

A COMPUTER EXPERIMENT TO STUDY THE CHARGING PROCESS FOR DUST GRAINS IN THE PLASMA

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Abstract

Dust grain in plasma is charged up by collecting electrons and ions from the plasma, this charging process has been studied for laboratory dusty plasma. The Orbital Motion Limited theory predicts the electron and ion currents toward the grain, the discrete charging model uses these current values and converts it to probabilities for collecting individual electrons and ions, this model assumed that discrete charges will be collected at random intervals in a random sequence.

A program with FORTRAN programming language has been built to translate the discrete model to simulate the charging process. Then, the value of the charge number and their fluctuations as a function of time, charging time and mean equilibrium charge number on the grain surface have been predicted. It has been concluded that the grains were charged with negative and the charging process, in general, was affected by grain size, electron temperature, and the background plasma type.

تجربة حاسوبية لدراسة عملية شحن الحبيبات الغبارية في البلازما

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الخلاصة

تشحن الحبيبة الغبارية، بجمع الكترولونات وايونات من البلازما التي تحويها. وبهذا البحث، درست عملية شحن هذه الحبيبات في البلازما المغيرة التي تنتج في المختبرات باستخدام نموذج الشحن المنفصل، الذي يعتمد نظرية الحركة المدارية المحددة في ايجاد التيارات الالكترونية والايونية التي تصل سطح الحبيبة الغبارية ، حيث يتم ، بواسطة هذا النموذج ، تحويل هذه التيارات الى احتماليات لجمع الشحنات المنفردة من الالكترونات والايونات، وقد افترض هذا النموذج ان الشحنات تصل الى سطح الحبيبة بفواصل زمنية عشوائية ويتتابع (الكترولون- ايون) عشوائي ايضا.

وفي هذه الدراسة، تم بناء برنامج بلغة فورتران لترجمة النموذج المذكور الى تجربة حاسوبية لمحاكاة عملية الشحن لايجاد مقدار الشحنة وتقلبات هذا المقدار على سطح الحبيبة مع مرور زمن التجربة، وكذلك زمن الشحن و معدل شحنة التوازن. ووُجد، من التجربة ان الحبيبة الغبارية تشحن بشحنة سالبة وان عملية الشحن عموماً تتأثر بحجم الجسيمة ودرجة حرارة الالكترونات وكذلك نوع البلازما التي تحوي الحبيبة.

Introduction

Dust is found everywhere throughout the universe and much of the solid part of universe is in the form of dust. Therefore, plasmas and dust are the two main ingredients of the space. The interplay between both has opened up a new and great research domain, that of dusty plasma. Dusty plasma defined as gas plasma consisting of electrons, ions and neutral atoms that additionally contains microscopic dust grains with sizes ranging from 10 nm to some 100 μm [1]. It is found in various space environments as well as laboratory devices and industrial processes. In space, it is found in the interplanetary medium, interstellar clouds, comet tails, and the ring systems of the giant planets as well as in mesospheric noctilucent clouds [2]. As a result, the physics underlying the manner in which dust grains interact with one another and their plasma environment is a field of research having broad implications depending on our understanding of the development of astrophysical systems. The presence of dusty plasmas in space can be considered as a starting point for the understanding of the laboratory dusty plasmas, which can be studied by injection of spherical micron sized grains in noble gas plasmas [3]. It's present or occurred in the laboratory devices, particularly in direct current (DC), radio frequency (RF) discharges, plasma processing reactors and fusion plasma devices. Most ordinary plasmas in space and laboratory are weakly coupled, but strongly coupled dusty plasma can be produced in which the negative charge is so large that the interaction energy of nearest neighbors exceeds their thermal energy, so the suspended dust particles can organize themselves to form dust crystals [2, 4]. Weakly and strongly coupled dusty plasma can be decided according to Coulomb coupling parameter Γ . This parameter represents the ratio of electrostatic potential energy to the particle kinetic energy. The dusty plasma is strongly coupled when $\Gamma \gg 1$, and plasma is strongly coupled when $\Gamma \gg 1$, and order structures, known as plasma crystals, may form, or weakly coupled when $\Gamma \ll 1$ [5, 6].

In the last few years, industrial plasma processing researchers have discovered that dust grains suspended in plasmas are a major cause of costly wafer contamination during semiconductor manufacturing. It was found that the plasmas used for deposition and etching can grow particles in the gas phase, or they can

release them from vacuum vessel walls. The dust grains become charged in the plasmas, and they levitate above the wafers, until the critical moment comes, when the plasma is switched off, and they fall on the substrate. Much effort has been made to understand particle growth, charging of the dust, levitation and transport in order to devise schemes aimed to avoid contamination. Any dust grain generated or immersed in the plasma tends to acquire an electric charge and hence responds to electric forces; it was charged by collection of plasma electrons and ions as well as by photo or secondary electron emissions. In laboratory plasmas usually the collection processes dominate and the particles attain a high negative charge. But in space, photoemission and secondary electron emission become more important and they either reduced the negative charge or even lead to positively charged particles [2]. Since the collection charging process depends on the particle's surface potential relative to the plasma potential, then the dust particles do not charged to a fixed value, but it would be fluctuate. These fluctuations can be characterized by charge distribution function [7,8]. Calculation of charge on a particle is the starting point of every theory of dusty plasmas, and it's important to study the charging of particles because it is necessary in determining or predicting most of the plasma properties. The often applied charging theory for particles is the "orbital motion limited" theory (OML) [9].

Orbital Motion Limited Theory (OML)

Dust particles in plasma behave as a microscopic probe. So, the general aspects of probe theory are important for dusty plasmas. The traditional method used to determine the charge acquired by a dust particle in plasma is the orbital motion limited theory (OML), which was originated from probe theory [9]. The charge and potential of a dust grain immersed in plasma are determined by the balance between the electron and ion current towards the dust particles surface. These currents are predicted by the OML currents, when the condition $a \ll \lambda_D \ll \lambda_{\text{mfp}}$ applies, where a is the particle radius, λ_D is the Debye length and λ_{mfp} is a collision mean free path between neutral gas atoms and either electrons or ions. In this case, the currents are calculated by assuming that the electrons and ions are collected if their collisionless orbits intersect the grains surface [10, 11].

The OML theory is a relatively simple and widely used theory for the charging of dust grains in plasma, it has been developed for Langmuir probes. It considers a spherical grain with radius a , which is smaller than the Debye Length λ_D , (i.e. it considers a thick sheath around the grain $a \ll \lambda_D$). The electron density around the dust grain is given by the Boltzmann distribution

$$n_e = n \exp[e\phi(r) / K T_e] \dots\dots\dots (1)$$

Where n is the plasma density, e the electron charge, $\phi(r)$ the electric potential of a distance r and $K T_e$ is the electron thermal energy. Bernstein and Rabinowitz have developed a theory in the case of monoenergetic ions. Laframboise had enhanced it for the case of Maxwellian distribution function for the ions. As the dust grain is negatively charged, the ions are attracted by it. An ion would be collected, if its trajectory reaches the surface of the dust grain. It is assumed that the sheath around the dust grain is collisionless, (i.e. the ions do not undergo collisions in it), $\lambda_D \ll \lambda_{mfp}$. The cross-section for ion collection by the dust grain is defined via the critical parameter as follows [12]:

$$\sigma_{coll} = \pi a^2 [1 - e\phi/E_0] \dots\dots\dots (2)$$

Where

$$E_0 = m_i v^2 / 2 = m_i v D^2 / 2 + e\phi_s \dots\dots\dots (3)$$

Assuming a mono energetic ion stream, the ion current, I_i , be:

$$I_i = env\sigma_{coll} = \pi a^2 n_e (2E_0/m_i)^{1/2} (1 - e\phi_s/E_0) \dots\dots\dots (4)$$

Where the grain have a potential $\phi_s < 0$. In the same manner the electron current can be determined. However the electrons need to overcome the potential barrier $e\phi_s$, and thus only electrons with a higher energy will reach the grain and the other electrons will be deflected. For a Maxwellian energy distribution of the ions, the ions and electrons currents have similar form [7,8,10]:

$$I_e = I_{0e} \exp(e\phi_s / K T_e) \quad \phi_s < 0 \dots\dots\dots (5)$$

$$I_e = I_{0e} (1 + e\phi_s / K T_e) \quad \phi_s > 0 \dots\dots\dots (6)$$

$$I_i = I_{0i} \exp(-z_i e\phi_s / K T_i) \quad \phi_s > 0 \dots\dots\dots (7)$$

$$I_i = I_{0i} (1 - z_i e\phi_s / K T_i) \quad \phi_s < 0 \dots\dots\dots (8)$$

Where:

$$I_{0j} = 4\pi a^2 n_j q_j (K_B T_j / 2\pi m_j)^{1/2} \dots\dots\dots (9)$$

Where j is an ion or an electron. The charge Q is

related to the grain's surface potential ϕ_s , respect to the plasma potential of zero, [7,8,13,14] by

$$Q = C_d \phi_s \dots\dots\dots (10)$$

Where C_d is the capacitance of the grain in the plasma, for a spherical grain satisfying $a \ll \lambda_D$ the capacitance is:

$$C_d = 4\pi\epsilon_0 a \dots\dots\dots (11)$$

Many dust grains are non-spherical, so the assumption of a spherical shape limits the validity of the theory if the case $a \ll \lambda_D$ is treated. The electrostatic equipotentials can be distorted from spherical shape only within a radius $a \ll \lambda_D$. Therefore the spherical assumption introduces only a small error as long as $a \ll \lambda_D$, as it is in many dusty plasmas [8].

Modeling of the charging process

Charging processes have been studied intensively by many researchers; most of them have used the familiar continuous charging model which assumes that the charge on the grain is determined by currents collected from plasma and ignored the discrete nature of the charge carriers so the currents are treated as if they are continuous in time. A dust grain with zero charge that is immersed in plasma will gradually charge up by collecting electrons and ions.

The Discrete Charging Model studied the charging process of a dust grain due to collecting discrete charge carriers, and it assumes the fact that the electron and ion currents collected by the dust grain actually consist of individual electrons and ions. The charge on the particle is an integer multiple of the electron charge, $Q = Ne$ where N changes by -1 when an electron is collected and by Z_i when an ion is collected. The collection of this charge Q has been done using the currents predicted by the Orbital Motion Limited Theory to find the probabilities per unit time of collecting an electron or ion.

The model has described the charging process of an isolated dust grain immersed in plasma. Spherical grain with radius, a , which initially uncharged under the condition $a \ll \lambda_D \ll \lambda_{mfp}$. This model is characterized by:

1. It is based on the assumption that the plasma particles arrive at random time intervals Δt_j , which is not fixed.
2. The probabilities of arriving electrons and ions depend on the surface potential of the dust grain.

3. The total probability, per unit time of collecting plasma particle, depends on grain surface potential and on the charge Q and It is given as [7]:

$$P_{tot} = \sum P_j \dots\dots\dots (12)$$

Where j means electron or ion, and

$$P_j = I_j / q_j \dots\dots\dots (13)$$

4. The time interval Δt_j depends on the potential of the grain ϕ_s and the random number R_1 , where $0 \leq R_1 \leq 1$ that we generated.

5. The model assumes that plasma particles arrive in a random sequence in consistent with the probabilities.

6. To recognize the plasma particle type, it must compare the probability P_j / P_{tot} with another random number R_2 , where $0 < R_2 < 1$.

7. The charge Q_j of the dust grain would be changed after each electron or ion collection, and it is increased by one charge, thus the surface potential and the probabilities per unit time will be increased.

The Computer Simulation

A computer simulation can predict the results faster than setting up of most experiments especially with the aid of new fast computers. Here, we translate the physical idea of the discrete charging model to a computer experiment, which simulates the charging process of a dust grain immersed in plasma.

At first the dust grain would be uncharged so the simulation starts with a zero charge $Q_j = 0$ at a time step equal zero $t_j = 0$ where j refers to plasma particles electron or ion, then two steps will be repeated for each plasma particle which will fall on the grain.

A. The Random Time Intervals

This step is based on the physical idea, which assumes that the plasma particles (electrons and ions) arrive at random time intervals, there will be one time step per particle that is collected and it corresponds to:

$$\Delta t = t_j - t_{j-1} \dots\dots\dots (14)$$

The currents I_e, I_i must be calculated from equations (5-9) that predicted by the OML theory to find the probabilities.

The random time step Δt depends on the probability per unit time of collecting a plasma particle, $P_i(\phi_s), P_e(\phi_s)$ and the total probability is given in equation (12). The probability of collecting a plasma particle is [7]:

$$P = 1 - \exp(-\Delta t \cdot P_{tot}) \dots\dots\dots (15)$$

To calculate the random time interval one must generate a random number R_1 , and equate it to the previous equation of probability to yield:

$$\Delta t_j = -\ln(1 - R_1) / P_{tot} \dots\dots\dots (16)$$

B. Second step of the Experiment

The plasma particle arrives in a random sequence. Generate a random number R_2 to determine whether the next collected particle is an electron or an ion, where $0 < R_2 < 1$. The probability that the next particle is electron or ion will be P_e / P_{tot} and it is compared with R_2 as follows:

1) If $R_2 < P_e / P_{tot}$ then the charge will be $Q_j = Q_{j-1} - e$ that means the process is electron collection.

2) If $R_2 > P_e / P_{tot}$ then the charge will be $Q_j = Q_{j-1} + z_{ie}$ that means the process is ion collection.

The Results

The program has been written with FORTRAN programming language to employ the discrete charging model to study the charging process for a dust grain in dusty plasma. It consists of three subroutines each one gives data outputs that saved at different files, for each parameter, to be plotted later.

This part is devoted to present the results of the experiment. The results presented as the same sequence of the subroutines with grouping them according to the effect of some important parameters (such as grain size, electron temperature and plasma type).

1- Picture of the Charge Fluctuations

The presence of a dust grain in a plasma leads to charging this grain by collecting electrons and ions from the plasma, the charge of grain will be increased gradually with increasing the electron and ion currents that consist of discrete charges. The charge on the grain will reach the equilibrium state in which the charge Q will fluctuate around equilibrium charge $\langle Q \rangle$. Figure (1) Shows the charge number, $N = Q/e$, as a function of the experiment time for a dust grain with radius $a = 10\text{nm}$ immersed in hydrogen (H) plasma of $T_e = 1\text{ eV}$ and $T_i / T_e = 0.05$.

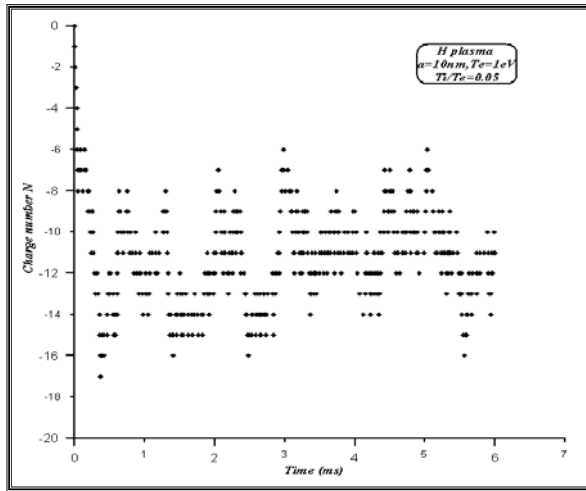


Figure 1: The general picture of the charge fluctuations on the dust grain surface.

Initially, this figure starts with zero charge since the grain is uncharged, and in early parts of it for $t < 0.25\text{ms}$ where the charge has not yet reached the equilibrium value, the grain mainly collects electrons since $m_e \ll m_i$ and it moved with large thermal energy greater than that of ions, $T_e > T_i$. So the probability for collecting electrons is much greater than that for ions, that means the number of electrons that reach the dust surface are larger than ions. Since the dust collects electrons more than ions, so its surface potential is negative, which increases the probability of collecting ions, $P_i(\phi_s)$, until reaching the equilibrium state in which the probabilities are less unequal. The charge remains fluctuate at random times around a negative equilibrium charge ($\approx -12e$, e is the electron charge) according to the random sequence of arriving plasma particles.

2- Dust Grain Size Effect

The grain size is an important parameter that affects the rate of charge collected by dust grain and its fluctuations. According to equation (11), the relation between the grain radius and charge is linear, so increasing the dust radius (its size) means large surface area exposed to the plasma and more ions and electrons will be collected by the grain.

Figure (2) shows the temporal evolution of charge number for different values of dust grain size with $T_e=1\text{ eV}$ and $T_i/T_e = 0.05$. Very small grain like the first case $a = 1\text{nm}$ will charge up with long charging time (the time of the first reaching to the equilibrium charge) and collecting few charges and the fluctuations around the equilibrium charge, $\langle Q \rangle \approx -1e$, is rather slow.

For larger grain ($a = 20, 40$) it is clear that with increasing the grain size, the dust will be charged with shorter times and more charges will be accumulated on the dust surface and the fluctuations around the equilibrium charge, $\langle Q \rangle \approx -23e$ and $-45e$ respectively, arise with increasing the charge on dust.

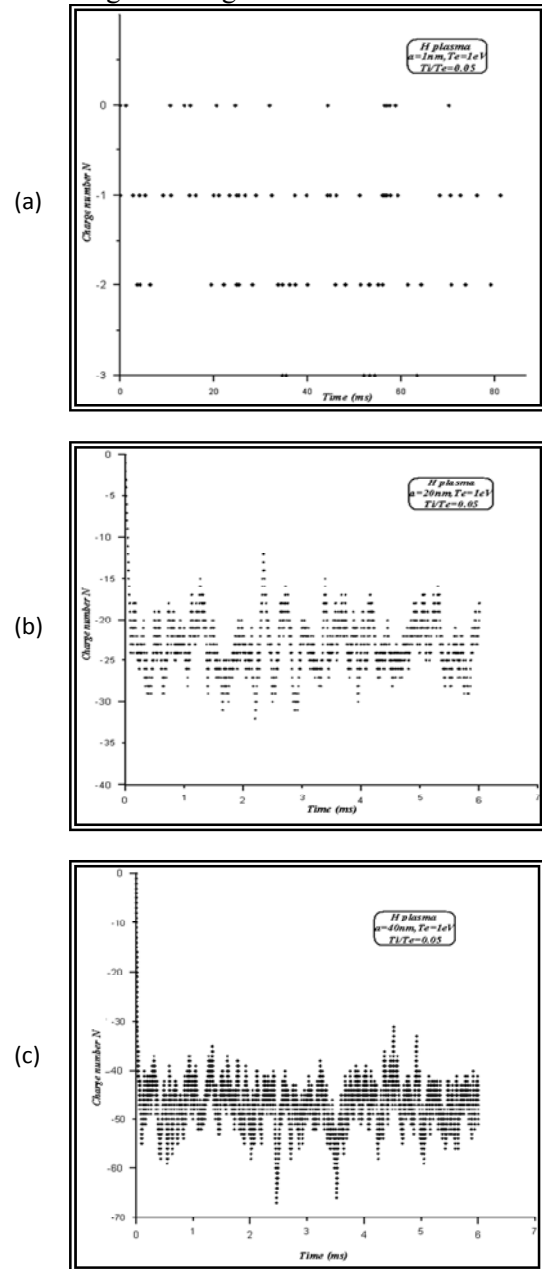


Figure 2: Temporal evolution of charge number for dust grains of radius a)1nm, b)20nm, c) 40nm.

3- Electron Temperature Effect

Another important parameter must be taken into account that is electron temperature T_e . Figure (3) shows the temporal evolution of charge number for $a=10\text{nm}$ and different values of electron temperature T_e with $T_i/T_e=0.05$.

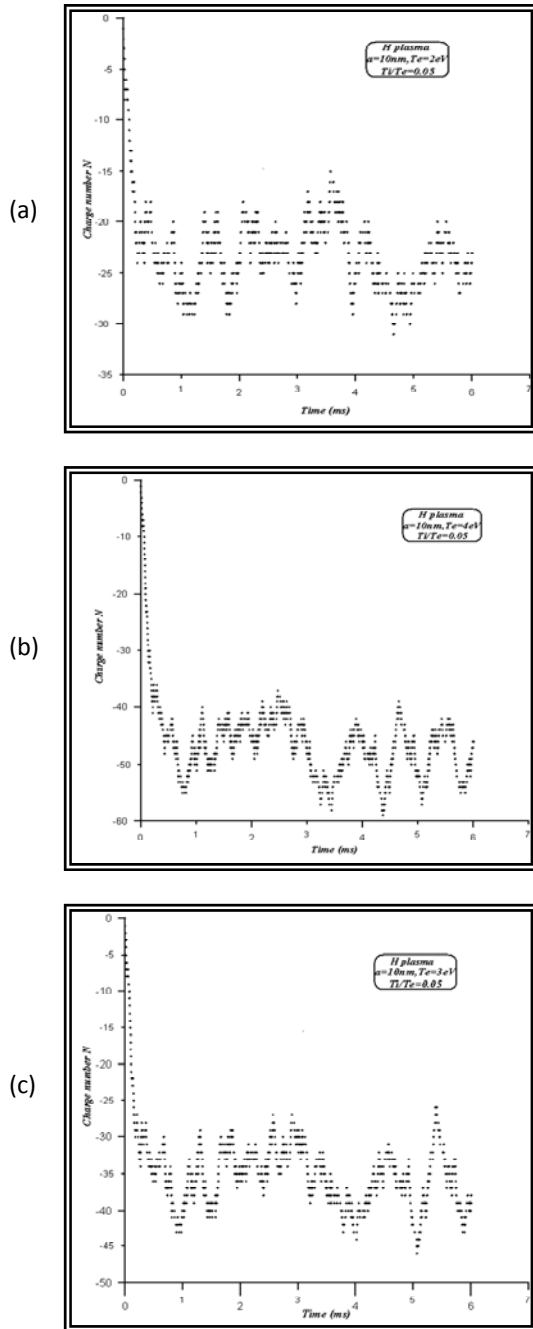


Figure 3: Temporal evolution of charge number for electron temperature of a)2eV, b)3eV, c) 4eV.

For cases of $T_e = 2, 3, 4$ eV, the dust grain collects more charges with increasing T_e since electrons are moved with large thermal energy, KT_e , than ions with, KT_i . So, the probability for collecting electrons is more than for ions and the surface potential of the grain will be negative. Later, the equilibrium charge $\langle Q \rangle$ becomes large with increasing electron temperature. This result is consistent with that obtained by continuous charging model [8].

4- Plasma Type Effect

Figure (4) shows the temporal evolution of charge number, N , for different types of plasmas such as hydrogen H, argon Ar, and neon Ne plasmas.

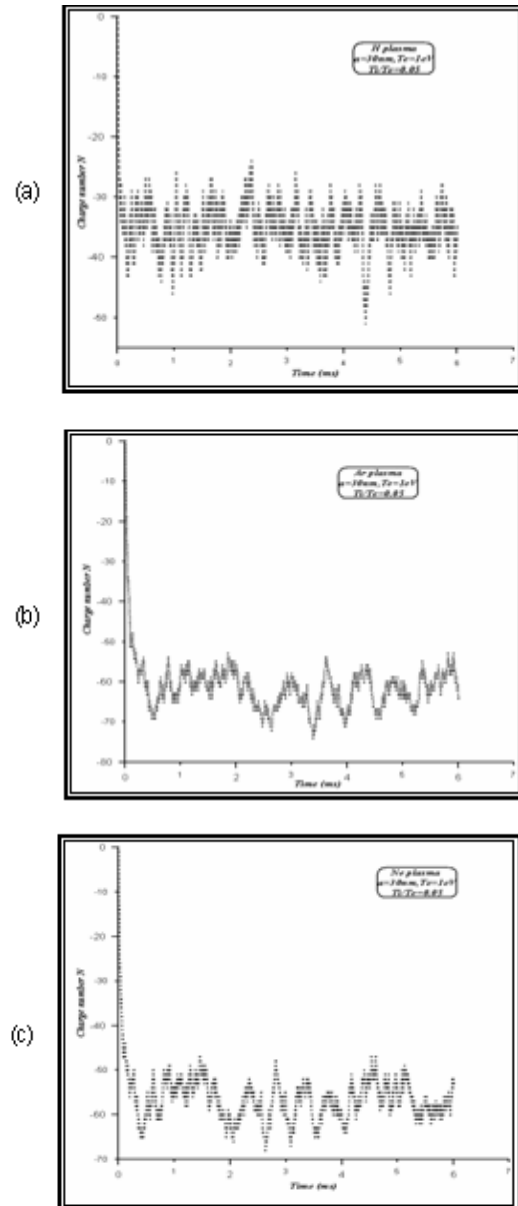


Figure 4: Temporal evolution of charge number for plasma types of a) H, b) Ar, and c) Ne.

The presence of heavy ions in plasma like Ar^+ ($m_i=40amu$) and Ne^+ ($m_i=20amu$), comparing with H^+ ($1amu$) lead to decrease the number of ions arrived to grain surface. So that, the probability of collecting electrons $P_e(\phi_s)$ is more than that of ions, and this makes the dust surface potential negative. Then the probability for collecting ions increases until the dust reach equilibrium state with charge $\langle Q \rangle$, this charge will be larger for each increase in ion mass. In

other words, the grain will collect the greater charge in the plasma of the heavier ions if the other parameters are constant.

Conclusions

The conclusions derived from this work can be summarized as:

- 1) The dust grains are more probably charged with negative charge, because the electrons are lighter than ions, and they have larger thermal energy comparing with the ions.
- 2) The increase of dust grain size leads to decrease in charging time so larger dust grains are charged faster, and collect more electrons and ions than smaller one.
- 3) Dust grain collects more electrons than ions when electron temperature is increased. Since electrons move with thermal energy higher than that for ions, so the dust surface potential will be negative.
- 4) The charge magnitude on the surface of the dust grain depends on the plasma type.

References

1. Goree, J. **1992**. Ion trapping by a charged dust grain in a plasmas. *Physical Review Letter*, **69**:277-280.
2. Piel, A. and Melzer, A. **2002**. Dynamical Processes in Complex Plasmas. *Plasma Physics and Controlled Fusion*, **44**(1):R1-R26.
3. Matsoukas, T. and Rruel, M. **1995**. Particle Charging in Low-Pressure Plasmas. *J. Applied physics*, **77**(9): 4285-4292.
4. Robert, L. M. **2005**. Experimental Investigations of Dusty Plasmas. Proceedings of the fourth International Conference on Physics of Dusty Plasmas .Orleans, 17 June.pp.1-9.
5. Mendis, D.; Shukla, P. K.and Desai, T. **1966**. Physics of dusty plasmas: an historical overview. Proceedings of the International Conference on Physics of Dusty Plasmas. Goa, India, 21–25 October. pp.3-19.
6. Morfill, G. E., Thomas, H. M., and Zuzic, M. **1996**. Plasma Crystals- a review. Proceedings of the International Conference on Physics of Dusty Plasmas. Geoa, India, 21 – 25 October. pp.99-142.
7. Cui, C. and Goree, J. **1994**. Fluctuations of the Charge on a Dust Grain in a Plasma. *IEEE Transaction on Plasma Science*, **22**(2):151- 158.
8. Goree, J. **1994**. Charging of Particles in Plasma. *Plasma Source Sci. and Technol.*, **3**(3):400-406.
9. Allen, J. E. **1992**. Probe Theory-The Orbital Motion Approach. *Physica Scripta*, **45**(5): 497-503.
10. Whipple, E. C. **1981**. Potentials of Surfaces in Space. *Reports on Progress in Physics*, **44**(11):1197-1250.
11. Goertz, C. K. **1989**. Dusty Plasma in the Solar System. *Review of Geophysics*, **27**(2):271-292.
12. Paeva, G. V. **2005**. Sheath Phenomena in Dusty Plasmas. Ph. D. Thesis. Techniquial University Eindhoven, Eindhoven, Bulgaria. pp.19-21.
13. Khrapak, S. A.; Nefedov, A. P.; Petrov, O. F. and Vaulina, O. S. **1999**. Dynamical Properties of random Charge Fluctuations in a Dusty Plasma with Different Charging Mechanisms. *Physical Review E*, **59**(5):17-22.
14. Stefanović, I.; Berndt, J.; Marić, D.; Šamara, V.; Radmilović – Radjenović, M.; Petrović Z. Lj; Kovačević, E. and Winter, J. **2006**. Secondary Electron Emission of Carbonaceous Dust Particles. *Physical Review E*, **74**:0264061-1-026406-11.