

FORMATION OF SPATIALLY ORDERED STRUCTURES BY WATER DROPS IN ATMOSPHERIC CLOUDS

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Laboratory measurements of geometric and electrical parameters of spatially ordered charged water drops prompt that such structures may form in atmospheric clouds and in fog. The ordered structures of water drops influence the surface tension and shear viscosity of clouds.

The extraterrestrial space and terrestrial atmosphere contain a great number of dust particles which constitute the so-called dusty plasma. At certain conditions, dust particles – like atoms and molecules – can form ordered structures as in crystals or liquids [Fortov *et al.*, 2004]. With formation of these structures, dusty plasma behaves as a non-Newtonian liquid: first, it does not flow at some shear stress below the critical value and, second, its shear viscosity decreases as shear stress increases. According to laboratory measurements [Vorona *et al.*, 2007], the contribution of the ordered component into shear viscosity of dusty plasma can reach tens of percent or more.

We [Shavlov and Dzhumandzhi, 2010] hypothesized that structure formation by charged water drops and ice crystals may be possible also in clouds and in fog, the structures being able to change the physical and mechanic properties of the atmosphere. Ordered structures of water drops were obtained at laboratory conditions over a heated water surface [Fedorets,

2004]. In those experiments, water drops, several tens of micrometer in diameter, were localized in a single layer and were hexagonally ordered relative to one another, with a spacing of two to five drop diameters; the height of the layer above the water surface was commensurate with the drop diameter.

In this respect, given that water drops are capable of structure formation, the objectives of our study were to measure their charges inside a drop structure, to calculate surface tension in this structure, and to estimate the effect the drop structures may cause on the properties of atmospheric clouds and fog.

Drop clusters were obtained experimentally following a procedure similar to one reported in [Fedorets, 2004]. See Fig. 1 for a typical ordered drop structure, with its round shape being evidence of surface tension. The geometric and electrical parameters of the drop clusters were investigated as a function of temperature T (Fig. 2), namely the spacing L , the diameter D , the height above the water surface H , and

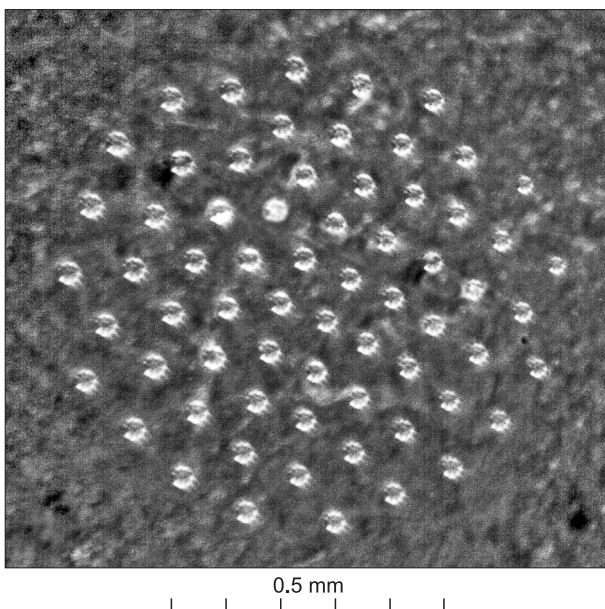


Fig. 1. A plane spatially ordered structure of water drops.

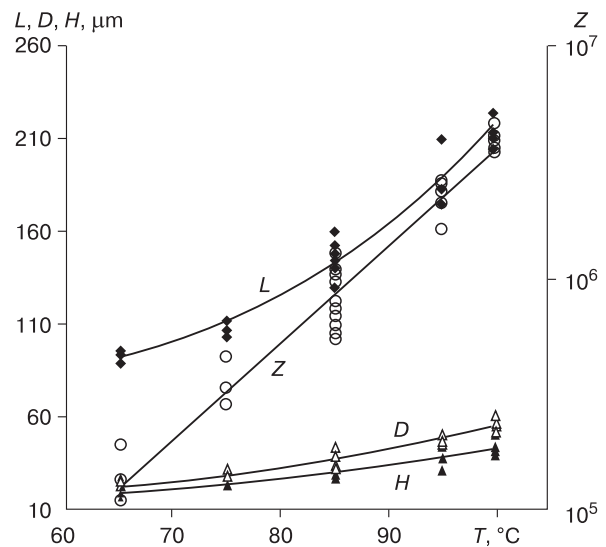


Fig. 2. Temperature dependences of the spacing L , diameter D , height above the water surface H , and height Z of water drops.

the charge Z (in elementary charge units). The geometric parameters were estimated according to the number of pixels in a video image recalculated into length units, to an error of ± 0.5 pixel or ± 2 microns. The height H was measured as a half of visible distance between the centers of a drop and its mirror image in water viewed at an angle close to the water surface tangent. The drop charge Z was found from the height relative change $\Delta H/H$ caused by the external electric field E_{ex} between water and an electrode above the drop structure, as

$$Z = \frac{Mg}{eE_{ex}} \frac{\Delta H}{H}.$$

The equation for the drop charge was obtained assuming electric-gravity equilibrium between the charged drop and the charged water surface of the same polarity:

$$Mg = Ze(E + E_{ex}),$$

where E is the field produced by the charged water surface (inversely proportional to the height $E \sim 1/H$); M is the mass of a drop; g is the gravitation acceleration; e is the unit charge. In this way, the charge of water drops was estimated to an error of $\pm 15\%$, while the error in water surface temperature was $(+1/ - 10)^\circ\text{C}$.

The parameters showed decreasing trends as the temperature decreased (Fig. 2) and, within the $60\text{--}100^\circ\text{C}$ range we investigated, were related as

$$D \approx 1.26H, L \approx 4.8H, Z \sim D^4.$$

Both water drops and water surface below them were positively charged, the charge polarity apparently being defined by the fact that more hydroxide than hydrogen ions pass from water to vapor during evaporation. The charge Z of a drop changed as a function of its diameter D more rapidly than D^2 , i.e., additionally to the drop's surface area, which is proportional to D^2 , it must depend on the rate of the water-to-vapor phase transition.

The drop spacing L was hypothesized to be twice the Debye length (L_D) in vapor:

$$L = 2L_D.$$

In order to check the hypothesis, we calculated, using the Debye equation, the concentration of charge carriers for the case of a plane charged water surface, and found the Debye length. For the latter we obtained the theoretical relationship $L = 2.7H$, in which the factor 2.7 is in an order-of-magnitude agreement with the factor 4.8 in the empirical relationship $L \approx 4.8H$. This appears to be satisfactory support for our hypothesis. The $2L_D$ spacing of particles in dusty plasma was validated experimentally [Fortov *et al.*, 2004] and theoretically [Shavlov and Dzhumandzhi, 2010].

The L and L_D relationships were used to predict whether water drops may form spatially ordered

structures (clusters) in atmospheric clouds and in fog. The calculated theoretical concentration of ordered drops can be compared with the empirical concentration of drops in clouds using the Debye length found from the air conductivity $a = 10^{-13} \text{ Ohm}^{-1}\cdot\text{m}^{-1}$ and the average ion diffusion coefficient $B = 10^{-8} \text{ m}^2/\text{s}$ [Grigoriev and Meilikhov, 1991]:

$$L_D = (\epsilon_0 B/a)^{0.5} = 10^{-3} \text{ m},$$

where ϵ_0 is the electric constant.

The concentration of drops calculated as $N = (2L_D)^{-3} = 1.5 \cdot 10^8 \text{ m}^{-3}$ turned out to be of the same order of magnitude as the statistically average concentration of water drops in clouds and fogs, which is $N = 3 \cdot 10^8 \text{ m}^{-3}$ [Mazin and Khrgian, 1989]. Thus, indeed, water drops can form ordered structures in clouds and fogs.

The surface tension of a drop structure is given by [Shavlov and Dzhumandzhi, 2010]

$$\sigma = \frac{e^2}{24\epsilon_0} Z^2 N.$$

The drop charge Z in clouds reaches $10^3\text{--}10^6$ [Grigoriev and Meilikhov, 1991]. At $Z = 10^4$, for instance, $\sigma = 10^{-11} \text{ J/m}^2$. Knowing the surface tension σ , one can estimate the stability of the drop structure surface to shear flow using the Kelvin–Helmholtz stability criterion

$$\frac{\rho v^2}{2} \leq \frac{2\pi}{x} \sigma,$$

where $\rho = 1 \text{ kg/m}^3$ is the air density; $v = \frac{\partial v}{\partial l} l$ – is the interfacial velocity difference; $\frac{\partial v}{\partial l} = 3 \cdot 10^{-3} \text{ s}^{-1}$ is the average gradient of the medium horizontal velocity along the normal to the ground surface; $l = 10^{-3} \text{ m}$ is the thickness of the surface layer of the drop structure equal to the Debye length; x is the characteristic length of the instability zone.

Therefrom $5 \cdot 10^{-12} \leq 10^{-10}/x$, which fulfills at $x < x_0 = 20 \text{ m}$.

Thus, the surface of a cloud drop structure can be stable to shear flow when the cloud size is within a few tens of meters. In larger clouds, the surface acquires a roughness with the characteristic size x_0 . It follows from the above that structure formation in water drops can be an important agent in the stability of the cloud geometry.

The shear viscosity η of a drop cluster can be estimated and compared with that of air using a formula similar to the Frenkel equation [Fabelinsky, 1997]:

$$\eta = C \exp\left(\frac{U}{kT}\right),$$

where $C \sim hN$; h is the Plank constant; N is the concentration of particles; U is the viscosity activation energy; k is the Boltzmann constant; T is the temperature.

Shear viscosity was investigated with reference to the dislocation mechanism of shear flow typical of crystals. The activation energy of dislocations in metal and ion crystals U is known to be 10^3 – 10^4 times as low as the atomic bond energy U_b . Describing numerically the viscosity of a dust crystal with the above formula requires that U were 1500 times lower than $U_b = Z^2 kT/6$ [Shavlov and Dzhumandzhi, 2010]. The viscosity of a drop structure estimated with the activation energy $U = U_b/1500$ was $\eta = 10^{-23}$ Pa·s at $Z = 10^4$, which is much lower than the air viscosity 10^{-5} Pa·s. However, already at $Z = 10^5$ this viscosity can reach or even exceed the air viscosity.

The viscosity increase may lead to a decrease in convective thermal conductivity. For instance, in some convection problems, the Rayleigh number $R = g\beta Ad^3/(\chi\mu)$ can characterize the stability of gas in the gravity field in the presence of a downward temperature gradient A , where β is the thermal expansion coefficient; χ is the gas thermal diffusivity; μ is the kinematic viscosity; d is the characteristic linear size of the structure. Viscosity changes control the presence (absence) of free convection and the heat transfer rate.

Thus, structure formation by water drops in an atmospheric cloud can change notably its hydrodynamics and heat transfer patterns. This effect may be more prominent in the clouds that contain ice crystals with their charges tens of times those of water drops.

The existence of spatially ordered structures of water drops and ice crystals in atmospheric clouds and fogs, as well as their effect on mechanic and thermophysical properties of clouds appears to be quite realistic. This phenomenon is worth being studied in detail in terms of atmospheric physics, as well as in terms of Earth's cryology which is a science that deals with objects containing water near or below the freezing (crystallization) point.

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