Research on the Formation Mechanism and Characteristics of Ball Lightning

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ABSTRACT: This paper discusses the lightning discharge initiation process under positive polarity thundercloud, and the analyzed formation process includes procedure from electron avalanche to streamer discharge. The dynamic spatial distribution of the concentrations of electrons, positive ions and electron thermal energy are obtained. The influences to the electric field added by the action of the electron concentration combined with the positive ions are calculated. By analyzing the results, the distribution of electron thermal energy is not according with that of high electron density.

INTRODUCTION

Since the phenomenon of ball lightning has been identified by scientists, the strange characteristics of ball lightning have been considered a question hard to explain. Some witnesses may misunderstand the irrelevant phenomenon as lightning ball lightning, that makes the explanation be more difficult. The phenomenon associated with ball lightning is bead lightning that is classified as ball lightning in some reference, for both of them being considered as weaken plasma. Models for ball lightning explanation can be divided into chemical, physical and optical model class. Chemical model can explain the long life of ball lightning and the energy existing in ball lightning, but can not explain its stability. For this reason, some chemical model proposed in recent years, has filament structure in the fire ball, and others are that of a hybrid of plasma and aerogel structure. The optical model takes the ball lightning as an purely optical phenomenon, and in document the characteristics of the supposed, self-regulated spherical layer with internal light reflection is analyzed. Most of the physical models are the discharge circuit model and plasma models.

The document proposed a model of spinning electric dipole model, but only explains the shape of ball lightning. The document proposed a circuit model of ball lightning, and explains the stability through the coupling of the air ball and the magnetic knot, assuming that current flow in a ball along the $\nabla \times B$ line. Through this model, the general life span, energy, radiant energy of the ball lightning can be well explained. However, this model does not explain the way and the speed of the ball motion. And in this model, the existence of the magnetic knot needs to be verified. In document the equation of relationship between the life and spherical radius based on plasma model is derived. The document proposed that the

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ball lightning can be a vortex structure, and explain the motion way, but did not explain the formation, the shape and the stable structure of the ball lightning. Now again, the present paper suppose that ball lightning is a kind of vortex structures, and the vortex formation process and stability of ball lightning have also been given.

THE FORMATION MECHANISM OF BALL LIGHTNING

After the formation of the lightning flash from the cloud layer to earth, the lightning channel can be considered as a plasma column. When the ionization current flows through the plasma column, the magnetic field lines will be generated around within and outside, and accordingly the poloidal magnetic field. The lorentz force by the interaction of magnetic fields and currents generated always points to the central axis, and thus plasma column pinches to the inside, and plasma column cross section is nearly circular. This plasma can be seen as magnetic fluid.

Applicable to neutral, no loss (no viscosity, no thermal conductivity), isotropic and infinite conductivity magnetic fluid, and the ideal magnetohydrodynamics equations is as follows:

$$\frac{\partial r}{\partial t} + \nabla \bullet (r\mathbf{u}) = \frac{dr}{dt} + r\nabla \bullet \mathbf{u} = 0 \tag{1}$$

$$r\frac{d\mathbf{u}}{dt} = -\nabla p + \mathbf{j} \times \mathbf{B} \tag{2}$$

$$\frac{d}{dt}(p\,r^{-g}) = 0 \tag{3}$$

$$\mathbf{E} + \mathbf{U} \times \mathbf{B} = \mathbf{0} \quad (s \rightarrow \infty) \tag{4}$$

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} \tag{5}$$

$$\nabla \times \mathbf{B} = m_0 \mathbf{j} \tag{6}$$

Where r is fluid density, $\mathbf{u}$ is the average fluid velocity, p is the isotropic pressure, $\mathbf{B}$ is magnetic induction intensity, $\mathbf{E}$ is the electric field intensity, g is the ratio of specific heat, s is the conductivity, and m_0 is the magnetic permeability.

For the equilibrium plasma column, if existing the occasional local small bending, the bending part can be seen as magnetic fluid tube as Fig.1. The forces acting on the tube are inner side force F_{si}, outside force F_{se}, the upper section force F_{tu} and the lower section force F_{tl}.

The magnetic field stress tensor is

$$\mathbf{T} = -\frac{1}{m_0}\mathbf{BB} + \frac{B^2}{2m_0}\mathbf{I} \tag{7}$$

The force acting on the surface is

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$$-d\mathbf{S} \bullet \mathbf{T} = \frac{1}{m_0}(d\mathbf{S} \bullet \mathbf{B})\mathbf{B} - \frac{B^2}{2m_0}d\mathbf{S} \qquad (8)$$

The magnetic field density B can be expressed as

$$\mathbf{B} = B_q \hat{q} \qquad (9)$$

Therefore the first item of equation (23) is zero, and the force on all of the surfaces can be expressed as

$$-d\mathbf{S} \bullet \mathbf{T} = -\frac{B^2}{2m_0}d\mathbf{S} \qquad (10)$$

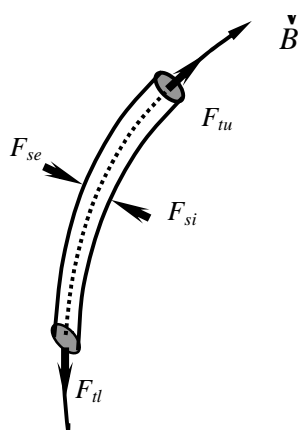Where minus sign means that all the magnetic forces act as pressure.

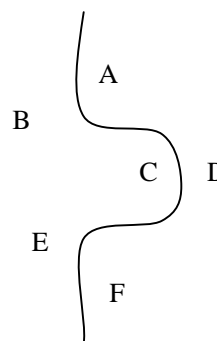Figure 1. The magnetic fluid tube force analysis diagram   Figure2. Schematic diagram of the plasma column

If existing the occasional local small bending, the magnetic field of the concave side increases because of the denser magnetic force line, while that of convex side of reduces, resulting in the external magnetic pressure of the concave side is bigger than the inner pressure, meantime the oppose case occurs for the convex side, that makes F_{si} bigger than F_{se}, and the boundary change for further bending, and the magnetic initial disturbance grow further. Additionally, the forces F_{tu} and F_{tl} which caused by the magnetic stress and plasma pressure on the section of the magnetic also make the bending further more.

The distortion is supposed to occur in the C and D region of Fig. 2. In the C region, the magnetic field strength will increase, while in D region, the magnetic field strength will be reduced. That makes the magnetic pressure increase. Deformation will increase further. Also in the A, B, E, F region the same case occurs. Because of the magnetic pressure difference, the particles move toward outside and meantime downwards. The process may produce a fluid back flow, that makes the plasma fluid in the plasma channel will form a vortex. That is the embryonic form of the ball lightning what we have seen.

When the tube dimension is fixed, the position of the vortex in the bending tube is related with the velocity and the electrical current density. When the velocity reduces or the current increases, leading the increasing of Lorentz forces, the vortex can occur nearby the middle part of bending tube. But the vortex

would not be easy to form near the inlet because the back flow is easier to happen at lower part where more particles concentrating on one side cause the back flow on the other side.

THE DISCUSSION OF THE RELEVANT CHARACTERISTIC OF BALL LIGHTNING

According to the literature, for validation of the model ball lightning, we must explain the following characteristics: long life time nature, floating movement, the way disappearing, getting through the pane or slit, and the ball being hot or cold. In accordance with the proposed model, explanation is as follows.

The long life time

Since the existence of ball lightning vortex, vortex will not go away by itself, only fade away because of the existence of viscosity. This make the plasma will not quickly spread, therefore extending the life of the plasma.

The motion

Ball lightning is spherical plasma. It can float in the air. Because the ball lightning is the combination of a vortex ring, the motion of the vortex makes it rotate. Even with no wind, it will move at some speed. In the case of the wind, it will move with the wind, meantime rotate.

The colour changes and thermal radiation

Whether the ball lightning ball is hot or cold is a controversial topic. Some witnesses consider it being cold, because they feel no heat when ball lightning gets through near their hands. However, there existing the records of some people being burned and hurt. In fact, the initial ball lightning is high temperature plasma, it has a higher temperature, but due to the external radiation energy, and the energy exchange at the boundary of plasma and the atmosphere, the ion temperature decrease gradually and become low temperature plasma. For the plasma whose ion temperature being close to air temperature, the people may not feel the presence of the heat. But because the electron temperature is high, one can see the light. In the process of ion temperature decreasing, the color of ball lightning changes from the blue to orange, red and so on gradually. As the plasma temperature decreases exponentially in the lower temperature process, people observe more frequently the orange and red.

Character of getting through the object

When viewing into the atom's interior, it is empty. Thus, the structure of any object can be similar to the overall multi-layer net structure, and some mesh are large, while other small. At the same time the vortex structure of ball lightning make micro plasma parcels have the same rotation, when it comes to a similar loose molecular or thin structure of glass and the like, free plasma parcels will be separated and easily access through these objects. After that, the micro plasma parcels group together because of strong mutual attraction, and form a new ball lightning.

The explosive properties and the way of disappearing

At first, within the plasma of ball lightning, plasma is composed of N, O ions, H ions. As the energy level decrease down to a certain extent, it will gradually produce unstable substance O_3，N_5+ and so on, also the generally stable materials such as NH_3. N_5+ is highly explosive, also known as "salt bombs." Accordingly the ball lightning is strongly explosive. If the ball lightning in the movement does not encounter any object, it will gradually disappear. In the process of disappearing, unstable substances will

transit to stable material, N5+ will make the ball lightning self-explosion phenomenon during the transition.

CONCLUSIONS

As the lightning channel is not stable, prone to distort, that may lead to the vortex formation, and further the generation of ball lightning. And in essence, the ball lightning shape should be the ring body, and the shape is stable in a short period. It is the stability of the shape that extends the life of the plasma ball. Therefore, the life time of ball lightning plasma is significantly longer. According to these theories, the phenomenon of ball lightning can be explained. The ball lightning getting through the object is based on the supposition that the vortex of micro plasma parcels can pass through objects, and micro parcels are strongly mutual attractive. The validity of the hypothesis needs to be testified by the further research and verification.

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