Coulomb clusters in a cusp magnetic trap under microgravity condition

L. D'yachkov (*)1, S. Savin 2, M. Myasnikov 1, O. Petrov 1, V. Fortov 1,
A. Kaleri 2, A. Borisenko 2

1 *Joint Institute for High Temperatures, Russian Academy of Sciences, 125412 Moscow, Russia*
2 *S.P. Korolev Rocket-Space Corporation "Energia", 141070 Korolev, Russia*
(*) dyachk@mail.ru

We studied the formation of Coulomb clusters consisting of thousands of charged diamagnetic (graphite) particles in a cusp magnetic trap under microgravity conditions on the board of the International Space Station. After a dynamic impact on clusters their oscillations were observed. Using the data of the observations the magnetic susceptibility and charge of the particles have been estimated. The distributions of the magnetic and electrostatic fields have been calculated. MD simulation of the cluster formation was performed.

Strongly coupled Coulomb systems (SCCS) are of considerable fundamental and applied interest. They have been theoretically and experimentally investigated during many decades. In recent years, ordered dust structures of liquid-like and crystalline type in discharge plasma is often considered as a physical model of SCCS that can visually be observed. Recently we proposed a new way for formation and investigation of SCCS [1,2]. It is based on the known possibility of the levitation of diamagnetic bodies in a nonuniform steady-state magnetic field that was earlier applied only for levitation of single macroscopic bodies [3]. In a nonuniform magnetic field, any particle is acted upon by the effective force $\mathbf{F}_B = (\chi m/2)\nabla(\mathbf{B}^2)$, where χ is the specific magnetic susceptibility of the particle matter and m is the mass of the particle. For diamagnets $\chi < 0$, consequently, diamagnetic bodies are forced out from the region with high magnetic field to the region with lower field, but a field exhibiting a local minimum can easily be generated. Thus, the state of stable equilibrium in a static magnetic field is possible for diamagnetic bodies in contrast to paramagnetic and ferromagnetic bodies. We have experimentally and theoretically shown that a trap for a cluster of charged diamagnetic particles can be created [1,2]. However, under conditions of terrestrial laboratory, using magnetic fields $B \sim 1$ T, we have formed only small clusters consisting of a few graphite particles. And our next step is the investigation of rather extended three-dimensional Coulomb clusters under conditions of microgravity. First experiment on the formation of strongly nonideal systems containing a large number of charged diamagnetic (graphite) particles in a cusp magnetic trap was performed on the board of the International Space Station (ISS) [4]. In the present communication we discuss the experiment and report the results of analytical estimations, numerical calculations and MD simulations.

Experimental setup consists of a specially designed electromagnet and replaceable containers with graphite particles. A cusp magnetic field is generated by two identical coils located on the same axis, in which currents circulate in the opposite directions. If the currents in both the coils are identical, the point with zero magnetic field (zero point O_B) is placed in the center of the setup between the coils on the symmetry axis. The case of the electromagnet is a magnetic circuit connecting the cores of the coils, it has a cylindrical shape with a diameter of 15 cm and a height of 18 cm. The distance between the cores is 6 cm, and their diameter is 5 cm. When the current in one of the coils is changed, the point O_B is shifted along the axis. In the area around O_B of radius no less than 2 cm, the field depends linearly on the coordinates (within a few percent). In the middle of the replaceable container, a cylindrical glassy cell with a diameter of 52 mm and a height of 40 mm filled with argon at atmospheric pressure, is located. Graphite particles are placed in the cell. We used four containers with particles of different sizes: 100, 200, 300 and 400 μm. In each container about 2000 particles were placed. Charging of the particles was carried out using a central wire electrode of diameter 200 μm that passed along the axis of the cell (z axes). A semicircle grounded outer electrode with a diameter of 51 mm was placed in the cell near the glassy side wall. The other half of the glassy wall was free for observations. The electric potential on the central electrode was varied from 0 to 24 V. For more details see [4].

Initially, the particles were on the walls of the glassy cell, and after shaking they filled its volume. When a potential was applied to the central electrode, particles were charged in collisions with it. Switching on the electromagnet causes the displacement of graphite particles to the zero point O_B and the formation of a cloud of charged particles in the shape of an oblate ellipsoid of revolution (Fig. 1, on the left). When the current in one of the electromagnet coils was increased (decreased), the point O_B shifted from (to) this coil along the symmetry axis. In this case, all the particles acquired dynamic momentum. After a certain time (2 to 4 s), the current in the other coil was increased (decreased) by the same value, and the zero point returned to its initial position. The dynamic momentum excited oscillations of the particle ensemble as a whole along the *z* axis. Due to the friction of the particles with the gas, oscillations damped during a few periods. Observing the oscillations, we found their initial amplitude (~ 1 cm), period (8 - 10 s) and damping decrement (~ 0.1 s^{-1}). From these data we have obtained the specific magnetic susceptibility χ of the particle matter. Graphite has a layered structure, and the value of strongly depends on the direction. For polycrystalline graphite the average value χ = $-3\cdot 10^6$ cm^3/g, but the magnetic susceptibility may significantly differ from the average value if there is some anisotropy of the particle graphite. We have obtained χ = $-(4\text{-}5)\cdot 10^6$ cm^3/g for dust particles of different sizes. From the balance of magnetic and electrostatic forces we have estimated the charge on the particles. For particles 400 μm in size it is about $4\cdot 10^4$ elementary charges.

To simulate the formation of Coulomb clusters in the cusp magnetic trap, we need to know the distributions of the magnetic and electrostatic fields inside the cell containing dust particles. Numerical calculation of the fields was produced by the finite element method [5]. Magnetic field was calculated by two ways: using the approach proposed in [6,7] and in terms of vector potential. Both the ways give similar distributions of the magnetic field. MD simulation of the Coulomb cluster formation yields the size and shape of the dust cloud similar to the observed ones (Fig. 1, on the right).

This study was supported by the program for basic research of the Presidium of the Russian Academy of Sciences "Matter at high energy densities" and by the RFBR Projects 10-02-01428, 10-02-90056 and 11-02-01051.

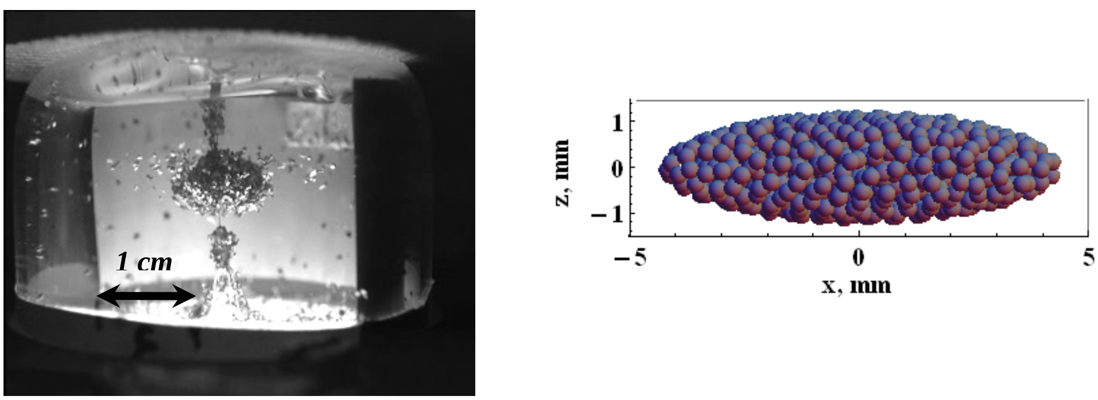

Fig. 1: Formation of a cluster of graphite particles 400 μm in diameter: experiment on the left, MD simulation on the right.

References

[1] S.F. Savin, L.G. D'yachkov, M.M. Vasiliev, O.F. Petrov, V.E. Fortov, *Europhys. Lett.* **88** (2009) 64002(1-6).
[2] S.F. Savin, L.G. D'yachkov, M.I. Myasnikov, O.F. Petrov, V.E. Fortov, *Phys. Scr*. **85** (2012) 035403 (1-11).
[3] A. Geim, *Phys. Today* **51** (1998) N 9, 36-39.
[4] S.F. Savin, L.G. D'yachkov, M.I. Myasnikov, O.F. Petrov, M.M. Vasiliev, V.E. Fortov, A.Yu. Kaleri [2], A.I, Borisenko, G.E. Morfil, *JETP Lett.* **94** (2011) 508-512.
[5] G. Strang, G.J. Fix, *An Analysis of The Finite Element Method* (Wellesley-Cambridge Press, Wellesley, MA, 1988).
[6] J. Simkin, C.W. Trowbridge, *Int. J. Numerical Methods in Engineering* **14** (1979) 423.
[7] J. Simkin, C.W. Trowbridge, *Institution of Electrical Engineers Proceedings* **127** B (1980) 368.