right]$$

with $\tau_0 = const$ and sn the Jacobi elliptic function of modulus k [12]. The BL oscillates with the period $T = [2K(k)k/\Omega_0]$, with $K(k)$ the elliptic integral of the first kind [12];

ii) For $\left(\dot{\theta}_0/2\Omega_0\right)^2 + \sin^2\left(\theta_0/2\right) < 1$, the solution becomes:

$$\theta = 2\arcsin\left\{k\, sn\left[\Omega_0\left(\tau - \tau_0\right)\right]\right\}.$$

The BL oscillates with the period $T = [4K(k)/\Omega_0]$.

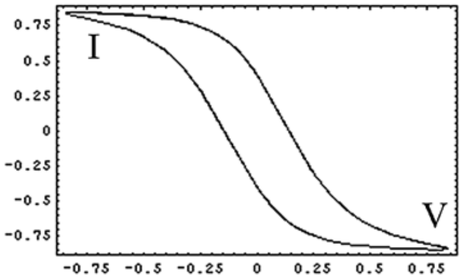
It results two oscillation regimes of the BL, according to the experimental observations. More of these, eliminating the τ parameter between the current and voltage expressions, the BL hysteresis are established (see Fig. 2a–c). It results that the BL has memory too according to the experimental observation from [9–11].

For $\theta << 1$ the equation (9a, b) with the substitution $\theta = \sqrt{6}\cdot f$; $\xi = \Omega_0 \cdot \tau$ takes the form:

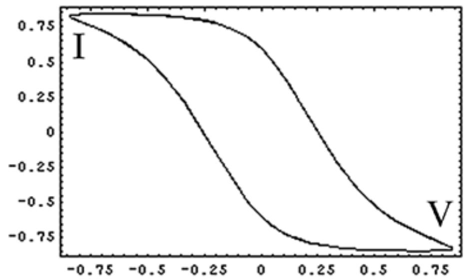
$$\partial_{\xi\xi} f = f^3 - f \tag{10}$$

The equation (10) is a Ginzburg-Landau equation type [8] and admits the kink solution $f = \tanh(\xi - \xi_0)/\sqrt{2}$, $\xi_0 = const$. It results:

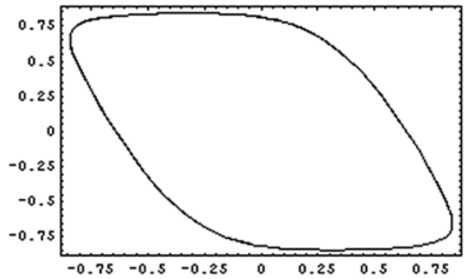
i) The kink breaks the “vacuum” symmetry and generates Cooper type pair (electron-positive ion) by a “charge” separating mechanism (similarly with the mechanism of spontaneous symmetry breaking from the field theories [8]);



a) α=13π/5

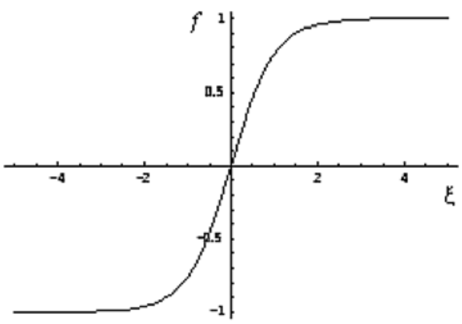


b) α=27π/10

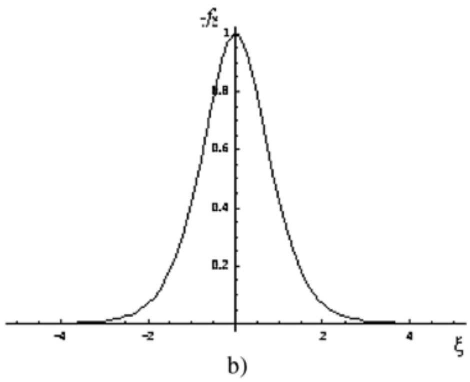


c) α=3π

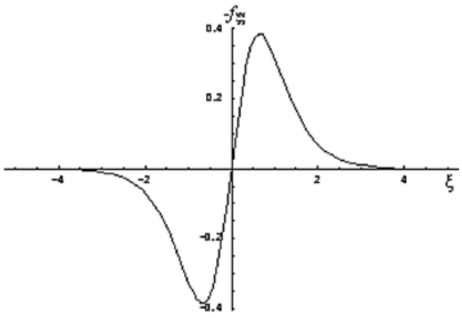
Fig. 2 – The BL hysteresis for different coherence states (the synchronization in phase α of the Cooper pairs type).



a)



b)



c)

Fig. 3 – Theoretical distributions of the potential, electric field and charge density of the BL.

ii) The coherence of the electron-positive ion pairs will produce a self-organizing of P_1 P_2 interface as a BL.

These are confirmed by potential distribution $V_r = GV/\sqrt{6}I_M = f = \tanh[(\xi-\xi_0)/\sqrt{2}]$ (see Fig. 3a), electric field distribution $E_r(\xi) = -\left(\partial V_r(\xi)/\partial\xi\right) = -f_\xi = (1/\sqrt{2})\cosh^{-2}[(\xi-\xi_0)/\sqrt{2}]$ (see Fig. 3b), and the charge density distribution $n_r(\xi) = -\left(\partial^2 V_r(\xi)/\partial\xi^2\right) = -f_{\xi\xi} = \sinh[(\xi-\xi_0)/\sqrt{2}]/\cosh^3[(\xi-\xi_0)/\sqrt{2}]$ (see Fig. 3c). All theoretical profiles are in concordance with those obtained in the experiments [11].

4. CONCLUSIONS

The main conclusions of the present paper are the followings: i) using the scale relativity theory, the BL is described by a set of time dependent Schrödinger type equations and the self-organizing of the plasma–plasma interface is given by means of a negative differential resistance condition; ii) Two oscillation regimes, hysteresis and consequently the memories of the BL are given; iii) Through the spontaneous symmetry breaking the potential, field and charge distributions of the BL are established.

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