J. Jpn. Soc. Microgravity Appl. Vol. 28 No. 2 2011 (S27–S30)

8th Japan-China-Korea Workshop on Microgravity Sciences
for Asian Microgravity Pre-Symposium

Strongly Coupled Plasmas under Microgravity

Hiroo TOTSUJI[1], Kazuo TAKAHASHI[2], Satoshi ADACHI[3],
Yasuaki HAYASHI[2], and Masahiro TAKAYANAGI[3]

Abstract

Fine particle (dusty) plasmas provide us with a unique system in the sense that constituent particles are strongly coupled enough to manifest collective properties and, at the same time, their orbits are separately observed. We are thus able to investigate long-ranged statistical phenomena at the kinetic level. The only difficulty is the large effect of the gravity acting on fine but still macroscopic particles. Therefore the microgravity is the ideal environment of experiments for these purposes. Among many interesting phenomena, we have been especially working to observe peculiar behavior of thermodynamic quantities of strongly coupled plasmas as modeled by one-component plasma (OCP). This has been long known to be common in many systems including the Yukwa system but the possibility to observe in fine particle plasmas has been pointed out only recently by one of the authors (H. T.). After brief general introduction of fine particle plasmas, the critical point and related phenomena are described in relation to experiments under microgravity.

1. Introduction

The fine particle (dusty) plasma is a charge-neutral mixture of micron-sized fine (dust) particles and ambient plasma composed of ions and electrons. Typical densities of fine particles and ambient plasmas are $(10^4\sim10^5)$ cm^{-3} and $(10^6\sim10^8)$ cm^{-3}, respectively. Images of fine particles are easily captured and identified by CCD cameras through the scattering of the laser beam and we are able to make particle level observations. In contrast to ions and electrons which are singly charged, fine particles have large negative charges which are 10^3 to even 10^4 times as large as that of an electron. We are thus able to observe various effects of Coulomb coupling between fine particles and this is the main reason why a lot of researches on fine particle plasmas have been done recently[1-4].

One of the most interesting phenomena in strongly coupled systems may be the ones related to the critical point. In this article, we give a short description our proposal of observation of critical phenomena in fine particle plasmas under the condition of the microgravity and the present status of experiments.

2. What Is Strongly Coupled Plasma?

We denote the number densities, the charges, and the temperatures of fine particles, ions and electrons by (n_p, n_i, n_e), $(-Qe, e, -e)$, and (T_p, T_i, T_e), respectively. We assume that the charge neutrality is satisfied as

$$(-Qe)n_p + en_i + (-e)n_e = 0 \quad (1)$$

The temperatures of three components are usually different and we have

$$T_e >> T_i \sim T_p \quad (2)$$

Typical values of temperatures are $T_e \sim$ 1eV (10^4 K) and $T_i \sim T_p \sim$ 0.03eV (300K), respectively.

2.1 Characteristic Parameters

The interaction between fine particles is screened by ambient plasma and can be regarded as the Yukawa repulsion in the first approximation:

$$\frac{(Qe)^2}{4\pi\varepsilon_0 r}\exp(-r/\lambda_D) \quad (3)$$

Here the screening length λ_D is given by the Debye length of the ambient plasma

$$\lambda_D = \left(\frac{n_i e^2}{\varepsilon_0 k_B T_i} + \frac{n_e e^2}{\varepsilon_0 k_B T_e}\right)^{-1/2} \quad (4)$$

Our system is characterized by the parameters Γ and ξ defined respectively by

$$\Gamma = \frac{(Qe)^2}{a k_B T_P} \quad (5)$$

and

1 Okayama University, 3-1-1 Tsushimanaka, Kitaku, Okayama 700-8530, Japan
2 Kyoto Institute of Technology, Matsugasakigosyokaidocho, Sakyoku, Kyoto 606-8585, Japan
3 Institute of Space and Astronautical Science, Tsukuba Space Center, Japan Aerospace Exploration Agency, 2-1-1 Sengen, Tsukuba 305-8505, Japan
(E-mail: totsuji@elec.okayama-u.ac.jp)

$$\xi = \frac{a}{\lambda} \tag{6}$$

$a = (3/4\pi n_p)^{1/3}$ being the mean distance between particles. The parameter Γ expresses the strength of the Coulomb coupling between particles and ξ, the strength of screening, both measured at the mean distance. Taking the effect of screening into account, the effective coupling between particles is roughly given by $\Gamma\exp(-\xi)$.

2.2 Divergence of Isothermal Compressibility and Critical Phenomena

When $\Gamma\exp(-\xi) >> 1$, the system shows various phenomena due to strong coupling including the formation of structures usually called Coulomb crystals (exactly, they are finite Coulomb clusters). One of the authors (H. Totsuji) has pointed out[5] that fine particle plasmas give a possibility to observe a peculiar phenomenon which is common to Coulomb and Coulomb-like systems but suppressed by the background charges in most cases.

It has been long known that, when we focus on the pressure of strongly coupled component of Coulomb and Coulomb-like systems, the isothermal compressibility has a tendency to diverge with the increase of the coupling. This kind of model where one considers mainly only one of charged components is called one-component plasma (OCP) model.

In real charge-neutral systems where we have other component with opposite (compensating) charges, the large pressure of the latter is considered to mask this divergence. (The compensating component of charge is usually called 'background'.) In the case of fine particle plasmas, however, this divergence and related critical phenomena can be observed when fine particles are in the state of very strong coupling.

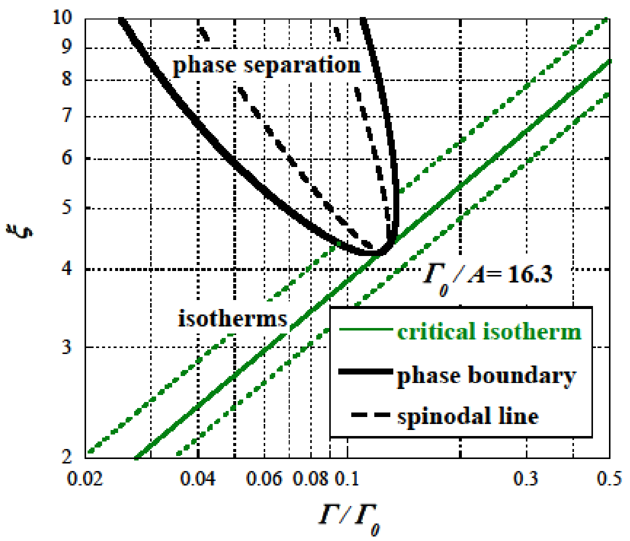

Fig. 1 Example of phase diagram and critical point with the critical isotherm in (Γ, ξ)-plane which corresponds to (ρ, T)-plane in usual gas-liquid transitions[5]. (Isothermal changes occur along straight lines when both axes are in the logarithmic scale.)

2.3 Phase Diagrams and Density Fluctuations

A typical set of the resultant phase diagrams is shown in **Figs.1** and **2** which correspond to those of usual gas-liquid transitions in the density-temperature plane and in the pressure temperature plane, respectively. In **Fig.1**, the thick solid line is the boundary between the one-phase domain and the phase-separated domain (the latter being the inner part). In **Fig.2**, we have coexisting phases on the lines and the critical point corresponds to the termination of the coexistence line. It has been also pointed out that, when appropriate conditions are satisfied, we may have a critical point in the solid phase.

One of critical phenomena is the enhancement of density fluctuations. The behavior of the structure factor at long wavelengths are related to the divergence of the isothermal compressibility as[5]

$$S(k;3d) = \frac{1}{\left(\frac{\partial p_{total}}{\partial n_p}\right)_T \frac{1}{k_B T_p} + O(k^2)} \tag{7}$$

Large enhancement of the long wavelength density fluctuations is expected near the critical point where the derivative of the total pressure vanishes as shown in **Fig.3**.

2.4 Experimental Conditions and Experiments on ISS

For experiments, the characteristic parameters at the critical point need to be rewritten into physical parameters such as densities and temperatures. Since the charge on a fine particle is not a given quantity but a function of the latter parameters, we have to solve a nonlinear equation in this process[6]. The experimental conditions have been analyzed[6] as shown by

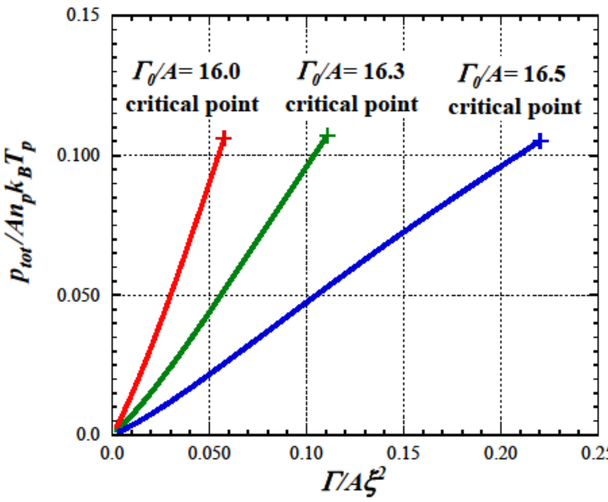

Fig. 2 Examples of phase diagram and critical point in (Γ/ξ^2, p)-plane which corresponds to (p, T)-plane in usual gas-liquid transitions[5].

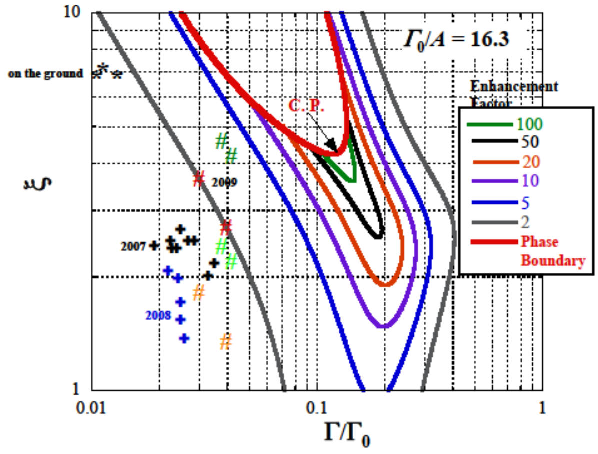

Fig. 3 Example of density fluctuation enhancement in (Γ, ξ)-plane[5]. Thick line going through 'c.p.' (critical point) is the boundary of coexisting phases, inside being two-phase domain. Lines with numbers are conditions for enhancement of designated number. Symbols are rough estimations of parameters in experiments.

examples in **Figs.4** and **5**.

It is shown that the radius of fine particles need to be rather large and the microgravity environment is necessary to have a finite system where many fine particles are kept afloat uniformly. This observation has been proposed to the experiments on the International Space Station (ISS) which are performed jointly by Max-Planck Institute for Extraterrestrial Physics (MPE) in Germany and Joint Institute for High Temperatures (JIHT) in Russia.

3. Two-Dimensional vs. Three-Dimensional Observations

In fine particle plasma experiments, the positions of particles are recorded by the CCD cameras as two-dimensional images through the scattering of the laser beam sheet. In complete experiments, the sheet laser beam is scanned and three-dimensional information is to be obtained. Since we may have the cases where the scanning is not available for some reason, it is necessary to have the relations between three-dimensional information and two-dimensional one.

It has been shown[7] that the two-dimensional information obtained by the sheet laser beam of finite thickness reproduces the three-dimensional information. The relations between the two- and three-dimensional structure factors are given by

$$S(K;2d)-1=\frac{b}{\pi}\int_K^\infty \frac{dkk}{\sqrt{k^2-K^2}}\left[1-\frac{b^2}{12}(k^2-K^2)+\frac{b^4}{360}(k^2-K^2)^2\right][S(k;3d)-1] \quad (8)$$

and

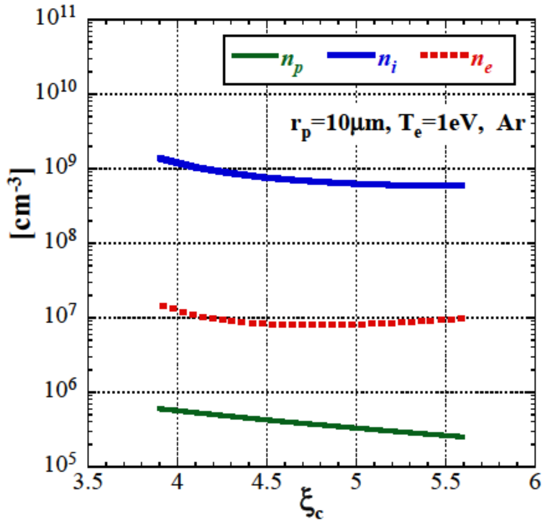

Fig. 4 Example of experimental conditions at the critical point[5,6].

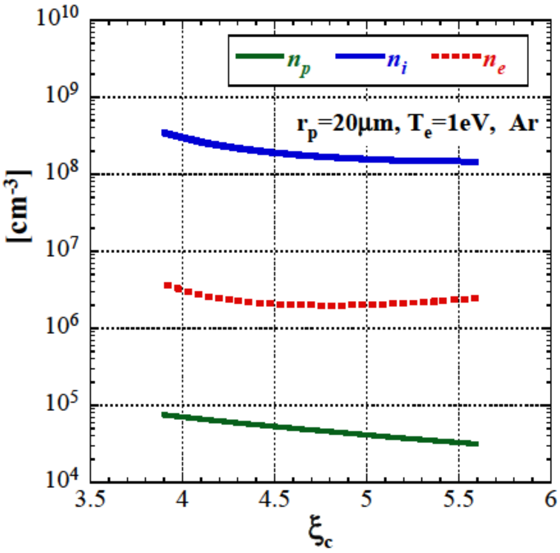

Fig. 5 Example of experimental conditions at the critical point[5,6].

$$S(k;3d)-1=\int_k^\infty \frac{dK}{\sqrt{K^2-k^2}}\left[-\frac{2}{b}\frac{d}{dK}+\frac{b}{6}K-\frac{b^3}{360}K(K^2-k^2)\right][S(K;2d)-1] \quad (9)$$

Here the two-dimensional wave vector is denoted by *K*.

When the three-dimensional structure factor shows the critical behavior at long wavelengths in the form

$$S(k;3d)\sim\frac{1}{c^2+(k/k_0)^2} \qquad k\to 0 \quad (10)$$

with $c^2\to 0$ at the critical point, the two-dimensional structure factor observed by the laser beam of thickness *b* takes the form given by (8). When *b* is sufficiently small, we have

$$S(K;2d)\sim\frac{bk_0}{2}\frac{1}{\sqrt{c^2+(K/k_0)^2}}\quad K\to 0 \tag{11}$$

The two-dimensional structure factor observed by the laser beam of thickness b thus has a weaker divergence in proportion to c^{-1} as

$$S(K;2d)\sim\frac{bk_0}{2c}\quad K\to 0 \tag{12}$$

in comparison with the (true) three-dimensional one

$$S(k;3d)\sim\frac{1}{c^2}\qquad k\to 0 \tag{13}$$

A method to obtain k_0 from two-dimensional observations is also given.

4. Present Status of Experiments

The high density states of fine particle plasmas have been tested with various experimental parameters such as rf power and neutral gas pressure. The information of the optimum conditions for these states has been collected and two-dimensional images have been obtained. Though we are not so close to the critical point itself and the quantity and quality of data are not sufficient, two-dimensional analyses show a possibility that density fluctuations are enhanced at long wavelengths. We are now waiting for the three-dimensional data from the high-resolution camera.

Acknowledgements

This work has been done as an international collaboration with Max-Planck Institute for Extraterrestrial Physics in Germany and Joint Institute for High Temperatures in Russia. H. T. and K. T. would like to thank Professors G. Morfill, H. Thomas, V. Fortov, V. Molotkov, A. Lipaev and research groups of both institutes for their kind guidance and instructions on occasions of experiments on ISS.

One of the authors (H. T.) has been partly supported by the Grant-in-Aid for Scientific Research (C) Nos. 19540521 and 21540512 from the Japan Society for the Promotion of Science.

References

1) P. K. Shukla and A. A. Mamun: *Introduction to Dusty Plasma Physics*, Institute of Physics Publishing, Bristol, 2002.
2) V. E. Fortov, A. V. Ivlev, S,. A. Khrapak, A. G. Khrapak, and G. E. Morfill: Phys. Reports, **421**(2005) 1.
3) G. E. Morfill and A. V. Ivlev: Rev. Mod. Phys., **81** (2009) 1353.
4) H. M. Thomas, G. E. Morfill, V. E. Fortov, A. V. Ivlev, V. I. Molotkov, A. M. Lipaev, T. Hagl, H. Rothermel, S. A. Khrapak, R. K. Suetterlin, M. Rubin-Zuzic, O. F. Petrov, V. I. Tokaraev, and S. K. Krikalev: New J. Phys., **10** (2008) 033036.
5) H. Totsuji: J. Phys. A: Math. Gen., **39** (2006) 4565; *Non-Neutral Plasma Physics VI, Workshop on Non-Neutral Plasmas 2006*, ed. M. Drewsen, U. UggerhØj, and H. Knudsen, AIP Conference Proceedings **862**, American Institute of Physics, New York, 2006; J. Jpn. Soc. Microgravity Appl., **25** (2008) 343; Phys. of Plasmas, **15** (2008) 072111.
6) H. Totsuji: Plasma and Fusion Research, **3** (2008) 046.
7) H. Totsuji: J. Phys. Soc. Jpn. **79** (2009) 064002; *ibid.* **80** (2010) 065004.

(Received 25 Oct. 2010; Accepted 12 Apr. 2011)