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"Waterspout" as a Special Type of Atmospheric Aerosol Dusty Plasma

V.A. Rantsev-Kartinov

NFI RRC "Kurchatov Institute", Moscow, Russia

1. Introduction.

This paper demonstrates that the water spout (WS), a severe weather phenomenon, at the initial phase of its formation may be considered as an aerosol dusty plasma. The Earth atmosphere is a weakly-ionized plasma, therefore the WS dynamics must be considered with allowance for this fact. The presence of charged microscopic water drops over the water surface can also play an important role in the evolution of severe weather phenomena.

In the process of their formation, the drops always acquire electric charge $q = q_{min} = Ne = \varphi r_D$, which is determined by the physical properties of the water. Here: N – number of electrons absorbed by the drop; e is electron charge; φ is electric potential, which is determined by the surface tension σ and the water dielectric constant ε. $\varphi = (8\pi d\sigma/\varepsilon)^{1/2} = 0.26$ V, where d is the diameter of water molecule. During drops' motion towards the mammatus cloud (MC) q value may increase and attain its maximum value $q_{max} = (24\pi r_D^3\sigma)^{1/2}$, for which the energy of surface tension is not able to balance that of electrostatic repulsion. The respective Coulomb explosion breaks the drop into smaller ones or evaporates it. The condition $r_D < (3E\varphi/4\pi\rho g)^{1/2}$ must be fulfilled in order to tear the drop (of density ρ and radius r) from the capillary and lift it up at the altitude of a strongly charged MC due to electric field (EF) of a strength E. If E ~ 10^4 V/cm (the value, typical for WS), then $r \le 2.6 \cdot 10^{-3}\, cm$.

2. Capillaries in an electric field.

In the paper [1] Tonks derived the critical EF value needed for a breakdown of the free water surface. Its magnitude for water is $E^0_{min} \sim 1.75\ 10^4$ V/cm. In the presence of partially wetting capillaries, it can be shown that similar magnitude is $E^C_{min} \sim 4(\pi\sigma\delta)^{1/2}/r_C$, where $\delta < r_C << 0.4$ cm. Here $\delta = 5\ 10^{-8}$ cm is the scale of action of intermolecular forces. For $r_C > 0.67$ cm the height of the water lifting up in the partially wetting capillary is $h < r_C$; i.e., in this case the capillary force acts on the water only at the very top of the capillary. For $r_C \sim 10^{-3}$ cm, one has the value $E^C_{min} = 4\ 10^3$ V/cm, which is about 5 times smaller then that for free water surface. Thus, the presence of the capillaries makes the breakdown of the water essentially easier.

An analysis of databases of photographic images of ocean's surface, taken from various altitudes and for various types of rough ocean surface, revealed the presence of an ocean's skeletal structures (OSS) [2]. The OSSs differ from the formerly found skeletal structure [3] only by the fact that OSS, in their interior, are filled in with non-ideal closely packed blocks of a smaller size, up to tens of microns for thin capillaries (with the partially wetting walls).

Here we turn to the phenomenon of OSS's blocks in the form of vertically oriented floating cylinders (VFC) because in [1] the hypothesis was suggested that *the VFC is a stimulator of the initial phase of the waterspout phenomenon.*

Already in a low-magnitude EF the capillary produces electric current due to formation of a charged aerosol on the acute edge of the water (AEW) at the upper edge of the capillary. The fluid surface in the capillaries has negative curvature and negative pressure above it. The capillary tension pulls the AEW up along the capillary walls, until it reaches the butt-end of the capillary. Fluid increases its curvature additionally due to the action of the EF. The EF may pull out a fluid knitting needles (FN) in the places where the capillaries adjoin each other. The upper endings of such FN have size δ. On such a FN, the EF becomes stronger by the factor $\xi \sim r_C/\delta$ and it forms the ultra-dispersion charged aerosol which may short the circuits in the discharge space. Thus, the presence of such capillaries facilitates electric breakdown in the discharge space.

3. Formation of aerosol column of WS.

Observations show that the WS column has radial size $R \sim 5\ 10^2$ cm, height $H \sim 10^5$ cm, EF magnitude $E \sim 10^4$ V/cm, and the velocity of the motion, both axial one and rotation, of WS column is $V^{WS} \sim 1.5\ 10^4$ cm/s. Initial phase of WS is characterized by the presence of some luminescence on the water surface in the WS column, and by the absence of any rotation both outside and inside it.

According to hypothesis [1], the tubular structures of 3-rd generation and higher , assembled from carbon nanotubes, are the basic building blocks of OSS's cylindrical blocs. VFC is one of typical blocks of OSS, which may be represented in the form of a big cylinder of radius $R \sim 5\ 10^2$ cm which in its interior is filled in with closely packed blocks of a smaller size, up to tens of microns-sized thin capillaries of radius r_C.

When a strongly charged mammatus cloud (MC) is appeared over the VFC, its capillaries are dragging up due to the EF of the MC and begin to emit the faintest charged water drops on their butt-ends. The above-mentioned condition for lifting the water drops, in this case, gives $r_D < 2.6\ 10^{-3}$ cm. Let's assume that radius of capillaries which form the VFC [2] is $r_C \sim 10^{-3}$ cm (that corresponds to cited above condition). Then $q_{min} \sim 2\ 10^3 e$, $q_{max} \sim 5\ 10^6$ e. Even the q_{max} value is not sufficient to tear off a drop from the capillary's butt-end, if $E \sim 10^4$ V/cm. VFC in the presence of EF can produce the drops of different size: namely, ultra-disperse drops, which are born by the FN, and those which are born at basic capillaries of the VFC. The WS starts with formation of an aerosol on the FN, which is composed of water molecular ions and may carry the charge $q_i \sim e$. The water output of this FN can be estimated from the expression for the liquid outflow rate of the capillary, $Q_f \sim \pi r_f^4 p/8\eta L \sim E^2\delta^2 r_C^2/64L\eta \sim 2\ 10^{-13}$ cm^3/s, here η is the viscosity of water, and the substitutions $p = E^2\ r_C^2/8\pi\delta^2$ and $L \sim 2\ 10^{-5}$cm are made. When the air mass is going to run up, the output from the FN in the entire WS cross section is $Q_i^{ws} \sim 5\ 10^{-2}$ cm^3/s, that corresponds to current $I_i \sim 30$ A. Later on only a small portion of I_i will be needed for maintenance of a certain density of aerosol drops.

The motion of water ions and the air in the WS column at initial stage of WS may, in first approximation, be described by the equations:

$$Ee/m_i - F_i/m_i = dV_i/dt, \qquad n_iF_i/\rho_a = dV_a/dt,$$

where

$$n_iF_i \sim n_i 8(2\pi)^{1/2} r_i^2 n_a T_a(V_i - V_a)/3V_T = n_iB(V_i - V_a),$$

where m_i, V_i are the mass and velocity of water ions, respectively, V_a is velocity of the air, F_i is friction force for ions in the air at the stage when the FNs operate. Solution of the first equation (when $V_a = 0$) is $V_i \sim Ee/B[1-\exp(-t/\tau_i)]$, where $\tau_i = m_iB \sim 0.4$ ns is the time of attaining an uniform velocity of water molecular ions while the air is not involved in the motion yet. Then $V_i \sim 2\ 10^5$ cm/s, and $n_i \sim 4\ 10^{10}$ cm^{-3}. Solution of the second equation is $V_a \sim V_i\ [1-\exp(-t/\ \tau_a)]$, where $\tau_a \sim \rho_a/Bn_i \sim 0.4$ s. The time of attaining the velocity V_a over the entire WS column is $t_r \sim H/V_i \sim 0.5$ s.

Note that the minimum decrease of the atmosphere pressure in the column (needed for transition from breakdown process at FNs only to that at the entire perimeter of basic capillaries) for the case of $E \sim 10^4$ V/cm amounts to $\sim 5\ 10^{-5}$ atmosphere only, that corresponds to velocity of the air $V_a \sim 2.5\ 10^2$ cm/s. It follows that in a subsecond time this velocity may rise up to really measured value at the stationary stage of WS, $V_a^s \sim 1.5\ 10^4$ cm/s. This velocity value leads to fall down of atmospheric pressure in the WS column to a value $p^s \sim \rho_a(V_a^s)^2/2 \sim 0.15$ atmospheres, which sum up with the pressure of the EF. Under this condition, liquid toroids may form on the AEW. They tear off the capillaries and assemble into drops of a radius r_d. The condition of formation of such a toroidal drop is $[\rho_a(V_a^s)^2/2 + E^2r_C^2/8\pi(r_f^c)^2]r_f^c = \sigma$, where r_f^c is the size of a ring slit of the AEW, which forms such a drop. Further, the optimal size is $(r_f)_{opt} = Er_C/\ 4V_a^s\,(\pi\rho_a)^{1/2} \sim 1.7\ 10^{-5}$ cm, that corresponds to $r_d \sim 10^{-4}$ cm. The charge of these drops $q_{min} \sim 2\ 10^2e$. The EF under action of the negative pressure p^s pulls out the capillaries from the water up to the height $L \sim (\rho_a/\rho)(V_a^s/2g) \sim 1.6\ 10^2$ cm. The output of the capillaries due to action of the AEW is determined by the output of basic capillaries in the VFC. At this conditions one has $Q_C \sim \pi r_C^4 p/8\eta L \sim 4\ 10^{-6}$ cm^3/s, and the output of the entire WS cross section is $Q_{ws} \sim 10^6$ cm^3/s. This corresponds to WS's current $I_{WS} \sim 8$A and the density of drops $n_d \sim 10^7$cm^{-3}.

The parameter of non-ideality for such an aerosol dusty plasma is $\Gamma_D = q^2n_d^{1/3}/T_d \sim 50$. As stated above, the fall down of the pressure in the WS column boils up the water surface inside it due to pumping out of the air which was dissolved in the water. This favors a massive production of charged water drops as well.

4. Mechanism of WS rotation.

At the beginning of the WS formation, there is no rotation both inside and outside it's column. Atmosphere is a weakly-ionized plasma with ions density $n_i \sim 10^7$ cm^{-3}, as determined by the leakage current value. Upward motion of gas in the column leads to a radial gradient of atmospheric pressure outside the column. Therefore, radial motion of gas due to the presence of vertical component of the Earth magnetic field favors the tendency toward azimuthal rotation of molecular ions inside/outside column, which especially strongly manifests itself near the border of WS column. Ions' rotation drags on the neutral gas, which, in turn, involves the drops. Charged particles are subject to centrifugal force, EF and gas pressure gradient, with the latter being due to gradient of air velocity, both inside and outside the column. This leads to spiral trajectories of gas inside/outside column. Radial components of these forces at both sides of the column's border must be balanced. With evolving WS, the output of capillaries increases and the rotation is settled both in the column and in the gas around it. This results in formation of a thin rapidly rotating water film, as a boundary, in the periphery of the column. This leads to a very fast discharging of MC due to high electric conductivity of sea water. This phase is the WS culmination and the beginning of its degradation.

Thus, the capillary structure of VFC is a trigger for the formation of WS. Therefore, the column of WS may be interpreted as a special type of atmospheric aerosol dusty plasma. In such a framework, the WS is considered as a long-lived filament, which is being formed in electric discharge in the presence of electric and magnetic fields in the course of electric breakdown between the MC and the VFC on water/ocean surface. Here, the charged water aerosol may work as an analog of a microdust which lifts upward to the MC due to effects of electrostatic forces.

5. Energy characteristics of WS.

At the stationary stage of WS evolution, the drops transfer the current $I_D \sim 8$ A. The power of such an electric machine is $W \sim 8\ 10^9$ W. For 20 minute operation at this stage, WS can produce the work $\sim 8\ 10^{12}$ J, and during this time it lifts into the MC the liquid about 10^9 cm^3 in volume (at expense of $\sim 10^{10}$ J). If the MC surface equals to ~ 20 km^2 (typical size of WS) and all the captured water falls down as a precipitation on the area equal to the MC surface, then the average level of precipitations will be as large as $\sim 5\ 10^{-2}$ cm. The WS energy is expended, mostly, at a supply of the air, which is involved in this process, with kinetic energy.

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