

Conditions for Producing and Maintaining Plasma Ball Lightning in the Atmosphere

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ABSTRACT

Based on the results of plasma experiments and research work done by Dawson and Jones, Trubnikov, Endean, and other researchers, three requirements for producing and maintaining plasma ball lightning have been found: 1) rotation of plasma, 2) the density of charged particles $n_e > 3.15 \times 10^{-10} \omega^2$, 3) a stable confinement of plasma. In this model, the energy density of ball lightning ranged from 10^{-2} J/cm^3 to 10^4 J/cm^3 , the formation, shape, stability, energy, maintaining processes and other properties of ball lightning were explained reasonably.

1. INTRODUCTION

Ball lightning, a riddle in the atmosphere, has puzzled scientists for more than 200 years. Even nowadays it cannot be well explained because of the following two difficulties. First, we have not known what mechanism makes the plasma ball be stably confined in certain volume for a long time. Second, where does the energy for the longlife ball come from? As we know, without energy supply the plasma ball with high temperature will collapse immediately. The theory proposed by P.L. Kapitsa, an eminent scientist, of radio frequency (1955) explained some properties of ball lightning, such as entering room through chimneys, windows or gaps in the wall, or going into a cave, or penetrating the metal shell of an aeroplane etc. Later on, Dawson and Jones (1969), Trubnikov (1972), Jennison (1973) and Endean (1976) developed the ideas of stationary wave and resonant cavity in microwave band. But they did not explain how the resonant cavity forms in the beginning and how the instability of plasma confinement is overcome. Therefore they have not thoroughly solved the problems of shapes and energy supply of ball lightning.

The relationship between the existence and maintenance of ball lightning and the surrounding electric environment has also been a controversial problem so far. However, lightning-triggering experiments and photograph research conducted by Fieux et al. (1975) is worth noticing. They discovered that beard lightning often appeared after strong linear lightning and big beard lightning appeared where lightning tunnel curved. In one of their experiments, a lightning ball was observed after a strong linear lightning. When the ball rose to the experimental tower of 24 meters in height, another lightning discharge struck the top of the tower. But the ball was not affected. This fact demonstrated that lightning ball which comes mainly from normal lightning is an independent entity which preserves and releases energy on its own. The shape of the ball, having little connection with the surrounding electric field, is determined by its own internal electric and magnetic fields.

On the basis of observational facts and laboratory results, this paper attempts to discuss

the formation and maintenance of ball lightning.

II. THE CONDITIONS FOR PRODUCING BALL LIGHTNING: ROTATION OF PLASMA

In order to give a satisfactory explanation of the shape of ball lightning we propose the hypothesis that ball lightning is a body of rotating plasma. The reasons are as follows:

1) Up to now, all the observational facts have shown that ball lightning in the atmosphere is a rotating body in shape. 80—90% of ball lightning observed are in approximately globe shapes, others are in shapes of luminous rings, halos or coronas. Fire balls rapidly rotating or rolling along the earth surface were also reported. Fire balls associated with rotating wind, tornadoes were observed too. All of these reports support the hypothesis of rotating plasma.

2) Rotating plasma is closely related to the internal dynamic equilibrium of the ball. According to Lehort(1971), plasma rotating at high speed in magnetic field should satisfy the following expression:

$$\frac{1}{2} m |\vec{V}_\phi|^2 + q(\varphi_0 - \varphi) - \frac{1}{2} \frac{1}{mr^2} [mr_0 V_{\phi 0} + q(r_0 A_{\phi 0} - r A_\phi)]^2 \geq 0, \quad (1)$$

where A_ϕ , angular component of magnetic potential vector; m , mass of particles; q , electric charges of particles; r , rotation radius of particles; φ , potential of particles, footnote "0" for φ_0 , r_0 , $A_{\phi 0}$, $V_{\phi 0}$, refers to quantities at the initial time t_0 of the rotation.

From expression (1) we can see that, when magnetic field is strong enough to make Larmor radius much smaller than the macroscale and Larmor frequency ω much greater than particle's angular velocity Ω and the position of particles (r, z) moves slightly away from the shell of gyration $r_0 A_{\phi 0} = r A_\phi$, the value of terms on the left-side of expression (1) will become negative. This is impossible according to expression (1). Therefore expression (1) indicates that particles can only move near or on the gyration shell $r_0 A_{\phi 0} = r A_\phi$, which is called the forbidden regions. Finally many layers of plasma shell form. This is just the shape of ball lightning (fire ball).

In an axially symmetric rotating coordinate system when electric and magnetic fields are constant, it can also be proved that the rotating movement of plasma will reach dynamic equilibrium which obeys law of isorotation. The centrifugal force produces the curvature of magnetic lines which confines particles, that is the so-called "confinement of centrifugal force". Furthermore, the most important thing is the electric and magnetic fields inside the fire ball also confine charged particles.

We still adopt the argument of Dawson and Jones(1969) that the fire ball is maintained by resonant cavity with microwave inside the ball. We suppose that this cavity is initially formed by the rotating plasma. The distribution of electric and magnetic field inside the resonant cavity are shown in Fig.1.

As we see from Fig.1, field pattern inside the ball without rotation may be illustrated by 1(a) and 1(c). In the latter case, fire ball may be oval or other rotating bodies in shape. Under both of these circumstances electric fields are perpendicular to magnetic field within fire balls and the direction of $\vec{E} \times \vec{B}$ is always toward the center of the ball, which pinches the particles.

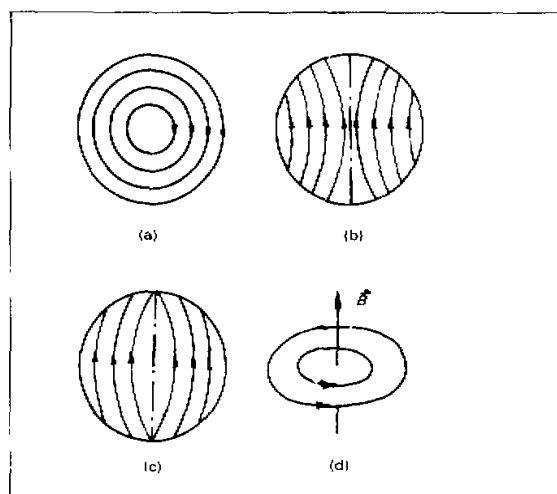


Fig. 1. Field distribution in the resonant cavity. (a) Electric field on the equatorial plane, (b) Magnetic field on axial section in resonant cavity without rotation, (c) Magnetic field on axial section in resonant cavity with rotation, (d) Magnetic oscillation and formation of fire ring.

There are high-frequency electromagnetic waves in the resonant cavity. Let us assume the variation of magnetic field as in Fig. 1(d). From Maxwell equation

$$\frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E}, \quad (2)$$

and

$$\vec{V}_F = \frac{\vec{E} \times \vec{B}}{B^2}. \quad (3)$$

we know that equation (2) indicates that high frequency magnetic field \vec{B} produces ring electric field \vec{E} and the interaction of \vec{B} and \vec{E} is described by equation (3), which induces the drift velocity of particles toward the center of the ball. This velocity confines particles. Fig. 1(d) can also be used to explain the formation of ring lightning because high frequency \vec{E} naturally gives out ring discharge and plasma. Consequently the case of Fig. 1(c) is just like a magnetic mirror in which magnetic moment μ is a quasi-constant,

$$\frac{d\mu}{dt} = \delta(W_{\perp} / B) = 0, \quad (4)$$

where $W_{\perp} = \frac{1}{2} m V_{\perp}^2$ is the kinetic energy in the direction perpendicular to magnetic lines.

Hence in the magnetic mirror particles will be bound in shapes of spheres, ovals, rotating bars, disks or doughnuts according to the strength of magnetic field \vec{B} and the velocity \vec{V} . A good instance of which is the Van Allen radiation zone of the earth.

In plasma experiments (Lehort, 1971), plasma rotation is generated by particle drift described in equation (3). The field distribution of ball lightning resonant cavity as Fig. 1, will

cause the drift velocities \vec{V}_c due to the curvature of field lines, $\vec{V}_{\nabla B}$ due to magnetic gradient, and $\vec{V}_{\nabla p}$ due to the pressure gradient:

$$\vec{V}_c = \frac{mV^2}{qB^2 r^2} \vec{r} \times \vec{B}, \quad (5)$$

$$\vec{V}_{\nabla B} = \frac{W}{qB_0^2} (\vec{B}_0 \times \nabla B), \quad (6)$$

$$\vec{V}_{\nabla p} = -\frac{1}{nqB^2} \nabla p \times \vec{B}. \quad (6')$$

Equations (3), (5), (6) and (6') are all the rotating movement. That means as long as the magnetic field exists, the plasma rotation will surely appear in the resonant cavity.

Summarily, the confinement of plasma in the direction perpendicular to magnetic lines is determined by the equilibrium of electric, magnetic, drift, centrifugal and pressure gradient forces. While along the direction of magnetic lines, confinement mainly depends on the centrifugal force and closed field lines.

3) The rotation of plasma is a manner of preserving energy by which initial rotating kinetic energy be stored in fire balls. These preserved energy then gradually be turning into electric and magnetic energy by the movement of rotation to lengthen the lifetime of the ball. This process was demonstrated by experiments made by Anderson and Baker(1958). If the initial rotating energy comes from lightning, we can estimate the total rotation energy of ball lightning. The medium velocity of lightning according to observation, is 10^7 cm/s (Ishikawa, 1961), then typical rotation energy density contained in lightning ball is

$$\frac{1}{2} \rho V^2 = \frac{1}{2} \times 1.29 \times 10^{-3} \times 10^{7 \times 2} \sim 10^4 \text{ J/cm}^3. \quad (7)$$

Rotation can also produce and maintain plasma resonant cavity, which is the wall catching microwave energy and preventing energy inside the ball from escaping. Without rotation, it is difficult to explain the long lifetime of the balls, and the large energy observed.

4) Rotation may overcome instability of plasma confinement. In experiment, the confinement of plasma is frequently unstable, which results in the failure of controlled thermonuclear reaction so far. But it has been found both in theoretical and experimental studies that the torque of magnetic lines can resist plasma instabilities. As the magnetic lines are frozen in plasma, the rotation of particles will certainly carry the lines to move and result in torsion. Experiments of θ pinch showed that at first lines were torqued by rotation, then internal transverse lines were completely separated from the external lines, and line loops appeared. These line loops confine particles. Rotation may also be a necessary condition for producing standing waves or solitons. It was observed in experiments that standing wave were formed in a plasma resonant cavity (Gaboviki, 1972) with the fundamental wavelength of

$$\lambda = 2L,$$

where L is the characteristic size of resonant cavity. And, the solitons were also formed in plasma resonant cavity due to plasma turbulence (Kim, 1974) especially the Langmuir

solitons with wave number k_0 observed in experimental Langmuir turbulence. These solitons have properties of self-focusing and self-concentrating. With the decrease of k_0 , wave packet solitons turn continuously into simple Langmuir solitons. When $k_0 = 0$, solitons standing at the same place, do not move any more (Kadomtsev, 1983). Solitons and standing wave can maintain plasma resonant cavity stably for a long time.

5) Other researchers work on the rotating of the ball lightning. Endean(1976) considered ball lightning as a rapidly rotating body with a magnetic boundary field of a speed greater than light speed. Therefore he dismissed the instabilities of plasma confinement. Morikawa and Rebhan (1970) found the toroidal hydromagnetic equilibrium solutions with spherical boundaries of plasma in vacuum. And hydromagnetic analogues of Hill's vortex were noted for many years to explain ball lightning. Ryan and Vonnegut's experiments of high-voltage discharges to a plane (1971) produced a small tornado-like vortex, the rotation of air current which makes the discharge stable was examined in laboratory. Wooding(1972) analogized an atmospheric laser to ball lightning because a plasma vortex is produced when laser pulse strike a solid surface. Voitsekhovskii B.V. and Voitsekhovskii V.V. treated ball lightning as an electrostatic vortex because a liquid drop falling into a stationary liquid produces a hydrodynamic vortex. Meissner(1930) suggested that rapidly rotating vortex formed where a sharp change in the direction of lightning channel was ball lightning, while Bruce(1963) thought that the escape of a high-pressure, ionized jet through the weakened magnetic sheath at a bend of lightning channel formed the ball.

III. CONDITION I FOR MAINTAINING BALL LIGHTNING: $n_e > 3.15 \times 10^{-10} \omega^2$

For the purpose of explaining the long lifetime of ball lightning, we should consider the energy contained in the ball and how the energy be prevented from dissipation. This discussion will lead to deriving the condition I for maintaining plasma ball: $n_e > 3.15 \times 10^{-10} \omega^2$ where, n_e is the electron density, ω is the frequency of microwave in plasma resonant cavity.

1. Energy Contained in Ball Lightning

We consider the energy carried by ball lightning consists of three parts: rotation, thermal and microwave, namely:

$$\varepsilon = \frac{1}{2} \rho V_\phi^2 + \frac{3}{2} nkT + \frac{1}{8\pi} (\vec{E}^2 + \vec{B}^2), \quad (8)$$

where, on the right hand-side of (8), the first term is the energy density of rotation; the second term is the internal energy density of plasma, the third term, the electromagnetic wave energy density captured in the ball's resonant cavity.

ρ , mass density of air, V_ϕ , rotating speed of air,

n , density of plasma, k , Boltzmann constant,

T , absolute temperature. ε , energy density of ball lightning.

Let us take typical measurement data of the atmosphere and lightning

$$\begin{aligned} \rho &\sim 10^{-3} \text{ g/cm}^3, & V_\phi &\sim 10^7 \text{ cm/s}, \\ T &\sim 10^4 \text{ K}, & n &\sim 10^{17} / \text{cm}^3 \text{ (at } T \sim 10^4 \text{ K, see Table 1).} \end{aligned}$$

Table 1. Plasma Density of the Contents of the Air (cm^{-3}), $P = 1$ atmos.

T, K	N ₂	O ₂	NO	N	O	N ⁺	O ⁺	O	N ₂ ⁺	O ₂ ⁺	NO ⁺	Ar ⁺	e
3000	1.80(18)	3.90(17)	1.01(17)	—	1.08(17)	—	—	—	—	—	—	—	—
4000	1.19(18)	5.31(16)	7.60(16)	2.52(15)	4.70(17)	—	—	—	1.09(11)	—	—	—	6.30(12)
5000	8.95(17)	3.43(15)	2.53(16)	3.67(16)	4.60(17)	—	—	—	3.19(11)	—	—	—	5.90(13)
6000	6.22(17)	3.08(14)	9.92(15)	2.06(17)	3.81(17)	2.86(12)	2.05(9)	6.58(12)	4.30(11)	1.46(11)	2.02(14)	3.00(10)	2.14(14)
7000	2.57(17)	4.18(13)	2.99(15)	5.10(17)	2.73(17)	1.65(14)	1.67(10)	8.57(13)	4.70(11)	2.40(11)	3.55(14)	7.08(11)	6.20(14)
8000	5.45(16)	8.76(12)	7.54(14)	6.52(17)	2.03(17)	1.51(15)	7.70(10)	3.82(14)	5.96(11)	2.21(11)	2.27(14)	4.96(12)	2.16(15)
9000	9.92(15)	2.93(12)	2.12(14)	6.20(17)	1.72(17)	5.53(15)	1.95(11)	1.10(15)	1.01(12)	1.98(11)	1.13(14)	2.03(13)	6.82(15)
10000	2.12(15)	1.21(12)	7.03(13)	5.45(17)	1.49(17)	1.44(16)	5.55(11)	3.59(15)	1.97(12)	1.85(11)	6.05(13)	6.25(13)	1.72(16)
11000	5.25(14)	5.49(11)	2.57(13)	4.62(17)	1.28(17)	3.03(16)	9.98(11)	5.21(15)	2.58(12)	1.69(11)	3.41(13)	1.55(14)	3.58(16)
12000	1.40(15)	2.52(11)	9.68(12)	3.77(17)	1.07(17)	5.45(16)	1.37(12)	9.29(15)	3.01(12)	1.48(11)	1.97(13)	3.20(14)	6.42(16)
14000	—	—	—	1.86(17)	6.00(16)	1.08(17)	1.25(12)	2.06(16)	—	—	—	—	1.29(17)
16000	—	—	—	6.18(16)	2.47(16)	1.48(17)	5.65(11)	3.30(16)	—	—	—	—	1.82(17)
18000	—	—	—	1.90(16)	8.16(15)	1.49(17)	1.02(11)	3.80(16)	—	—	—	—	1.87(17)
20000	—	—	—	6.50(15)	2.82(15)	1.49(17)	—	3.67(16)	—	—	—	—	—
				5.83(15)	2.57(15)	1.40(17)	—	—	—	—	—	—	—

We get

$$\frac{1}{2} \rho V_{\phi}^2 \sim 10^4 \text{ J/cm}^3, \quad \frac{3}{2} k n T \sim 10^{-2} \text{ J/cm}^3.$$

As for the microwave energy $\frac{1}{8\pi}(\vec{E}^2 + \vec{B}^2)$ in Ball lightning, according to Krider's measurement (1983), the peak radiation power of lightning return strokes is $2 \pm 2 \times 10^{10}$ W and the return strokes last about $4.4 \pm 1.8 \mu\text{s}$. It means that the maximum radiation energy produced by lightning strokes is about $10^4 \sim 10^5 \text{ J}$. If the energy is all captured by a 20 cm diameter lightning ball, the microwave energy density in the ball is about $\frac{1}{8\pi}(\vec{E}^2 + \vec{B}^2) \sim 10^1 \sim 10^2 \text{ J/cm}^3$. From the estimation above, we may see that, if a lightning ball does not contain energy of rotation and microwave (it will disappear immediately), the minimum energy density as plasma internal energy is about $\sim 10^{-2} \text{ J/cm}^3$, then, the range of ball lightning energy density is about

$$10^{-2} \text{ J/cm}^3 < \epsilon < 10^4 \text{ J/cm}^3. \quad (9)$$

The total energy for the ball of 20 cm in diameter is

$$\begin{aligned} \iiint \left[\frac{1}{2} \rho V_{\phi}^2 + \frac{3}{2} n k T + \frac{1}{8\pi} (\vec{E}^2 + \vec{B}^2) \right] dV = 10^7 \text{ J}|_{\text{rotation}} \\ + 10^5 \text{ J}|_{\text{wave}} + 10^1 \text{ J}|_{\text{therm}}. \end{aligned} \quad (10)$$

It shows that in the lightning ball, energy of rotation is much greater than electromagnetic wave and internal energy. The total energy $\sim 10^7 \text{ J}$ is in agreement with Singer(1971) and the lowest energy density $\sim 10^{-2} \text{ J/cm}^3$ is in agreement with Barry(1980).

2. The Processes of Energy Preservation and Dissipation in Microwave Resonant Cavity of Ball Lightning

The rotating plasma experiments have verified that the kinetic energy of rotation can be converted into plasma internal energy through the following three processes(Anderson, 1958). The 1st is particle drift movement which causes Joule heating process. The secondary electric field resulting from particle drifts of field curvature gradient and mass gradient caused by plasma rotation, turns the kinetic energy into electromagnetic energy directly. The secondary electromagnetic field in plasma stimulates many kinds of wave and radiation, heats plasma and accelerates particles to enhance collisions of particles. The second process is the heating effect of viscous drag and the third is the heating effect of turbulence converted by plasma rotation. These three processes constantly turned the rotation energy into internal energy of ball lightning.

The microwave energy captured in the ball can also be converted to internal energy of plasma. We can prove that, for cylindrical resonant cavity, plasma is resonant at the following frequency

$$\omega = \frac{\omega_p}{\sqrt{2}}, \quad (11)$$

while for the spherical resonant cavity, the resonant frequency is

$$\omega = \frac{\omega_p}{\sqrt{3}}, \quad (12)$$

where ω_p is the Langmuir frequency. The resonant frequencies consist of a series of frequency, formulae (11) and (12) express the fundamental resonant frequencies. On the other hand, plasma will give out various kinds of waves as observed in experiments (Gaboviki, 1972). One of these waves is radiated by ions at the following frequency

$$\omega_i = \frac{\omega_{oi}}{\sqrt{1 + \frac{n_e^2}{\gamma \pi k T_e} \lambda_i^2}}, \quad (13)$$

where ω_i and ω_{oi} are frequencies of ion wave and ion Langmuir wave, respectively. T_e , n_e are temperature and density of electrons, respectively, λ_i is the wave length of ion wave, γ is a constant between 1~3. All these waves produced in plasma will reheat the plasma.

3. The Effect of Energy Preservation and the Maintenance of Resonant Cavity for Ball Lightning

To lengthen the lifetime of fire balls, the energy inside the ball should be prevented from escaping. It has been demonstrated (Krall and Trivelpiece, 1973) that plasma shells could be treated as ideal conductor in terms of the absorption and reflection of electromagnetic waves, which require:

$$\omega^2 - \omega_p^2 < 0$$

$$\omega_p^2 = \omega_{pi}^2 + \omega_{pe}^2 = \frac{e^2 n_e}{m_e \epsilon_0} + \frac{z^2 n_i e^2}{m_i \epsilon_0} \quad (14)$$

$$\because m_i \gg m_e \quad \therefore \omega_p \approx 5.57 \times 10^4 \sqrt{n_e} \quad (15)$$

according to (14),

$$n_e > 3.15 \times 10^{-10} \omega^2 \quad (16)$$

(16) is the condition for maintaining ball lightning.

As mentioned above, rotation produces many layers of plasma shells which form the resonant cavity. Microwave absorption and resonance all take place in the cavity. Particularly we should point out that the rapid rotation of plasma can make plasma be in turbulent state in which solitons and standing waves are formed (Kingsep, Rudakov and Sudan, 1973). It has been observed in experiments that solitons created and strengthened resonant cavity (Kim et al. 1974) and that standing waves with wavelength λ appear in cylindrical or spherical plasma cavity (Gaboviki, 1972):

$$\lambda = 2L, \quad (17)$$

where L is the scale of the cylinder or sphere. λ is the wavelength of the standing wave. These solitons or standing wave strengthen the resonant cavity.

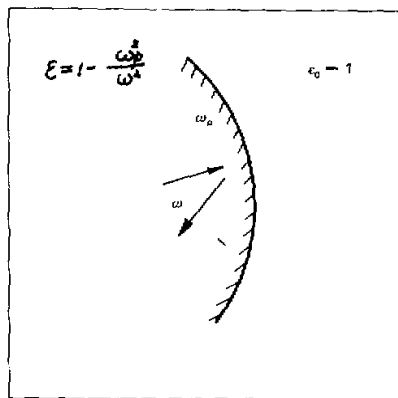


Fig.2. The reflection and absorption of electromagnetic waves by the plasma shell.

Now let us consider some actual lightning data and see if the (16) can be used to lightning in the atmosphere. According to Berger's(1975) spectral measurements, the frequency of microwave radiated by lightning is generally $3 \times 10^5 \sim 3 \times 10^7$ Hz, which requires $10 / \text{cm}^3 < n_e < 10^5 / \text{cm}^3$, while Orvill's(1968) measurements showed $10^{17} / \text{cm}^3 < n_e < 10^{18} / \text{cm}^3$. It follows that all actual lightning in the atmosphere can satisfy the requirements for maintaining ball lightning. Once lightning radiation is captured in plasma ball, it can not escape from the ball shells and will be absorbed gradually by the ball.

Energy dissipation of the plasma ball lightning is realized through three processes: the combination of charged particles, plasma convection and diffusion, and plasma radiation, we could compute the longest possible lifetime of ball lightning if we know the rate of energy dissipation in the three processes and the total energy contained in the ball.

Extinction results possibly from two processes. One is the perturbation resulting in the increase of plasma instability which causes the collapse of plasma confinement (explosively). The other is exhaust of energy in the ball (quietly).

IV. CONDITION II FOR MAINTAINING BALL LIGHTNING: A STABLE CONFINEMENT OF PLASMA

The instability of the plasma confinement is one of the most difficult problems in explaining ball lightning. As mentioned above, the torsion of magnetic lines resulting in plasma rotation can resist some of plasma instabilities and prevent momentum and heat of particles from escaping. However, it is not strong enough to overcome the instability of plasma confinement. One of the possible ways is through motion of the fire ball in the air(Endean 1976). Therefore, in laboratory experiments, especially in the experiments of high frequency discharge, a tangent rotating air current or axial air current is generally blown to stabilize the discharging plasma.

Now let us analyze the stability of a fire ball moving downward. Assuming magnetic lines in gravitational field is in Y direction (horizontal), the variation of plasma density and

magnetic field in Z direction (positive upward) satisfies the equilibrium condition

$$\frac{\partial}{\partial Z} \left(P_0 + \frac{B^2}{8\pi} \right) = -\rho g, \quad (18)$$

where P_0 is air pressure, $\frac{B^2}{8\pi}$ is magnetic pressure. ρg is gravity. perturbation velocity is assumed as

$$\vec{V}'(x, z, t) = \vec{V}'_0 e^{-i\omega t} = (V'_x \vec{i} + V'_z \vec{k}) e^{-i\omega t}. \quad (19)$$

Using the hydromagnetic dynamic equations and normal mode method, we obtain:

$$\frac{d^2 V'_z}{dz^2} + \left(\frac{1}{\rho} \frac{d\rho}{dz} \right) \frac{dV'_z}{dz} - k^2 \left(1 + \frac{g}{\omega^2} \frac{1}{\rho} \frac{d\rho}{dz} \right) V'_z = 0, \quad (20)$$

consider

$$\frac{1}{\rho} \frac{d\rho}{dz} = \text{constant} \quad \text{and} \quad \frac{d^2 V'_z}{dz^2} = \frac{dV'_z}{dz} = 0, \quad (21)$$

hence

$$k^2 \left(1 + \frac{g}{\omega^2} \frac{1}{\rho} \frac{d\rho}{dz} \right) V'_z = 0, \quad (22)$$

\therefore the disturbance $V'_z \neq 0$,

$$\therefore \omega^2 = -\frac{g}{\rho} \frac{d\rho}{dz}, \quad (23)$$

from Eq.(23) we can see that when $d\rho/dz > 0$, namely density increases upward, then $\omega^2 < 0$, plasma is unstable; but when $d\rho/dz < 0$, density decreases upward, then $\omega^2 > 0$, plasma is stable. If disturbed plasma oscillates at the following frequency

$$\omega_r = \left(\frac{g}{\rho} \frac{d\rho}{dz} \right)^{\frac{1}{2}}. \quad (24)$$

From Eq.(24) we know that in gravitation field, a plasma ball falling freely across magnetic lines is in dynamically disequilibrium but in stable state. This can explain the fact of ball lightning falling downward. This also prompts us that it may be an outway to pinch plasma in disequilibrium process for the stable confinement of plasma.

On the other hand, it is very important to analyze the condition under which atmospheric solitons are produced to discuss the stability of ball lightning. Plasma experiments (Kim et al., 1974) have verified that solitons were formed in turbulence of plasma. This turbulent plasma were produced by strong electromagnetic wave or electronic stream. In turbulence, microwave resonant cavity with much lower particle density appeared and wave energy exerted was converted to plasma waves and then trapped and resonated in the cavity of solitons. Electromagnetic waves in these resonant cavity produced a so-called pondermotive force,

$$F_p = \frac{1}{n} \frac{\partial}{\partial x} (2T\delta n), \quad (25)$$

which pushed particles out of the wave packets (solitons) and resulted in a density cavity

$$\delta n = - \frac{e^2 n}{8m_e \omega_{pe}^2 T} E_0^2. \quad (26)$$

where T is the plasma temperature; n , plasma density; δn , density change in the resonant cavity; ω_{pe}^2 and E_0^2 are the frequency and electric field exerted to produce plasma turbulence.

From (26) we know that density change δn in solitons is in direct proportion to exerted electric field E_0^2 . Eqs.(25) and (26) confirm the ideas of Dawson and Jones(1969), Trubnikov(1972).

In practical lightning discharge, the rapid movement of rotation and electromagnetic waves radiated by lightning may produce plasma turbulence and form plasma solitons. The idea of solitons may well explain the ball lightning appeared in aeroplane. However, the detail relationship between lightning and solitons, especially the connection of solitons with rotating plasma, requires further study.

V. CONCLUSIONS

We have discussed the processes of production, maintenance, extinction of ball lightning and its shape, energy and stability in this paper. As we adopt ideas of Kapitsa (1955), Dawson and Jones(1969), Trubnikov(1972), Endean(1976) and other former researchers, who reasonably explained the movement as well as other properties of the ball, we can describe the general picture of ball lightning. Firstly, a plasma with density of $n_e > 3.15 \times 10^{-10} \omega^2$ should be produced by no matter what processes, such as lightning discharge, violent electromagnetic oscillation in the atmosphere, eruption of volcanoes, tornadoes and earthquake. These processes are all able to produce high density plasma, which makes it possible for us to explain other fire ball in the atmosphere, for example, UFO, earthquake fire balls and fire balls appearing in volcanic eruption or tornadoes, etc. Secondly rapid rotation should exist, by which plasma resonant cavity or solitons forms. Rotating energy, wave energy in the cavity are continuously converted to plasma heat energy, to heat and maintain the fire ball. On the other hand, inside the ball microwaves radiated by plasma itself and standing wave form to strengthen the resonant cavity. The rotation of the ball and its relative movement with respect to the air resist the instability of plasma confinement and create possible conditions for producing solitons. The energy inside the ball including rotation, magnetic waves and internal energy determine the lifetime. The extinction of the ball is completed through two processes. One is energy exhaustion which results in smooth disappearance of the ball. The other is disturbance which stimulates the development of the instability in the plasma ball and results in explosive disappearance or collapse of the ball. Injury may happen in explosion because there is still a lot of energy containing in the ball. *This picture is only a rough framework for ball*

lightning. The more detailed understanding, especially the resonant cavity formed by solitons need further study.

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