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Metastable states and coalescence of charged water drops inside clouds and fog

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ABSTRACT

The free energy of the charged drops of water and of light ions inside drop-ionic plasma of clouds and fog was calculated on the basis of the Poisson–Boltzmann equation. It is shown that when the charge is greater than several tens of elementary charge units, the positively and negatively charged drops can have metastable states which are characterized by the space-ordered arrangement of the drops. In general, the drop-ionic plasma has no metastable state. But, in the case that the average charges of positively and negatively charged drops differ in absolute value by less than 10–20%, drop-ionic plasma can have a metastable state as a whole. This state was thought to be responsible for the long confinement of drops in a compact volume and for their subsequent coalescence. It is shown that the electrostatic attraction of drops and their coalescence are capable of explaining the rapid growth of water drops up to rain size inside clouds.

1. Introduction

Water drops of micron size are formed inside clouds as a result of water vapor condensation on the active condensation nuclei. When further condensation and vapor diffusion occur, the drops can reach a radius of 10 μm. It is considered that drops with a radius of more than 50 μm inside the cloud develop a rather high speed of falling and grow further by a gravitational coalescence. What is not clear is the mechanism of the fast growth of drops from 10 to 50 μm. Observations show that the process of the formation of rain drops inside clouds takes 15–20 min only, while the existing theories predict the duration of the drops' growth from 10 to 50 μm to be in tens of hours (e.g., Devenish, Bartello, Brenguier, & Collins, 2012; Grabowski & Wang, 2013; Khain et al., 2007). The scientific literature refers to the problem of the fast growth of rain drops as a «condensation-coalescence bottleneck in rain formation».

To solve the problem, the majority of researches have concentrated on analyzing the increase of the drops' speed in a turbulent atmosphere; and on the turbulent-induced increase in the number of drop collisions resulting in coalescence (e.g., Elperin, Kleeorin, Liberman, L'vov, & Rogachevskii, 2007; Ghosh et al., 2005; Khain et al., 2007; Pinsky & Khain, 2004; Wang, Orlando, Rosa, & Grabowski, 2008). The research results on the «tangling clustering instability of small water droplets inside a turbulent temperature stratified atmosphere» (Elperin, Kleeorin, Liberman, & Rogachevskii, 2013) appeared ambitious, showing the possibility of the formation of clusters with a concentration of drops exceeding by several orders the average

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concentration inside a cloud. As the concentration and the speed of drops coalescence inside clusters both increase sharply, the typical time of drops coalescence also decreases sharply. This effect can increase in a stratified atmosphere (Eidelman, Elperin, Kleeorin, Melnik, & Rogachevskii, 2010; Elperin et al., 2013).

Study of the problem of the fast growth of rain drops has given unfairly little attention to research on electrostatic coalescence. Several decades ago (Fuchs, 1963; Gunn, 1954, 1955; Gatti & Kortshagen, 2008; Gopalakrishnan & Hogan, 2012; Ivlev & Dovgalyuk, 1999; Khrapak & Morfill, 2009), the elaborations noted a possibly important role of electrostatic coalescence in rain formation. Coalescence can occur both under the influence of external electric field, and because of the electric charge of the water drops. The external electric field can create an induced dipole moment, and all oriented dipoles will be mutually attracted. Self-charge of the water drops can also cause the attraction and coalescence of drops. It is known that inside plasma not only oppositely charged drops but also like-charged drops can be attracted (Shavlov & Dzhumandzhi, 2010a,b, 2013b, 2014).

The purpose of the present work is to calculate the free energy of the electrically charged water drops inside the plasma of clouds and fog; investigation of the existence of extreme points and metastable states; discussion of the possibility of the electric coalescence of drops and the role of its model in solving the problem of a condensation–coalescence bottleneck of rain formation. In contrast to the work (Shavlov & Dzhumandzhi, 2013a) devoted to the search for a metastable state of a drop-ionic plasma, the present work allows the simultaneous existence of positively and negatively charged water drops in the plasma of clouds and fog, which enlarges the range of metastable states of the drops. Among these, there is a new metastable state of a dropwise plasma as a whole, and this state may be responsible for coalescence. Please note that the basic possibility of the existence of metastable states of plasma is related to restriction on the free movement of heavy components of the plasma at certain plasma parameters.

2. The problem setting and solution

The drops get electric charge in the atmosphere during collisions with other drops and capture of the embedded charged particles, as well as in the course of the evaporation and condensation of water molecules and ions on the surface of drops. According to the reference data (Kikoin, 1976), the charge of individual drops of water inside atmospheric precipitation changes over a wide range, coming up to 10^5–10^7 units of elementary charge. The number of positively charged drops is about 1.5 times greater than the number of negatively charged drops. Meanwhile, the average charge of a negatively charged drop is approximately 1.2 times greater in absolute value than the charge of a positively charged drop. A simple calculation shows that, to fulfill the electroneutrality condition of the ionic-dropwise environment in the space between drops, it should contain a certain quantity of negatively charged ions. Therefore, the model of the cloudy environment will be a three-component drop-ionic plasma consisting of positively charged drops with the charge $Z_+ \gg 1$ (units of elementary charge) of radius R_+ and concentration N_+; negatively charged drops with the charge Z_-, radius R_- and concentration N_-; and negatively charged ions with the charge 1 of radius R_i and concentration N_i ($R_i \ll R_{+,-}$). We believe that hydroxide ions associated with one or several water molecules act as negatively charged ions. These ions come into interdroplet space out of drops during their evaporation–condensation. There are also protons in the interdroplet space, which are also coming out of water drops upon phase changes. So as not to complicate the task, we consider their concentration to be negligible in comparison with the concentration of the hydroxide ions. Let us also consider the absolute values of the charges of positively and negatively charged drops and their radii to be approximately equal among themselves, $Z_+ = Z_- = Z$, $R_+ = R_- = R$.

The equation of electroneutrality of plasma is as follows:

$$ZN_+ = ZN_- + N_i. \tag{1}$$

Let us designate the charge share of negative ions from the total negative charge of plasma particles as $\chi = N_i/(N_i + ZN_-)$, where $0 < \chi < 1$, then we divide both members of Eq. (1) by N_+. The electroneutrality equation per one positively charged drop will be the following:

$$\underbrace{Z}_{1} = \underbrace{Z(1-\chi)}_{2} + \underbrace{Z\chi}_{3}, \tag{2}$$

where the interlinear index 1 is the charge of a positively charged drop, 2 is the charge of a negatively charged drops, and 3 is the charge of negative ions.

Let us fix the system of coordinates in the center of a positively charged drop, as shown in Fig. 1. For illustration purposes, the drops in the figure are placed in the knots of a square lattice. Please note that regularity in the drops arrangement is not basic. According to the picture, the elementary volume of space limited by a square is per one drop. The charge of a positive drop in the elementary volume is completely compensated with the here located negatively charged drops, having a total charge of $Z(1-\chi)$ and the negative ions with a total charge of $Z\chi$. To simplify calculations, the elementary volume of a positively charged drop should be replaced with a spherical volume of radius $d/2$ (where d is the distance between the nearest positively charged drops ($d \geq 2R$)) and it is necessary to change the system of coordinates onto a spherical one. The charge of negatively charged drops will be considered to be regularly spaced over the $d/2$-sphere surface. The radial field is equal to zero on the $d/2$-sphere surface owing to its electroneutrality. (Upon the change onto a spherical volume the calculation error can be considerable, and the calculation results would be qualitative rather than quantitative.) Let us assume