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Study of Complex Plasmas with Magnetic Dipoles

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14. ABSTRACT
This research on complex plasmas with magnetic dipoles has been carried out at Chubu University in Kasugai, Aichi Prefecture from 13 August, 2014 to 12 August, 2017, after the transfer of the principal investigator from Yokohama National University to Chubu University. Research personnel included a principal investigator, Osamu Ishihara, and Visiting Professor Sergey Vladimirov of University of Sydney, Australia. The project involved the study of a complex plasma (a plasma with macroparticles). The study focused on a theoretical study of electromagnetic wave propagation in a complex plasma. The study was prompted by earlier experimental work of a complex plasma in the presence of magnetic field, carried out at Yokohama National University, supported by previous grant FA2386-12-1-4077 (Principal investigator: O. Ishihara). In a plasma, charged particles move freely with thermal energy much larger than Coulomb energy, showing the nature of a weak coupling. Such a weak coupling among particles is the basis for the variety of collective behavior manifested in a plasma, especially oscillations or waves characterized by high frequency accompanied by the motion of electrons and/or ions. On the other hand, the presence of dust particles, either conductors or nonconductors, in a plasma changed the concept of the plasma characterized by a weak coupling. Dust particles of micron size are negatively charged in a plasma by the current balance of ions and electrons on the surface of a dust particle, and are confined in a plasma to remain charge neutral as a system. Such a plasma was originally studied in a context of a plasma in universe and was often called as a dusty plasma in the field of astrophysics. Even in a recent study of accelerating expansion of the universe, the presence of dust particles in space must be considered to evaluate the observed red-shift properly.

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Abstract:

This report describes a research on the contract of investigation entitled by "Study of Complex Plasmas with Magnetic Dipoles" (Principal investigator: O. Ishihara, FA2386-14-1-4021, AOARD 144021). The research has been carried out at Chubu University in Kasugai, Aichi Prefecture from 13 August, 2014 to 12 August, 2017, after the transfer of the principal investigator from Yokohama National University to Chubu University. Research personnel includes a principal investigator Osamu Ishihara and Visiting Professor Sergey Vladimirov of University of Sydney, Australia. The project involves the study of a complex plasma (a plasma with macroparticles). The present study is focused on theoretical study of electromagnetic wave propagation in a complex plasma. The study is prompted by the earlier experimental work of a complex plasma in the presence of magnetic field, carried out at Yokohama National University, supported by contract FA2386-12-1-4077 (Principal investigator: O. Ishihara).

Introduction:

In a plasma, charged particles move freely with thermal energy much larger than Coulomb energy, showing the nature of a weak coupling. Such a weak coupling among particles is the basis for the variety of collective behavior manifested in a plasma, especially oscillations or waves characterized by high frequency accompanied by the motion of electrons and/or ions. On the other hand, the presence of dust particles, either conductors or nonconductors, in a plasma changed the concept of the plasma characterized by a weak coupling. Dust particles of micron size are negatively charged in a plasma by the current balance of ions and electrons on the surface of a dust particle, and are confined in a plasma to remain charge neutral as a system. Such a plasma was originally studied in a context of a plasma in universe and was often called as a dusty plasma in the field of astrophysics. Even in a recent study of accelerating expansion of the universe, the presence of dust particles in space must be considered to evaluate the observed red-shift properly. As industrial applications grow in our everyday life, the plasma processing became a popular tool to meet a modern electronics technology. Dust particles often born in a plasma by coagulation became the topic to eliminate from the processing itself. On the other hand, massive charged dust particles in a plasma gathered attention by plasma community largely because of the nature of strongly coupled state. The dusty plasma shows new physics of interaction between the collection of dust particles characterized by extremely low frequency modes and the collection of plasma particles characterized by high frequency modes. The interaction of the two entities shows the nature of a complex system, so the name of a complex plasma is used to emphasize the physics not involved in regular plasma physics. Our study has focused both on experiments and theories to reveal the basic nature of a complex plasma.

Our earlier experiment [Nakamura and Ishihara, Rev. Sci. Instr. **79**, 033504 (2008)] was carried out in a discharge tube with Ar gas of ~40Pa. Silica macroparticles of 5μm in diameter and the density of 2.6 g/cm^3 were introduced in the plasma. By changing the gas pressure the movement of macroparticles are controlled. In the lower gas pressure macroparticles are free to move around in a plasma and behave like insects moving around hastily, while macroparticles show no movement in a higher gas pressure. The neutral particles in a plasma are responsible to control the movement of macroparticles. Figure 1(a) shows the macroparticles move randomly in a plasma, while Fig. 1(b) shows no movement of the macroparticles. Figure 2 (a) shows a group of macroparticles like a cloud, while closer look clearly shows the cloud is indeed a collection of macroparticles in a structural form. Figure 2(b) shows an overall macroparticles photographed in black and white. By producing a plasma in an upright long tube of 5 cm in diameter, we can produce a pack of dust particles as shown in Fig. 3(a), while a rather limited number of dust particles are confined in a glass tube of 1.6 cm in diameter and the top view is shown in Fig. 3(b). Acrylic particles of 3 μm in diameter

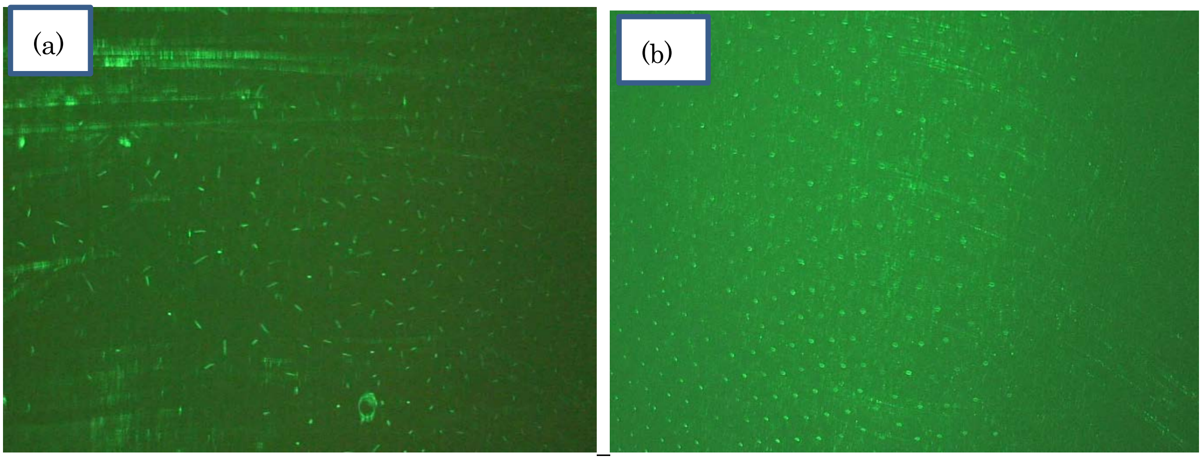


Fig. 1 Macroparticles levitate over the plate placed in a discharge tube and are illuminated by horizontal green laser light of wavelength 532 nm. (a) Macroparticles move randomly in a lower gas pressure (b) Macroparticles stop moving in a high gas pressure.

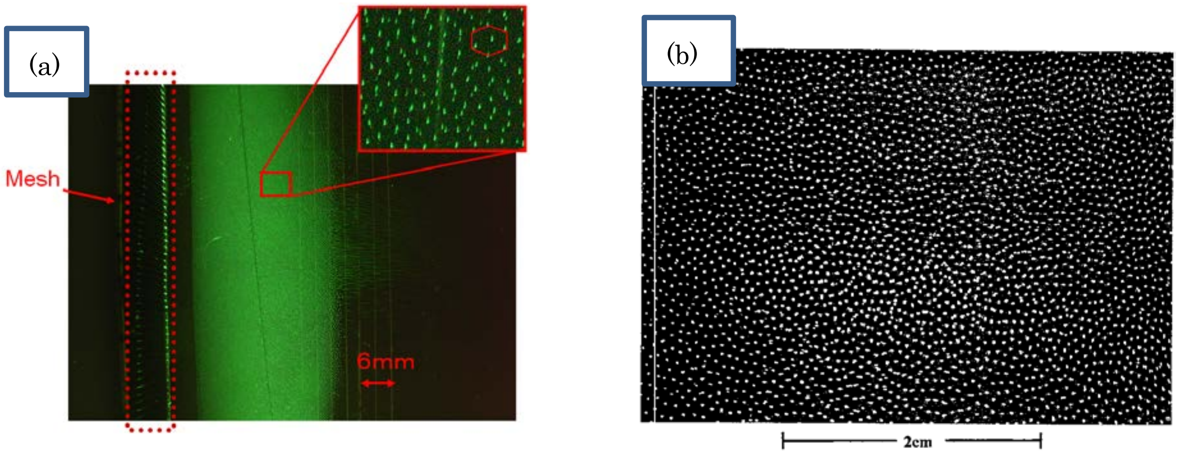
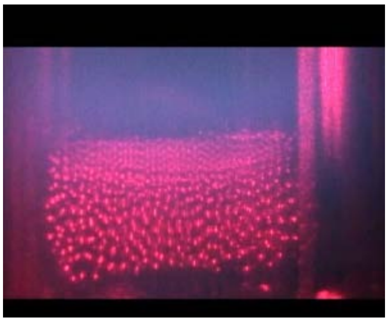


Fig. 2 (a) Macroparticles look like a cloud in a plasma, but when enlarged macroparticles are seen individually in a structured form. (b) Macroparticles float over the plate. *P*=20Pa. The rf power=25 W.



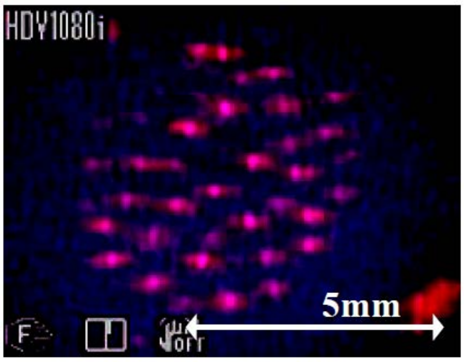


Fig. 3 (a) Side view of a pack of dust particles confined in a glass tube of 5 cm in diameter.
(b) Top view of a structured dust particles confined in a glass tube of 1.6 cm in diameter.
are levitated in a helium plasma at gas pressure of 66.5Pa. Dust particles are illuminated by He-Ne red laser of wavelength 632.8 nm [C. Kojima, M. Kugue, T. Maezawa, M. Shindo, Y. Nakamura and O. Ishihara, Complex plasma experiment in cryogenic environment, Proceedings of 13th International Congress on Plasma Physics, May 22-26, 2006, Kiev, Ukraine (Bogolyubov Institute for Theoretical Physics, Ukraine), E134p].

Our earlier experimental work prompted us to study the nature of electromagnetic wave propagating in a complex plasma.

Plasma electron oscillations are characteristics of plasma collective effects and are characterized by the electron plasma frequency ω_{pe}, or the dispersion is given by

$$\omega^2 = \omega_{pe}^2,$$

where $\omega_{pe} = \sqrt{ne^2 / \varepsilon_0 m_e}$ is the electron plasma frequency with electron density n, electron mass m_e and

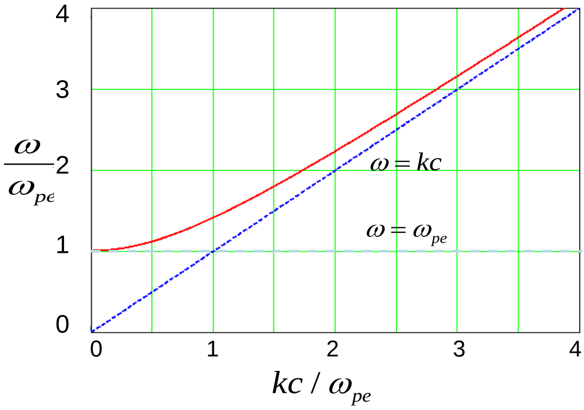


Fig. 4 Dispersion of electromagnetic wave in a plasma. Electromagnetic wave can propagate only above the plasma frequency. $\omega = kc$ is the dispersion of electromagnetic wave in vacuum.

vacuum permittivity ε_0. Electromagnetic waves in a plasma propagate only above the electron plasma frequency known as a cutoff frequency, or the dispersion is given by

$$\omega^2 = k^2 c^2 + \omega_{pe}^2,$$

where c is the speed of light. Figure 4 shows the dispersion of the electromagnetic wave. The electromagnetic wave dispersion in plasma plays a critical role in determining the characteristics of plasmas in the laboratory or in the cosmic environment. Frequency of the electromagnetic wave to use for communication purpose must be above the plasma frequency to go through the layer of plasma. Plasma containing dust particles has been attracting attention in basic plasma science as well as in space physics and astrophysics since the presence of macroscopic particles (macroparticles, "dust") significantly modifies plasma properties.

We have demonstrated that resonances with surface oscillations (surface plasmons) on macroparticle surfaces can have important consequences on electromagnetic wave propagation in complex plasmas resulting in a band mode related to surface plasmons and the frequency gap with the electromagnetic wave band [Ishihara and Vladimirov, Advances in Physics: X **2**, 462-480 (2017)]. Figure 5 shows the dispersion for electromagnetic waves in a complex plasma with metallic dust particles. And Fig. 6 shows the refraction index squared for a complex plasma with dielectric spherical dust particles.

Surface waves on interfaces of two media with opposite signs of permittivities have long history of research. Surface plasma waves (surface plasmons), when one of the media is plasma, attracted special interests for many applications, for example, in plasmonics, in light sources as spasers, and in nano-antennas. The surface wave fields include information on the properties of adjacent media and therefore can affect electromagnetic waves in one of them by properties of another one.

We have studied electromagnetic wave propagation in a plasma containing identical spherical macroparticles (dust) and take into account the presence of surface plasmons; we simplify the problem by excluding losses and effects of space dispersion. To calculate the effective permittivity, we employ the Maxwell Garnett (MG) approximation widely used in studies of two-component mixtures.

One of the novel features of our study is account of the influence of plasma host environment. Here, the main phenomenon is the surface plasmon resonance on dielectric particles, due to host plasma environment; this effect is absent for dielectric particles in dielectric host environment. The presence of such resonance makes it possible for electromagnetic waves to propagate at frequencies below the electron plasma frequency.

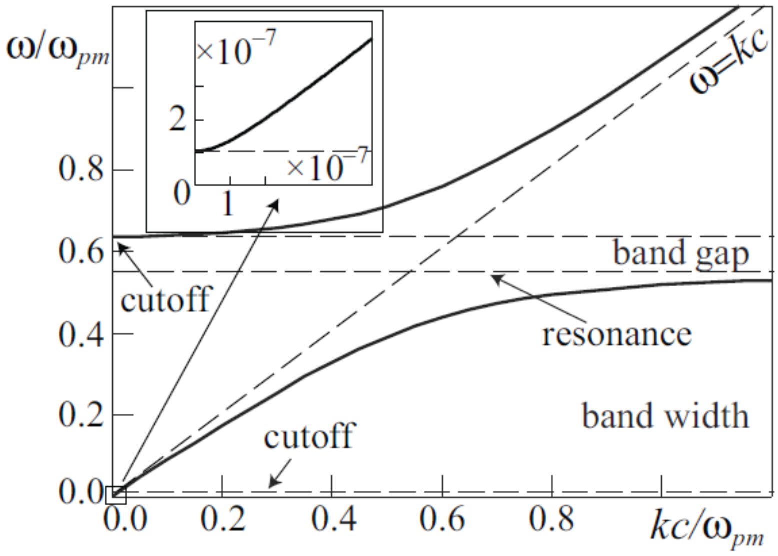


Fig.5: Calculated dispersion of electromagnetic wave bands in a plasma with metallic dust. The inset shows the cutoff at ω_{pe}. Here ω_{pm} is the plasma frequency of metallic electrons.

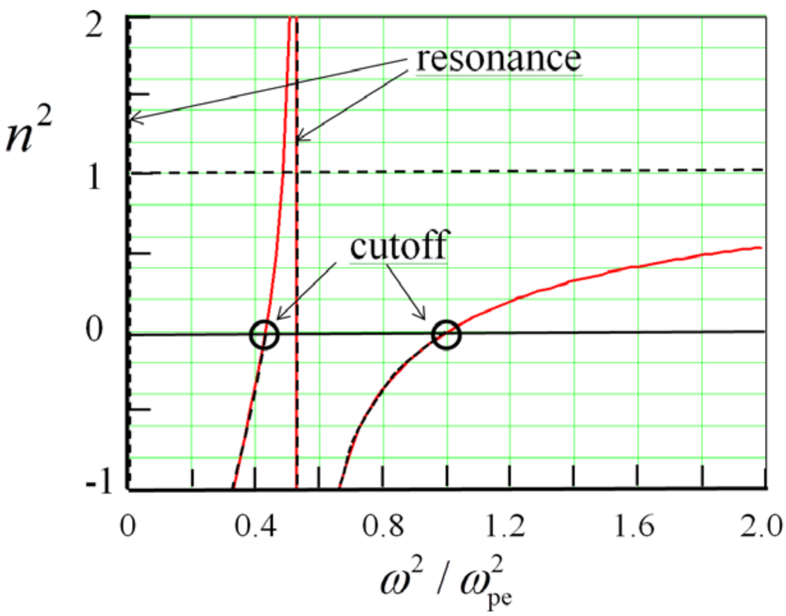


Fig. 6: Squared index of refraction n^2 vs squared frequency ω^2 of electromagnetic wave in a plasma with dielectric dust.

Personnel:

(1) Osamu Ishihara, a principal investigator (now professor at Chubu university and an emeritus professor of Yokohama National University)

(2) Visiting Professor Sergey Vladimirov (Professor, University of Sydney)

International Conferences/Meetings attended:

(1) The 40th COSPAR（The Committee on Space Research ）, Moscow, Russia, Aug 01-08, 2014, Scientific Assembly Organizing Committee.

(2) CAP (Canadian Association of Physics) Congress, Edmonton, Alberta, Canada, June 15-19, 2015

(3) 18th International Congress on Plasma Physics, ICPP 2016 Kasosiung, Taiwan. June 27-July 1, 2016, Scientific Program Committee, Low Temperature and Dusty Plasmas (Chair)

(4) International Symposium on Plasma Science and Technology, "Measurement, Analysis and Control of Plasma in a Form of Ordered Structure", Aug. 26, 2016, Kyoto Institute of Technology（Kyoto, Japan）.

(5) 2016 Plasma & Electro-Energetic Physics Annual Program Review, Basic Research Innovation and Collaboration Center, Arlington VA USA, November 29-30, 2016

(6) The 9th International Symposium on Advanced Plasma Science and its Applications for Nitrides and Nanomaterials(Chubu University, Kasugai, Japan) March 1-5, 2017.

Publications:

A1. Papers published in journals

1. Y. Saitou, A. A. Samarian, and O. Ishihara, Differential dust disk rotation in a complex plasma with magnetic field, JPS Conference Proceedings **1**, 015012-1~4 (2014).
2. M. Shindo, A. Samarian, and O. Ishihara, Dynamics of Charged Dust near Liquid Helium Surface, JPS Conference Proceedings **1**, 015049-1~4(2014).
3. Y. Saitou and O. Ishihara, Tempest in a Glass Tube - A Helical Vortex Formation in a Complex Plasma, Journal of Plasma Physics **80**, 869-876 (2014).
4. F. Sayed, S. V. Vladimirov, Yu. Tyshetskiy1, and O. Ishihara, Modulational and filamentational instabilities of a monochromatic Langmuir pump wave in quantum plasmas, Physics of Plasmas **22**, 052115.1~8 (2015).
5. F. Sayed, S. Vladimirov, and O. Ishihara, Zakharov equations in quantum dusty plasmas, Physics of Plasmas **22**, 083708-1~4 (2015)
6. S. Vladimirov and O. Ishihara, Electromagnetic band structure due to surface plasmon resonances in a complex plasma, Physical Review E, **94**, 013202- 1~8 (2016).
7. S. Vladimirov and O. Ishihara, Electromagnetic wave scattering and resonances in a complex plasma Advances in Physics: X **2**, 462-480 (2017).

A2. Papers published in rXiv preprint arXiv

1. SV Vladimirov, O Ishihara, Features of electromagnetic waves in a complex plasma due to surface plasmon resonances on macroparticles, rXiv preprint arXiv:1512.09124, 2015.

B. Conference Record

1. O. Ishihara, Vortex formation in a complex plasma, The 40th COSPAR（The Committee on Space Research）, Moscow, Russia, Aug 01-08, 2014.
2. O. Ishihara, Advances in Complex Plasma Research, Plasma Conference 2014 (Invited)（2014. Nov. 18－21, Toki Messe, Niigata）(18aC1-1) (in Japanese)
3. Osamu Ishihara, From Plasma to Complex Plasma, CAP (Canadian Association of Physics) Congress, Edmonton, Alberta, Canada, June 15-19, 2015 (Invited Talk)
4. O. Ishihara, Electromagnetic Wave Propagation in a Complex Plasma, International Symposium on Plasma Science and Technology, " Measurement, Analysis and Control of Plasma in a Form of Ordered Structure", Aug. 26, 2016, Kyoto Institute of Technology (Invited Talk).
5. O. Ishihara, Novel Features in Complex Plasmas, 2016 Plasma & Electro-Energetic Physics Annual Program Review, Basic Research Innovation and Collaboration Center, Arlington VA USA, November 29-30, 2016.
6. O. Ishihara, Role of Complex Plasma for Emerging Sciences, 9th International Symposium on Advanced Plasma Science and its Applications for Nitrides and Nanomaterials (Chubu University, Kasugai, Japan) March 1-5, 2017（Plenary Talk）.