A computer experiment to study the charging process of dust grains in negative ion plasma

Thamir H. Khalaf, Zainab A. Fatehi

Department of Physics, College of Science, University of Baghdad, Baghdad, Iraq

Email: thamiralkhazrajy@yahoo.com

Abstract

This work presents a computer studying to simulate the charging process of a dust grain immersed in plasma with negative ions. The study based on the discrete charging model. The model was developed to take into account the effect of negative ions on charging process of dust grain.

The model was translated to a numerical calculation by using computer programs. The program of model has been written with FORTRAN programming language to calculate the charging process for a dust particle in plasma with negative ion, the time distribution of a dust charge, number charge equilibrium and charging time for different value of η_e (ratio of number density of electron to number density of positive ion).

Key words
Dusty Plasma,
Dust charging,
Charging Simulation.

Article info
Received: Apr. 2012
Accepted: May. 2012
Published: Dec. 2012

تجربه حاسوبيه لدراسة عمليه شحن الحبيبات الغبارية في البلازما ذات الايون السالب

ثامر حميد خلف، زينب عبدالله فتحي

قسم الفيزياء، كلية العلوم، جامعة بغداد، بغداد، العراق

الخلاصة

يمثل هذا البحث دراسة حاسوبيه لمحاكاة عمليه شحن الحبيبات الغبارية المغمورة في بلازما تحتوي ايونات سالبه بالاعتماد على موديل رياضي يسمى موديل الشحن المنفصل بعد تطويره ليحتوي تأثير الايون السالب في عمليه شحن الحبيبات الغبارية. وهذا الموديل تم تحويله الى حسابات عدديه باستخدام البرامج الحاسوبية والبرنامج الحاسوبي المستخدم في هذا العمل تم كتابته بلغة الفورتران لبيان عمليه الشحن و زمن توزيع الشحنات وحساب شحنه الحبيبية وزمن الشحن لقيم مختلفة من η_e (نسبه كثافة الالكترونات الى كثافة الايونات الموجبة).

Introduction

A number of theoretical and experimental investigations have carried out for understanding the charging of dust grains in plasma under different conditions [1], the charge on a particle of solid matter immersed in plasma is an unknown parameter, which depends on the size of the particle and the plasma conditions. The charge is not a constant, but can fluctuate randomly, or in response to fluctuations in plasma parameters such as the electron density.

The charging of dust grains in a plasma consisting of positive ions, negative ions and electrons. In typical laboratory plasmas containing electrons and positive ions, dust grains acquire a negative charge. In negative ion plasmas, charging due to the negative ions, in addition to positive ions and electrons.

To estimate the charge of a grain, there are several theoretical models and some experimental methods as well. In general, none of them yields a result with perfect precision. Here we will consider theoretical models of charging, which in general are useful for estimating the charge with an accuracy of about a factor of two. These models will also be useful for gaining a conceptual understanding of how the charge varies with plasma parameters, and how it can vary in time [2].

The understanding of processes like charging and dynamics of dusty particles is necessary for the effective development of technological devices.

This work is a computer experiment to study some parameters which control the charge on a dust grain in negative ion plasma.

Orbital-motion limited theory

The starting point of this theory is a prediction of the electron and ion currents to the probe. The currents are termed "orbit-limited" when the condition $a \ll \lambda_D \ll \lambda_{mfp}$ applies, where a is the particle radius, λ_D is length, and λ_{mfp} is a collisional mean-free-path between neutral gas atoms and either electrons or ions. In that case, the currents are calculated by assuming that the electrons and ions are collected if their collisionless orbits intersect the probe's surface [2, 3].

This work, the charging of dust is investigating in plasma consists of positive ions, electrons and negative ions (for simplicity we refer to this as a negative ion plasma).

Consider an isolated spherical dust grain of radius a introduced into a plasma consisting of electrons of density n_e, singly charged positive ions of density n_+, and singly charged negative ions of density n_-, define

$$\eta_n = \frac{n_-}{n_+} \tag{1}$$

As the fraction of negative ions relative to positive ions, using the charge neutrality condition [5]

$$n_+ = n_e + n_- \tag{2}$$

then

$$\frac{n_e}{n_+} = 1 - \eta_n \tag{3}$$

Analytic models including the OML model typically assume that the particle is spherical, and its surface is an equipotential. In this case, even if the particle is not made of a conductive material, it can be modeled as a capacitor [2]. The charge Q_d is then related to the particle's surface potential as, with respect to a plasma potential of zero, by

$$Q_d = 4\pi\varepsilon_\circ a\phi_s \tag{4}$$

where a is the radius of the dust particle, and ϕ_s is the dust grain surface potential relative to the plasma potential [4].

For the collection of Maxwellian electrons and ions, characterized by temperatures T_e and T_i, the orbit-limited the electron and positive ion currents to the isolated spherical dust grain of radius a are given by:

$$I_e = I_{eo} \times \begin{cases} 1 + \dfrac{e\phi_S}{kT_e} & \phi_s > 0 \\ e^{\frac{e\phi_S}{kT_e}} & \phi_s < 0 \end{cases} \tag{5}$$

$$I_+ = I_{+o} \times \begin{cases} e^{\frac{e\phi_S}{kT_+}} & \phi_s > 0 \\ 1 + \dfrac{e\phi_S}{kT_+} & \phi_s < 0 \end{cases} \tag{6}$$

The negative ion current participates in the charging of a dust grain in plasma is [1]:

$$I_- = I_{-o} \times \begin{cases} 1 + \dfrac{e\phi_S}{kT_-} & \phi_s > 0 \\ e^{\frac{e\phi_S}{kT_-}} & \phi_s < 0 \end{cases} \qquad (7)$$

The coefficients I_{e0}, I_{-o} and I_{+0} represent the current that is collected for $\phi_s = 0$, and are given by [5]:

$$I_{jo} = q_j n_j \left(\frac{kT_j}{m_j}\right)^{\frac{1}{2}} 4\pi a^2 \qquad \dots\dots \quad (8)$$

The temperatures of the positive ions, electrons and negative ions are T_+, T_e and T_-, respectively. n_j is the number density of plasma species j (the positive ions, electrons and negative ions).

The charging model

Continuous charging model neglects the fact that the electron and ion currents collected by the grain actually consist of individual electrons and ions. Therefore, a charging model developed that includes the effect of discrete charges, this model is called discrete charging model. The charge on the grain is an integer multiple of the electron charge, $Q_d = Ne$, where N changes by -1 when an electron is collected and by z_i when an ion is absorbed. Electrons and ions arrive at the particle's surface at random times, like shot noise. The charge on a particle will fluctuate in discrete steps (and at random times) about the steady-state value $\langle Q_d \rangle$ [2, 7].

There are two key aspects of the collection of discrete of plasma particles (we use the term "plasma particle" to refer to either electron or ions).

- First is that the time interval between the absorption of plasma particles varies randomly.
- Second is that the sequence in which electrons and ions arrive at the grain surface is random.

But neither of these is purely random; they obey probabilities that depend on the grain potential ϕ_s.

Let us define $p_e(\phi_s)$ and $p_i(\phi_s)$ as the probability per unit time for absorbing an electron or ion, respectively. As the grain potential becomes more positive, more ions will be repelled and more electrons will be attracted to the grain, so p_i should decrease with ϕ_s and p_e should increase. We calculate $p_j(\phi_s)$ (j refers to the ions or electrons) from the OML currents $I_j(\phi_s)$ [2],

$$p_j = \frac{I_j}{q_j} \qquad (9)$$

This equation is the key to developing the discrete charging model. Basically, it converts the OML currents into probabilities per unit time of collecting particles. This relates the discrete charging model with its probabilities to the continuous charging model with its currents.

The total probability per unit time of collecting plasma particle is [6]

$$p_{tot} = \sum p_j \qquad (10)$$

The currents I_j depend on the grain surface potential ϕ_s, so p_{tot} also depends on ϕ_s and hence on charge Q_d.

This work is considered development for discrete model to include effect of negative ion on the charging process of dust grain in a plasma negative ion instead of plasma, The model will be useful for gaining a conceptual understanding of how the charge varies with plasma negative ion parameters, and how it can vary with time, which in general is useful for estimating the charge of dust grain.

The model has described the charging process of an isolated dust grain immersed in a negative ion plasma and assumed a spherical grain with radius *a* which initially uncharged under the condition

$$a << \lambda_D << \lambda_{mfp}$$

where *a* is the particle radius, λ_d is length, and, λ_{mfp} is a collisional mean-free-path between neutral gas atoms and either electrons or ions in this case.

The Simulation method

Our simulation method converts the physical discrete charging model to program which simulates the charging process of a dust grain immersed in plasma with negative ion.

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

A. First Step: Choose a Random Time Interval

This step is based on the physical discrete charging model, which assumes that the plasma particles arrive at random time intervals, there will be one time step per particle that is collected and it corresponds to:

$$\Delta t_j = t_j - t_{j-1} \qquad (11)$$

The currents I_e, I_- and I_+ must be calculated from Eq.5, Eq.6, and Eq.7 respectively that are predicted by the OML theory to find the probabilities.

The random time step Δt_j depends on the probability per unit time of collecting a plasma particle $[P_e(\phi)]_s)$, $[P_-(\phi)]_s)$, $[P_+(\phi)]_s)$ and the total probability is given in Eq.9.

The probability of collecting a plasma particle is [6]:

$$P = 1 - exp(-\Delta t_j . P_{tot}) \qquad (12)$$

To calculate the random time interval one must generate a random number *R₁* where $0 < R_2 < 1$ and equate it to the previous equation of probability to yield [6]:

$$\Delta t_j = -\frac{\ln(1 - R_1)}{P_{tot}} \qquad (13)$$

B. Second Step: Choose Electron, Negative ion or Positive ion

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 (negative or positive), where $0 < R_2 < 1$.

Probability that the next particle is electron, negative ion or positive ion will be $= p_j / p_{tot}$ and compared with R_2 as follows:

- **i.** 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. However, at state $R_2 > p_e / p_{tot}$ that means process isn't electron collection. The probability of other particle must be examined.
- **ii.** If $R_2 < p_- / p_{tot}$ then the charge will be $Q_j = Q_{j-1} - e\, z_{ni}$ that means the process is negative ion collection.
- **iii.** If $R_2 > p_- / p_{tot}$ then the charge will be $Q_j = Q_{j-1} + e\, z_{pi}$ that means the process is positive ion collection.

The program

The model was translated to a numerical calculation by using computer programs. The program has been written with FORTRAN programming language.

The computer experiment simulates the charging process for a dust grain in negative ion plasma by employing the discrete charging model. The program calculates statistical fluctuations such as the time distribution of a dust charge, number charge equilibrium and charging time for different value of η_e (ratio of number density of electron to number density of positive ion). The flow chart of program is illustrated in Fig.1.

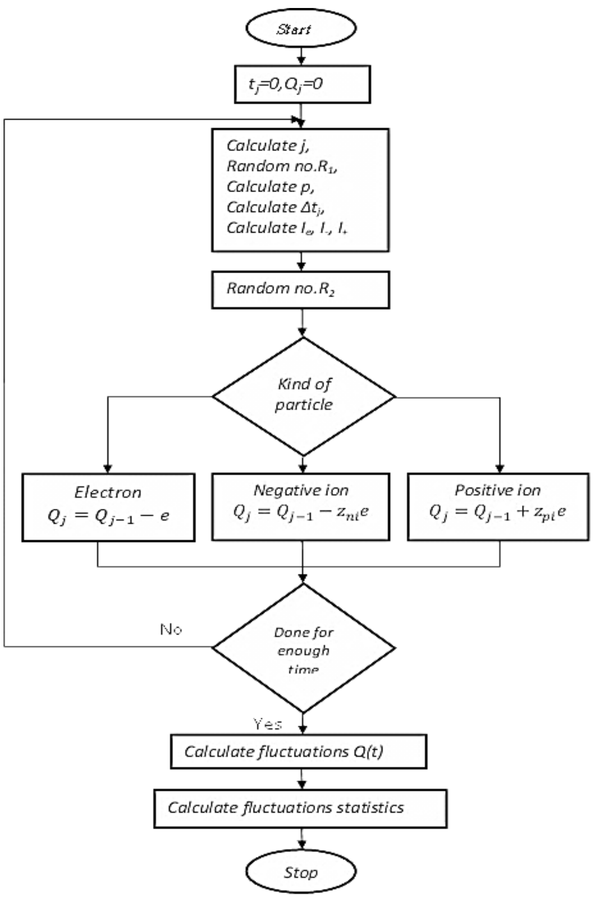

Fig. 1: Flow chart of the program

Results

The results of program are a sequence of the calculations process which is done as the following steps (subroutines):

1. The charge dust grain fluctuations

Calculations show the chraging process for a dust grain with dimeter=0.1µm immersed in K^+ plasma if a significant fraction of the electrons are attached to negative ions; the magnitude of the charge on the dust particles is reduced. If the ratio $\eta_e = n_e/n_+$ of the electron density to positive ion density is sufficiently small and the positive ions are lighter than the negative ions, then the dust charge can be positive. The ions and electrons have equal temperatures T_+ = Te = T_-= 0.2eV.

For comparison purpose, our simulation employed to show the charging process in an electron - K^+ ion plasma. The presence of the dust grain in this plasma (e- K^+ ion) leads to charging the dust negatively because the mobility of electrons larger than mobility of ions .The charge on the grain will reach the equilibrium state in which the charge Q will fluctuate around the equilibrium charge <Q>. Fig.2 shows the chraging process for a dust grain by collecting electrons, and positive ions from plasma with out negative ion,notes that the range of the charg fluctutions between -35 and-20

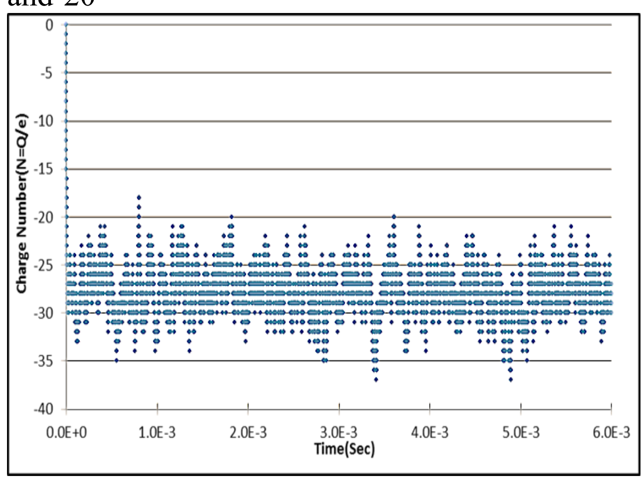

Fig. 2: Charge number on surface grain as a function time when D=0.1µm, η_e =1 (no negative ion)

Negative ion plasma is formed by attachment of electrons on the highly electronegative sulfur hexafluoride SF6 molecule by the reaction

$$e^- + SF_6 \rightarrow SF_6^-$$

When the SF_6 density is added into K^+ plasma, some electrons become attached to form SF_6^- ions and there is a corresponding reduction in the negative current due to the fact that the SF_6^- ions are considerably less mobile than the electrons, Fig.3 shows that the range of the charge fluctutions is between -25 and -5 and the renge drifts toward positive compare with Fig.2.

When the SF_6 density is increased in K^+ plasma, more electrons become attached to form SF_6^- ions and there is a corresponding reduction in the negative current of electrons. Therefore, the negativity of charge number on dust grain decreases gradually. Figs. 4, 5, 6, and 7 show that the range of the charge fluctutions is about (-8 to 4), (-6 to 6), (-2 to 8), and (-2 to10) respectivly.

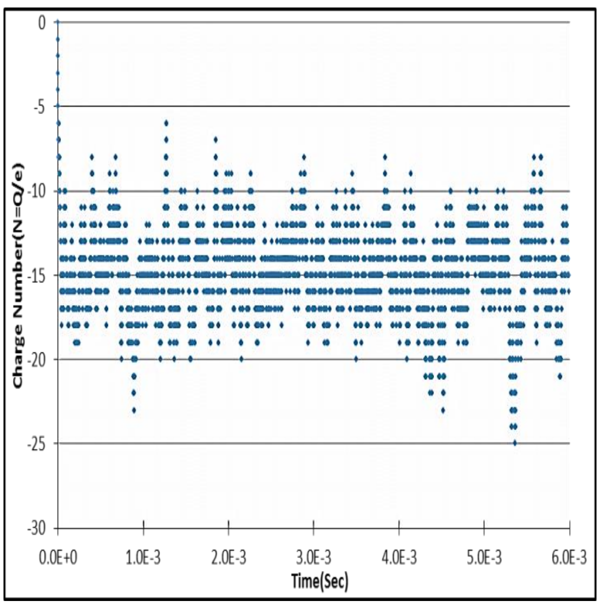

Fig.3: Charge number on surface grain as a function time when D=0.1μm, η_e=10^{-1}.

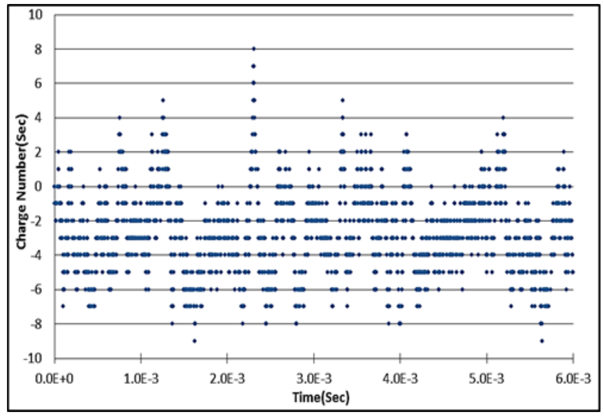

Fig.4: Charge number on surface grain as a function time when D=0.1μm, η_e=10^{-2}.

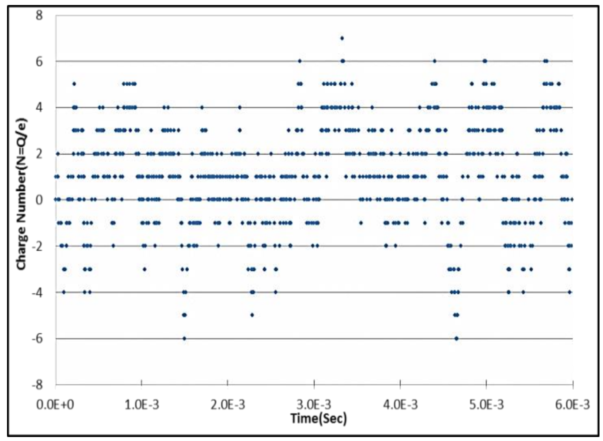

Fig.5: Charge number on surface grain as a function time when D=0.1μm, η_e=10^{-3}

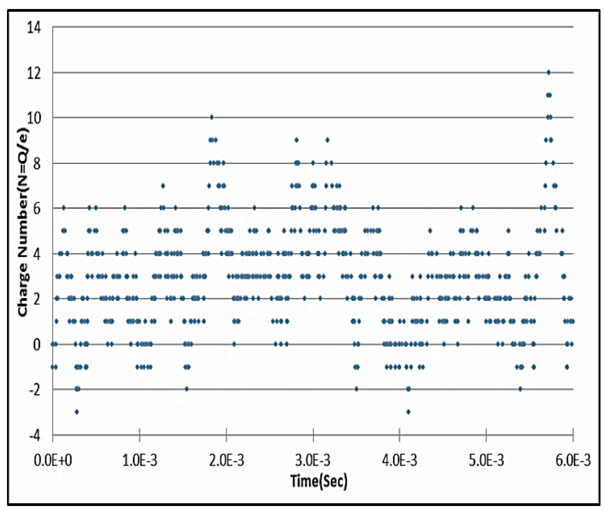

Fig.6: Charge number on surface grain as a function time when D=0.1μm, η_e=10^{-4}.

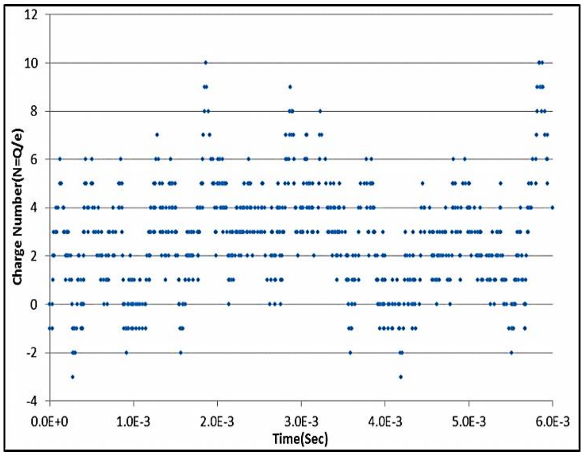

Fig.7: Charge number on surface grain as a function time when D=0.1μm, $\eta_e=10^{-5}$

2. The time distribution of the grain charge

After the collection of charges by dust grain, these charges will approach the equilibrium value <Q> and the probabilities for collecting electrons, negative ions, and positive ions are less unequal so the charge will always fluctuate around the equilibrium value. The charge distributions are determined from the time series by making histogram of time spent at each charge level to calculate charge equilibrium value, the equilibrium charge number takes larger time from computer experiment time. Figs. 8, 9, 10, 11, 12, and 13 show distribution functions for each case in the previous section.

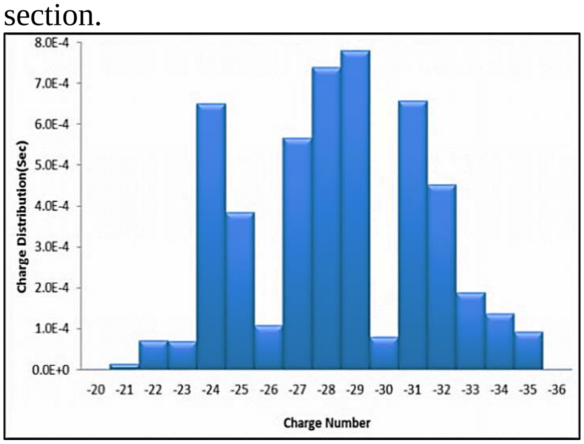

Fig.8: Charge distribution function for grain of D=0.1μm, $\eta_e=1$ (no negative ion). The equilibrium charge number is=-29.

In Fig.8 the chraging process for a dust grain by collecting electrons and positive ions (K^+) from plasma. Ions are much heavier than electrons therefore the dust grain becomes negatively charged. The equilibrium charge number is -29 because this level takes longer time in comparison with other levels.

When the SF_6 density is added into K^+ plasma, some electrons become attached to form SF_6^- ions and $\eta_e=10^{-1}$, the negativity of charge number on dust grain decreases and The equilibrium charge number becomes -12 as shown in Fig.9.

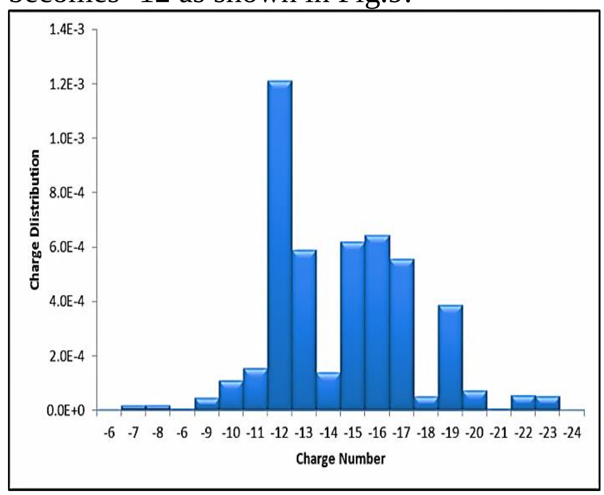

Fig.9: Charge distribution function for grain of D=0.1μm, $\eta_e=10^{-1}$.The equilibrium charge number is=-12.

If the SF_6 density is increased in K^+ plasma so as to $\eta_e=10^{-2}$, the equilibrium charge number becomes -1 (Fig.10).

In the state, the ratio of number density of electrons to number density of positive ions equals 10^{-3} , the charge number on dust grain becomes positive and equals one that means the positive current dominates on charging process of dust grain because the positive ions are lighter than the negative ions and number density of electrons is sufficiently small, Fig.11.

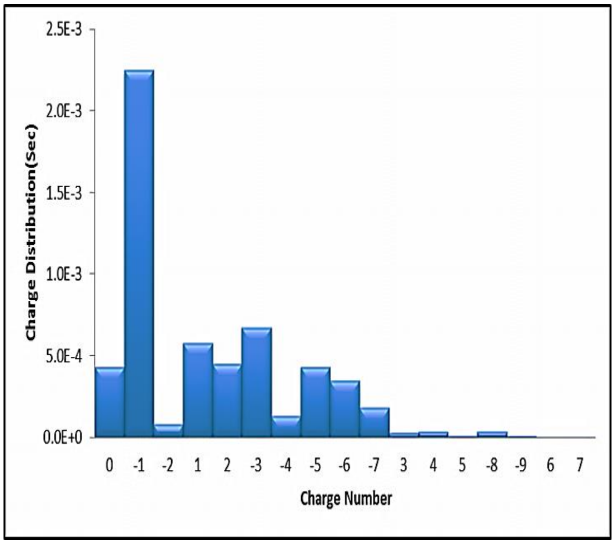

Fig.10: Charge distribution function for grain of D=0.1µm, η_e =10^{-2}.The equilibrium charge number is= -1.

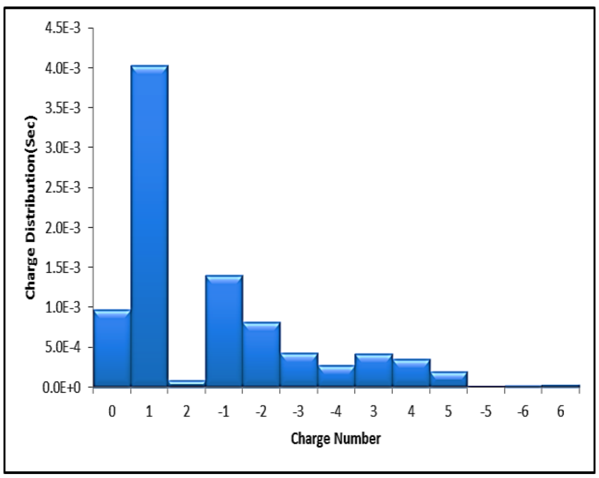

Fig.11: Charge distribution function for grain of D=0.1µm, η_e =10^{-3}.The equilibrium charge number is= 1.

The positive ions on dust grain increase whenever, the ratio of number density of electron to number density of positive ion is decrease. Fig. 12 shows that charge number equilibrium becomes three when the ratio of number density of electron to number density of positive ion (η_e) equals 10^{-4}. While Fig.13 shows the charge number equilibrium remains constant when the ratio of number density of electron to number density of positive ion (η_e) equals 10^{-5} because the effect of electron is neglected.

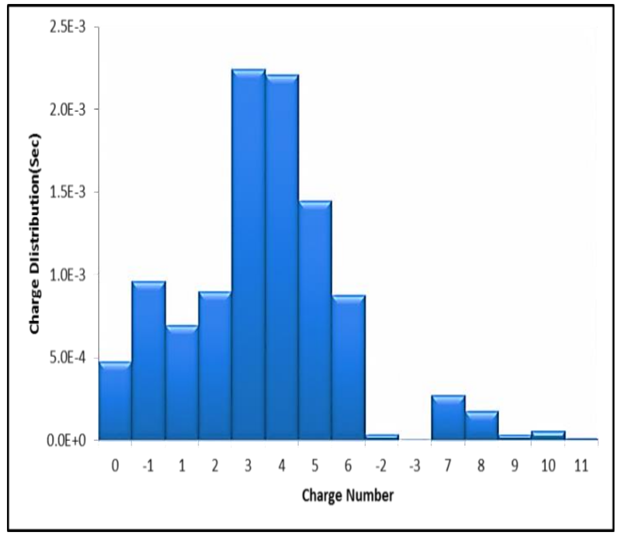

Fig.12: Charge distribution function for grain of D=0.1µm, η_e =10^{-4}.The equilibrium charge number is= 3.

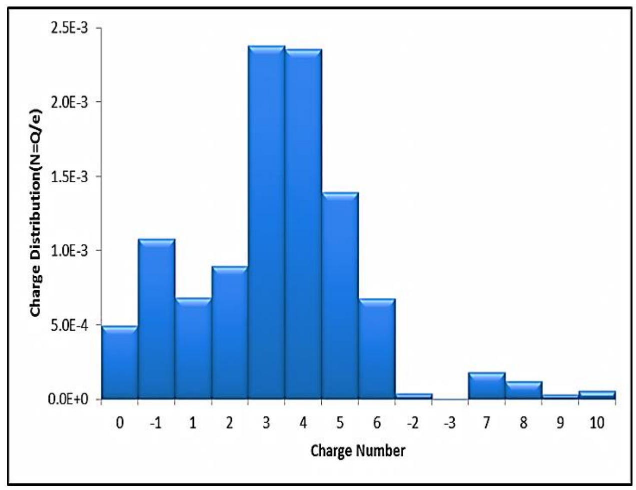

Fig.13: Charge distribution function for grain of D=0.1µm, η_e =10^{-5}.The equilibrium charge number is= 3.

3. The equilibrium charge number

A plot of the equilibrium charge number on dust (N) as a function of the ratio n_e/n_+ for the case in which the positive ion is potassium K^+ and the negative ion is SF_6^- shown in Fig. 14 for dust grain diameter equals 0.1µm. Notice that the charge on the dust is reduced, and the dust surface charge can be positive.

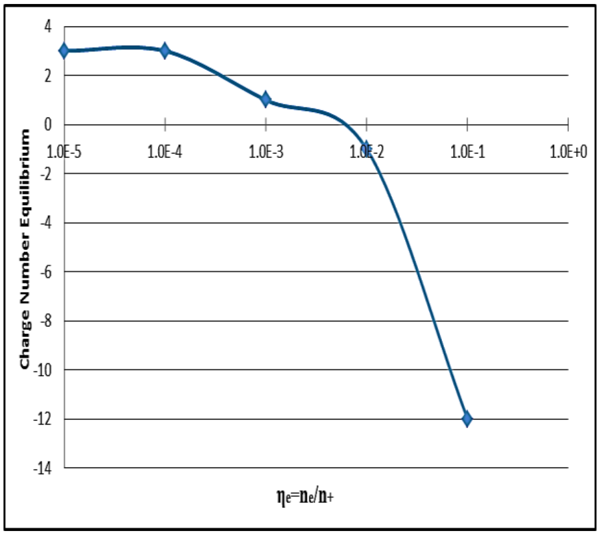

Fig.14: the equilibrium charge Number grain as a function of the parameter η_e when D=0.1µm.

4. The dust surface potential

When the dust is charged by the collection of the plasma particles flowing onto its surface, it acquires surface potential, this potential depends on the charge that acquired by grain surface. The dust surface potential (Φ_s) is plotted as a function of the parameter n_e/n_+ for the case in which the positive ion is potassium K^+ and the negative ion is SF_6^- as shown in Fig.15.

Notice that the positive ion is the lighter species. Thus in the presence of a heavy (compared to the positive ion) negative ion, the charge on the dust is reduced, and the dust surface potential can be positive. The positive ion, negative ion, and electron are at the same temperatures which are equal to 0.2eV. These results are in agreement with experimental results of Robert Merlino et.al [4].

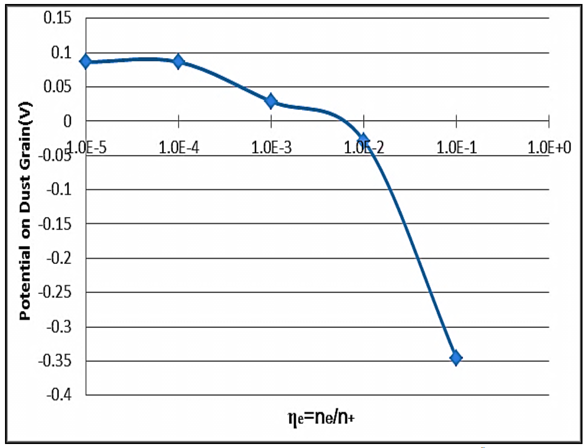

Fig.15: The dust surface potential Φ_s as a function for the fractional concentration of electrons in the plasma. $T_+ = T_e = T_-$.

5. The charging time

Fig.16 illustrates charging time of grain as a function of ηe. The results show that charging time decreases when the number density of electrons reduces from $\eta_e = 10^{-1}$ to 10^{-2} because the negativity of equilibrium charge on dust grain decreases gradually. Therefore, the time needed to reach charge number equilibrium decreases to equilibrium charge become-1. Therefore, the charging time is trivial when the η_e equals 10^{-2}.

When the η_e equals 10^{-3}, the positive ions current dominates on charging process of dust grain. So that, the equilibrium charge becomes positive but little value and equals one so that, the charging time is trivial.

Whenever the positivity of equilibrium charge on dust grain increases gradually, the charging time also increases as from $\eta_e = 10^{-3}$ to 10^{-4}. But from $\eta_e = 10^{-4}$ to 10^{-5} the charging time is constant because the charge number equilibrium is constant.

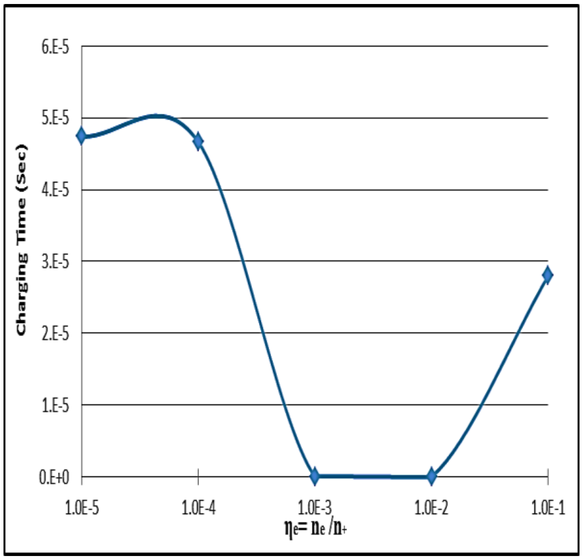

Fig. 16: The charging time as a function of the parameter η_e when D=0.1µm.

Conclusions

The charging of dust grains in negative ion plasma can be controlled by varying the relative fraction of negative ions in the plasma. As the negative ion density increases, the magnitude of the negative dust charge is reduced and a transition to positively charged dust.

The charging time of grain is inversely proportional to the absolute value of equilibrium charge number.

References

[1] A. A. Mamun and P. K. Shukla, Phys. Plasmas, 10 (2003) 5.

[2] A. Melzer, and J. Goree, "6 Fundamentals of Dusty Plasmas", WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim, Germany (2008).

[3] M. Schwabe, "Microparticles as Probes in a Highly Magnetized Dusty Plasma", Thesis in Technische Universität München (2006).

[4] S.-H. Kim and R. L. Merlino, Phys. Plasmas, 13 (2006) 52118.

[5] R. L. Merlino, and S. -H. Kim, Appl. Phys. Lett., 89, 091501, (2006) 1-3.

[6] C. Cui and J. Goree, IEEE Transactions on Plasma Science, 22, 2 (1994) 151-158.

[7] S. J. Choi, and M. J. Kushner, IEEE Transactions on Plasma Science, 22, 2 (1994) 138-150.