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The ball-lightning

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ABSTRACT. A theory is considered according to which the ball-lightning is a high density plasma having an important binding energy exceeding the average thermal translation energy.

1. Various observations and theories

The ball-lightning has received many observations the reliability of which has been recently discussed (Charman 1973). The explanation of the phenomena however is not fully understood and many theories had been propounded. A short summary is given below, more detailed references are found in the bibliography. From most observations (Uman 1968) the ball lightning appears as a luminous sphere of about 30 cm in diameter and lasting a few seconds. Silberg (1962) reported that a plasmoid very similar to the ball-lightning was accidently observed on a submarine when a short circuit happened during the charging of the batteries. It results in a green fire-ball (copper) which lasted about 1 sec. The energy stored in the fire-ball, computed from tne formula $W=UIt$ (U : potential difference, I: current, t : switching time) was estimated around 400 kilojoules. The author assumes that this plasmoid behaves as a spherical conductor of inductance L and so stores the energy $\frac{1}{2} LI^2$.

Altschuler *et al.* (1970) consider that the energy density in the ball-lightning can be as high as 10^3 joules/cm^3 but it is evaluated from calorimetric measurements taking into account the quantity of water that vaporized when a fire-ball entered a barrel. It looks difficult in such a case to ascertain whether water vapourised or splashed. The author considers the possibility of nuclear phenomena. Neugebauer (1937) proposed the hypothesis that the ball-lightning is a cold degenerated plasma where the correlations are high. Such hypothesis is interesting but in a cold plasma recombination is a very fast process and the long life-time of the ball-lightning remains unexplained.

In what follows the ball-lightning will be considered as a hot plasma completely ionized. The high temperature favours a low recombination coefficient and the high degree of ionization a high binding energy and an important energy storage. The confinement problems of such plasma are discussed in next section.

2. The ball—lightning considered as a hot self confined plasma

A plasma is confined when its kinetic pressure is balanced by other forces (Spitzer 1956), magnetic, electric or gravitational. The classical values for magnetic presure p_m and electric pressure p_e are

$$p_m = B^2/8\pi \qquad p_e = E^2/8\pi$$

where B is the induction in gauss and E the electric field in e.s.u. A pressure of 1 atmosphere can be obtained with an induction of 5,000 gauss (0·5 web/ m^2) and Stekolnikov (1943) considers the ball-lightning as a ring current to which the hydromagnetic theory could be applied but, as pointed by Powell *et al.* (1970) such current would be soon damped because of ohmic losses. The same pressure of 1 atmosphere could be also obtained with an electric field of $1{\cdot}5\times10^6$ volts/cm (*i.e.,* 0·015 volt/Angström). The use of such a high electric field rightly looks impracticable but, however, on the atomic scale, it is reached very easily and so electric effects could become important is a dense plasma. Physically this means that the attraction between ions and electrons actually lowers the pressure (*see* Appendix I). Now, the expansion of a plasma originates in the kinetic translation energy kT of the particles; however, if the electron-ion attraction results in a binding energy W larger than kT, then, as stated previously (Pozwolski 1973) the plasma tends to aggregate in a huge molecular assembly and will be very stable as long as the ionization keeps to a sufficiently high level. For the calculation of the binding energy the linearization of the equation should be avoided, the result is (Pozwolski 1973) :

$$W = Z^2 e^2/R' \left[1 - (1 + R'/2h) \exp(-2R'/h) - R'/2h \exp(-2R/h)\right] \quad (1)$$

where,

Z : ion charge number

e : electronic charge in e.s.u.

$h = (kT/4\pi ne^2)^{1/2}(Z+1)^{-1/2}$, Debye length

T : temperature, °K

n : electronic density, cm^{-3}

R' : ionic radius

R : radius of the electronic shell considered for the calculation of the mutual ion-electron energy, R must be smaller than the average distance between ions but however large enough so that the ion induced potential at R be significantly smaller than $E_t = kT/e$, the electron-volt equivalent of temperature.

As an example assume that the temperature is in the range of 25,000° K (E_t=2·15 eV) so air is completely dissociated to 0 and N atoms. Current observations on ordinary lightnings show the lines of N^{++} but this value $Z=2$ is not sufficient to lead to self confinement. We shall then assume $Z=3$, noting that the ball-lightning often occurs near the impact point of a stroke (Powell *et al*. 1970) and following a suggestion of J.E. Drummond (*see* ref.), namely, that perhaps the ball-lightning cannot form in air alone and a significant amount of a relatively low potential material such as metals must be vapourized and become part of the ball.

The main constituents of rocks are silicon and aluminium and the ionization energy involved are summarized in Table 1.

For an aluminium plasma the value $Z=3$ is much easier to reach than for nitrogen, the corresponding electronic density is $1 \cdot 76 \times 10^{18}$ cm^{-3} and the Debye length 41 Å. Taking R=30 Å it is found from (1) that W=4·38 eV=2.03 kT*.

TABLE 1

Element	Total ionization energy $\sum_{i=1}^{i=3} V_i$ (eV)	Energy difference between the third and second level
Al	53	28·4
Si	57·7	33·3
N	91	47·2

As long as the ball cools the ion charge number Z decreases and when $W<kT$ the fire-ball explodes. The cooling of the ball is expected to be a rather slow process since the transition from the 3rd to the 2nd level of ionization releases a very high amount of energy and this would explain the long life-time of the ball-lightning. Correlatively the energy density in the ball-lightning is also very high. The total average energy in air three times ionized is 93·4 eV per atom or 93·4×n/Z=8·75 joules/cm³ = 149,000 calories/g, a value 113 times larger than for nitroglycerine. For a pure aluminium or silicon plasma these figures are to be divided approximately by two but still correspond to a high energy storage.

3. Discussion

The above theory explains the problem of the very high energy content of the ball without appealing to nuclear reactions. On the other hand the spherical shape of the ball-lightning could be explained by a superficial density of charge carriers. But such density cannot be very high since the resulting field E is limited by the breakdown field in air, about 30,000 volts/cm (The associated electrostatic pressure is only 0·3 torr). However the ionization due to the field E may explain the hissing which often accompanies the ball-lightning. Furthermore the field will be higher in any point of the surface where the curvature happens to be smaller and this would cause an "electric wind" explaining the strange motion of the ball-lightning which otherwise, as a hot gas, would be only expected to rise vertically (Powell and Finkelstein 1970).

The induced image charges explain also the tendency of the ball to creep along surfaces.

* This high ion-electron interaction lowers by an amount $\triangle V \simeq W$ the ionization energy to be used in Saha's equation making possible to get a high ionization even at relatively moderate temperatures.

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APPENDIX I

The general expression of the pressure of a fluid is obtained from the free energy F by :

$$p = -(\partial F/\partial V)_T, \quad V\text{: volume}, \quad \partial\text{: partial}$$

For a plasma the calculation of the free energy is relatively simple for two extreme cases : ion-electron interaction very weak or extremely high. For the first case B.D. Fried finds (Kunkel 1966):

$$p = nkT\left\{(1 + 1/Z) - \frac{\pi^{1/2}}{3}\left[\frac{n^{1/3}(1+Z)e^2}{kT}\right]^{3/2}\right\} \qquad \text{(A-1)}$$

For the second case we find (Pozwolski 1976) :

$$p/n = kT - Z^2e^2/R' \exp(-2R'/h)\,[3/2 + 7h/4R' + 3h^2/2R'^2 + R'/2R \exp(2R'/h - 2R/h) \times (1 + R/h + 3h/2R + h^2/2R^2)] \qquad \text{(A-2)}$$

It can be shown (Pozowalski 1976) that when the ion charge number increases the pressure undergoes a maximum and then begins to *decrease*, leading to self confinement. In both Eqns. (A-1) and (A-2) substractive terms appear, meaning a negative pressure. This looks rather intriguing but has been experimentally checked for liquids (Bruhat 1947). For intermediate plasma densities it is not possible to compute exactly the free energy so we show that a significant electric potential energy can exist and conclude that when this energy exceeds kT there is a localization of the collection of charges, a concept comparable to those used to explain the binding energy of solids.