PHASE TRANSITIONS IN THE PLASMA RECOMBINATED IN A GASEOUS ATMOSPHERE

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Received June 2, 1997

Recombination peculiarities of a large plasma volume in a gaseous atmosphere are described. It is shown that the recombination of the plasma of a single-atom ions in a single-atom atmosphere always comes to its completion. Recombination of the plasma of two- or multiatomic ions in a two- or multiatomic gas can not be completed without a phase transition of the first kind. In this case, a metastable state of the plasma cloud appears. The plasma model of ball lightning is considered as an example. The interpretation of the observed behavior of ball lightning is presented.

INTRODUCTION

As was demonstrated in Ref. 1 the effect of plasma ionization degree freezing or recombination termination can occur during its free expansion into vacuum. References 2, 3, and 4 have shown that the rate of three-body recombination in the plasma expanding into a gaseous atmosphere always decreases.

If especially long-lived states of plasma exist (see Ref. 5) its long lifetime is connected with the adiabatic processes in plasma. Some aspects of this problem are considered in the present paper.

THERMODYNAMIC RECOMBINATION THEORY FOR LOW-TEMPERATURE PLASMA OF LARGE VOLUME IN A GASEOUS ATMOSPHERE

In this paper we consider fundamental thermodynamic regularities inherent to the recombination processes in large plasma volumes.

The adiabata index γ is taken as a generalized parameter of the gas and plasma media. Let us write the expression for recombination rates assuming that they are explicit functions of such variables as the electron number density n and electron temperature T. Let us also assume, that their dependence on other factors, for example on the buffer gas pressure, are indirect through the effect on n and T via the adiabata index. Therewith, the following expressions are valid if other possible parameters vary slowly as compared to n and T (see Ref. 4):

$$\frac{\mathrm{d}n_1}{\mathrm{d}t} \equiv \dot{n}_1 = -A\, n_1^k\, T_1^m; \tag{1}$$

$$\frac{\mathrm{d}n_2}{\mathrm{d}t} \equiv \dot{n}_2 = -A\, n_2^k\, T_2^m. \tag{2}$$

The numbers 1 and 2 designate two successive instants in time, $\dot{n} = \mathrm{d}n/\mathrm{d}t$ is the recombination rate, k and m are the power indexes describing recombination type (they will be defined below), A is a constant. The plasma is supposed to be quasineutral.

For k and m to be calculated let us assume the plasma to be adiabatically expanding (or weakly compressed). We can write the expression relating k to T in the adiabatic process assuming that the point volume under consideration is so small that it does not overlap with the surrounding volumes during the expansion (weak compression) and T and n do not change within this volume. The instances 1 and 2 in time are chosen close to each other so that the energy lost (or received) by the point volume in going from instant 1 to instant 2 is small as compared to the energy stored in the volume:

$$T_1 \cdot n_1^{1-\gamma} = T_2 \cdot n_2^{1-\gamma}; \tag{3}$$

$$T_1/T_2 = n_1^{1-\gamma}/n_2^{1-\gamma}. \tag{4}$$

Then

$$\frac{\dot{n}_1}{\dot{n}_2} = \frac{n_1^k\, n_1^{m(\gamma-1)}}{n_2^k\, n_2^{m(\gamma-1)}} = \frac{n_1^{k+m(\gamma-1)}}{n_2^{k+m(\gamma-1)}}\,. \tag{5}$$

Eq. (5) can be rearranged into the following form:

$$\dot{n}/n^{k+m(\gamma-1)} = \mathrm{const} \tag{6}$$

and assuming

$$k + m(\gamma - 1) = b, \tag{7}$$

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we can write

$$\dot{n}/n^b = \text{const.} \quad (8)$$

A particular solution to the latter equation for the case when the expansion (weak compression) is close to its completion and separate point plasma volumes do not overlap is sought in the form

$$(1 - b)^{-1}\, n^{1-b} = A_1 - B_1\, t. \quad (9)$$

Then, recalling the constants one can write

$$n^{1-b} = C - B\, t. \quad (10)$$

By raising both sides of the equation into the $1/(1 - b)$ power we obtain

$$n = (C - B\, t)^{1/1-b}. \quad (11)$$

The values of the fundamental plasma constants k and m should not depend on whether the recombination process is in its beginning or stage is almost completed. If this process is practically completed and plasma cloud expands following the ideal gas laws, Eq. (11) is valid when

$$b = 0. \quad (12)$$

Then the solution takes the form typical for free expansion of ideal gas

$$n = n_0 - B\, t. \quad (13)$$

In this case the fall off of the concentration of charged particles occurs only due to the expansion.

In the case of plasma expansion according to the ideal gas laws by substituting Eq. (7) into Eq. (12) and taking $\gamma = 5/3$ we obtain the condition relating k, m and γ:

$$m = -\, 3k/2. \quad (14)$$

Thus, in the case of the adiabatic expansion (or compression) of large plasma cloud in a gaseous atmosphere the only recombination process is allowed, in terms of thermodynamics, wherein the power indexes are related according Eq. (14).

The case of a three-body recombination occurs at $k = 3$. Then from Eq. (14) it follows that:

$$m = -\, 9/2. \quad (15)$$

In our consideration $k = -7/3$ corresponds to $m = -7/2$. This means that the recombination process is proportional to the one-third power of the electron number density.

If $k = 2$ Eq. (14) gives:

$$m = -\, 3. \quad (16)$$

Since constants the k and m are related by Eq. (14) the recombination types with other k are also allowed in the thermodynamics sense.

If k and m values obtained experimentally are not determined from Eq. (14) the recombination process observed, probably, is not dominant and inverse ionization processes superpose on the first one or walls near plasma boundary effects the recombination.

The requirement that the process be adiabatic means that the plasma cloud volume should first of all be relatively large and have sufficient density. In this case energy losses through emission in resonance lines are substantially reduced. This point is common for photoresonant plasma development and recombination of large plasma objects (see Ref. 6).

Then, the requirement that the process is adiabatic can be satisfied also for a weak compression of plasma (if compression rate is high, the plasma can be strongly heated that causes ionization process to develop). Therewith, γ will be decreased while the recombination rate increase. By contrast, in the case of free expansion γ value increases approaching that characteristic of ideal gas.

Returning to Eq. (5) we see that for all recombination types described by Eqs. (14)–(16) the recombination rate, similarly to Refs. 2–4, decreases with the expansion. Opposite situation is observed under weak compression. The differential expression (5) under the above assumptions is valid not only for the case of almost completed expansion, but for other stages of the plasma evolution, as well. .

PHASE TRANSITIONS IN A LARGE VOLUME PLASMA CLOUD RECOMBINATING IN A GASEOUS ATMOSPHERE

The fundamental thermodynamic plasma constants k and m are related by Eq. (14), which is valid in the case of free (unbounded by walls) recombination low-temperature plasma of a large volume. In contrast to these constants the adiabatic index changes during expansion and recombination of plasma. Let us set limits within which γ can vary. The adiabatic index of ideal gas $\gamma = \gamma_{max}$ is the upper limit ($\gamma = 5/3$). If $b > 1$ the electron concentration increases with time. This corresponds to the ionization process which is reverse to the recombination or has not a physical sense at all. At b approaching unity the concentration tends to infinity. So, the value b for the recombination process cannot exceed 1. If $b = 1$,

$$m\,(\gamma_{min} - 1) = 1 - k \quad \text{and} \quad \gamma_{min} = 1 + [2\,(k - 1)/(3k)], \quad (17)$$

and for $k = 3$, $m = -\, 9/2$

$$\gamma_{min} = 13/9. \quad (18)$$

Thus, if the recombination with $k = 3$ and $m = -9/2$ (three-body recombination) dominates, the γ value can not be lower than $1\frac{4}{9}$.

The numerical values of γ presented above do not mean, at all, that this index determined experimentally can not take values out of these limits. As known, the processes other than three-body recombination occur in plasma. In general, the account for these processes may change the above limits. While the numerical values presented can serve a criterion of whether the three-body recombination is the dominating process in plasma or not.

Now let us determine $\gamma_{\min}$ for other recombination types. For $k = 3$ and $m = -9/2$ one can write

$$\gamma_{\min} = 4/3 . \tag{19}$$

While for $k = 7/3$ and $m = -7/2$

$$\gamma_{\min} = 29/21 . \tag{20}$$

For a single-atomic gas $\gamma = 5/3$ while for plasma consisting of single-atomic ions γ may vary in the range from $1\frac{4}{9}$ to $5/3$. Hence, nothing prevents γ to vary within these limits and three-body recombination can smoothly go to completion. Different situation is observed if plasma consists of two-atomic ions. Here the adiabatic index can vary within the same limits. However, the final state is a two-atomic gas with the adiabatic index $\gamma = 1.4$. Hence, the plasma never can achieve the final state in the process of three-body recombination and a phase transition is necessary. This phase transition does not occur by itself and consumption of energy and external action are needed. If the plasma cloud in the atmosphere is not exposed to that action it transforms into a metastable state in the process of recombination.

From the above consideration it follows that real behavior of the plasma cloud relaxing in the atmosphere seems to involve at least two stages:

a) Plasma cloud expands into the atmosphere, its temperature, density and the recombination rate decreases, γ approaches $\gamma_{\min}$ which is equal to that of ideal gas.

b) Since the plasma cloud substance density is lower than that of ambient air and only small energy losses (for instance, via radiation) occur, the stage of plasma compression by surrounding gas is observed after termination of its expansion and some cooling. Therewith, γ approaches $\gamma_{\min}$ and the recombination rate increases. However, from the above reasoning it follows that recombination of plasma with two- or multiatomic ions dominating in two- or multiatomic gas can not come to the final state. Then the plasma cloud necessarily transforms to a metastable state. The phase transition from this state into the final state of ideal gas is possible only by a jump under the action of an external action similarly to the crystallization of a supercooled liquid.

CONCLUSION

One can conclude as a result of described observations that the thermodynamic approach allows:

1) to establish the relation between the power indexes in expression for the recombination rate and the dependence of the three-body recombination rate on $T^{-9/2}$;

2) to ascertain that the recombination rate decreases always during expansion of plasma;

3) to show that the plasma of single-atomic ions and electrons can achieve the final state during expansion always;

4) to show that the plasma cloud of two- and multiatomic ions with electrons transforms into a metastable state in the process of recombination in the gaseous atmosphere and a phase transition is necessary to come out this state and to complete the recombination.

The existence of longlived metastable states in a large size plasma cloud in an atmosphere (ball lightning) is the natural fundamental property of plasma the adiabatic processes proceed in which; no additional hypotheses need to substantiate the existence of these states .

The source compensating for energy losses of the metastable plasma cloud in the atmosphere is the compression of cloud under the action of external atmospheric pressure during cloud cooling.

SUPPLEMENT

BALL LIGHTNING, STABILITY OF BALL LIGHTNING, SOURCES COMPENSATING FOR ENERGY LOSSES DURING BALL LIGHTNING EVOLUTION, REASON FOR ONLY A RARE APPEARANCE OF THE BALL LIGHTNING

1. For the plasma to be long-lived the energy influx is not needed, it is only necessary to provide its adiabacity. If the plasma cell size is not large, so that the ratio between its surface and volume can not provide small energy losses for the adiabatic condition to be satisfied the plasma should absorb energy from the ambient medium to compensate for these losses.

2. During the plasma expansion into a gaseous atmosphere the rate of any type of recombination considered decreases. For the maximal, under a given conditions lifetime to be achieved the plasma should freely expand into the atmosphere or to compress under the action of atmospheric pressure without any contact with walls.

3. Recombination of plasma, consisting of single-atomic ions (inert gases, atoms and ions of chemical elements) during adiabatic process always can go to its completion while the recombination rate decreases as

the plasma expands. Therewith, longlived plasma state are impossible since the plasma can not transform to the final state without a phase transition.

4. In the adiabatic process of a weak compression from two-atomic ions (for instance, nitrogen in nitrogen atmosphere) three-body recombination involving third electron can not be completed (while the recombination rate increases under weak compression). Therewith, a break on the adiabata index γ is evident (while the recombination rate reaches its peak) and γ approaches $\gamma_{\min}$.

5. In the adiabatic process of weak compression of plasma of multiatomic ions both $\gamma_{\min}$ and final γ value increase by several times. This means that for realizing a phase transition higher energy is needed. In this case formation of a metastable state is more likely. Thus, *the property of recombination completeness in the atmosphere of two- and multiatomic gas is the fundamental property of plasma of two- and multiatomic ions and electrons if its size is reasonably large.*

At the same time, during the adiabatic expansion γ approaches the value 5/3, and two- and multiatomic plasma can never come to the final state. Further weak compression of the plasma by ambient air is the necessary condition for the recombination completion.

6. From the above reasoning it is clear that the ball lightning can result from the breakdown of the atmosphere enriched in water vapor with the following fast current interruption and free expansion of thus formed plasma into the atmosphere (with the further weak compression under the action of external atmospheric pressure, which compensates for the energy losses during the recombination process). Since at the final expansion stage the temperature of lightning ball plasma is still higher than that of the ambient air, the density of the lightning substance is lower than that of air and existence of some pushing force is evident. Therewith, the behavior of plasma ball is similar to that of a gas bubble inside a very light liquid and its stability is caused by the absence of appreciable currents in the plasma.

If the expansion stage after the energy deposition into the plasma is absent and the latter immediately begins to compress under the atmospheric action, its lifetime significantly reduces. This occurs in the case, when the energy ionizing and heating the plasma continues to inflow into the plasma during its expansion. This event is observed when linear lightning has a long period of the development. Therewith, the current of a linear lightning should be sharply interrupted (for example, branching discharge can occur along a more favorable path) for formation of ball lightning. Clearly, this is a very seldom event.

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