Charging Behavior of Dust Aggregates in a Cosmic Plasma Environment

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***Abstract*—In a complex plasma that is subject to UV radiation from a nearby star, the charging behavior of dust aggregates can differ from the expected norm. Using a modified OML theory, these charging conditions can be modeled for dust aggregates of different shapes and sizes. In this case, not only is a positive charge equilibrium common, but some aggregates will exhibit a mixed charging history, wherein the beginning of their charging history is positive and the latter part is negative.**

***Index Terms*—Aggregates, Coagulation, Dusty plasmas, Electromagnetic radiation**

I. INTRODUCTION

The behavior of a charged dust aggregate in a plasma is an essential component to understanding the formation and growth of dust aggregates in protoplanetary disks. Numerous studies have shown that the growth patterns of charged dust aggregates are significantly different from those of their neutral counterparts [1, 6].

In some cases, dust aggregates charged in a plasma environment that includes UV radiation can exhibit a mixed charging history. These aggregates which exhibit the "flip-flop" are positive for the beginning of their charging history, but negative for the latter part. This effect is similar to the "flip-flop" discussed by Meyer-Vernet [2]. Meyer-Vernet found that, for single dust grains in a cosmic plasma environment, the electric potential could spike at the beginning of the history and then level off to some lower value. He termed this phenomenon the "flip-flop," and it is the term we have adopted to describe the similar effect in the charge of dust aggregates.

Dust grains in complex plasmas may become charged by multiple phenomena; they become more negatively charged by the impact of electrons from a plasma, and they become more positively charged through similar impacts of positive ions from a plasma. Because electrons have much less mass than the positive ions in the plasma, they move with a greater velocity, and impact the dust grains much more frequently. In an isolated environment, dust grains generally reach a negative equilibrium charge, due to this difference in impact frequency.

When there is UV emission from a nearby star, the charging process evolves. Incident UV rays can excite electrons already in captured by a dust grain. These electrons are emitted from the grain; therefore, this process is a source of positive electric current to the grain.

For some aggregates, an electron that is ejected due to UV excitation will not always leave the aggregate. If an electron is ejected from a monomer along a path that collides with another monomer, the electron can be "recaptured" by the other monomer within the aggregate. Thus, the overall charge of the aggregate does not change with the emission of this electron.

This study employs the 3-D numerical model presented by Matthews, Land, and Hyde [1]. The model uses Orbital Motion Limited theory, which assumes that electrons or ions that fall into an orbital path around a dust grain contribute to that grain's charge as though the electrons had stuck in the surface of the grain. The model also calculates a Line of Sight factor for each monomer in an aggregate. If any electron is ejected along a path that is not a "free" line of sight, the charge remains in the aggregate.

II. METHODS

This study was conducted using a combination of Orbital Motion Limited theory with a Line of Sight adjustment. OML theory assumes that ions and electrons trapped in orbit about a dust grain are removed from the background Maxwellian distribution of the plasma. However, the calculation becomes more complicated for non-spherical species, namely, dust aggregates. For this reason, the incorporation of the LOS factor is necessary to determine which portions of an aggregate's surface are exposed.

A. OML Theory

The equilibrium charge to a dust grain is reached once the sum of electric currents to the grain is equal to zero. The current density to a grain as a result of a specific plasma species α is given by

$$J = n_{\alpha\infty} q_\alpha \int f v \cos\theta \, d^3\vec{v} \qquad (1)$$

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where $n_{\alpha\infty}$is the number density outside the dust grain's potential well of the plasma species α, q_α is the charge on the plasma species α, f is the distribution function given below (2), and θ is the angle between the path of the plasma species and the dust grain surface. The integration is carried out over the velocity space $d^3\vec{v}$ for all orbits that intersect the grain surface for the first time.

We assume a Maxwellian distribution for the plasma, so the distribution function is given by

$$f = \left(\frac{m_\alpha}{2\pi k T_\alpha}\right)^{\frac{3}{2}} \exp\left(-\frac{m_\alpha}{2kT_\alpha} v^2 - \frac{q_\alpha \varphi}{kT_\alpha}\right) \tag{2}$$

where m_α and T_α are the mass and temperature of the plasma species α, respectively; k is Boltzmann's constant; and φ is the potential of the dust grain.

We can use the substitution

$$d^3\vec{v} = v^2 d^2\omega \, dv \tag{3}$$

where $d^2\omega$ is the differential solid angle. Using this method, we can separate the integration over the velocity from the integration over the angles [7].

B. *LOS Factor*

The Line of Sight (LOS) factor is used to determine which orbital paths are unobstructed on the surface of an aggregate. In this approximation, the flux to a specific monomer for an impinging electron or ion is discounted when its "line of sight" to the grain is blocked by another grain within the aggregate. In this case, the electron or ion is captured by the blocking grain.

The flux to the aggregate for electrons being emitted along blocked lines of sight is discounted entirely, though the flux on an individual monomer may change. These blocked lines of sight are excluded from the integration discussed above by replacing the factor $d^2\omega$ with the LOS factor, which is calculated individually for each monomer within the aggregate [7].

This method operates under the assumption that electrons and ions approach a dust aggregate along a straight path from infinity. In most cases, this is fairly accurate. However, when a dust aggregate become highly charged, the paths of the charged particles can be curved significantly, and the model is less accurate.

C. *Compactness Factor*

The "fluffiness" of an aggregate can be described in multiple ways. One parameter is fractal dimension, in which the mass of the aggregate contained within a radius *r* is plotted log-log against *r*. The fractal dimension is the slope of the best-fit line for this plot [3]. However, this method has largely been replaced in favor of a simpler method.

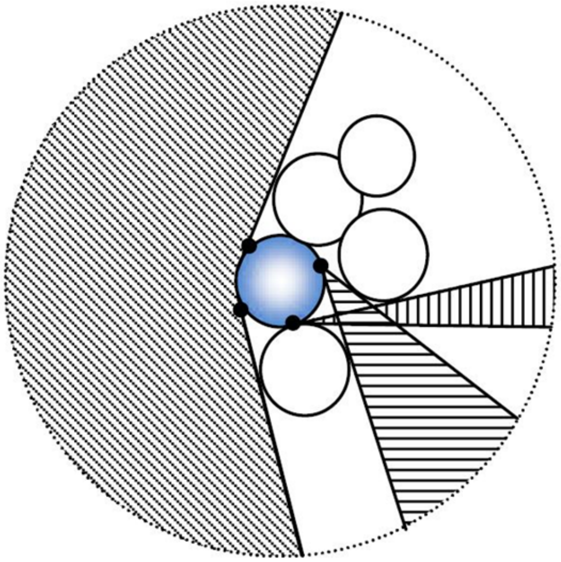

Fig. 1. The LOS factor is calculated by finding the paths to the monomer's surface which are unblocked. For the four test points on the blue-shaded monomer depicted in the 2-D cross-section, an ion or electron would have to be ejected along one of the gray-shaded paths in order to leave the dust aggregate.

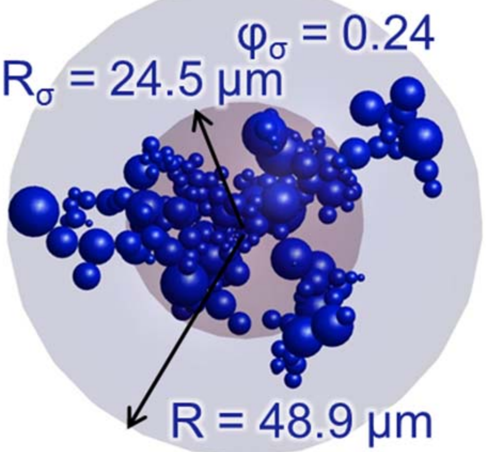

Fig. 2. The compactness factor of a dust aggregate is determined by the ratio of the actual volume of the aggregate to the volume of an equivalent sphere. The equivalent sphere's radius is the average radius of the projected cross-sections of the aggregate.

The most effective way to describe the "fluffiness" or "openness" of a dust aggregate is the compactness factor, φ_σ. To calculate this parameter, a dust aggregate is projected repeatedly onto a surface, and the average radius of these projections is taken. This average radius, R_σ, is used to create a sphere with said radius. Finally, the compactness factor is calculated using the ratio of the actual volume of the dust aggregate versus the volume of the previously calculated sphere [7].

$$\varphi_\sigma = \frac{\sum r_i^3}{R_\sigma^3} \qquad (4)$$

For a perfectly compact aggregate (a single sphere) the compactness factor is 1, so for more compact aggregates, the compactness factor approaches 1. Conversely, for “fluffier” aggregates, the compactness factor approaches zero [3, 4].

D. *Variation of Parameters*

Several hundred unique aggregates were charged under the conditions found in a hydrogen plasma at 1 AU. The aggregate library used was made up of polydisperse spherical monomers. Many of these aggregates would begin their history with a positive charge, even though they eventually became negative. This effect is similar to the “flip-flop” discussed by Meyer-Vernet [2]. Meyer-Vernet found that the electric potential of single dust grains in a plasma environment can spike at the beginning of its history, which he termed the “flip-flop” of the electric potential. One hypothesis for the explanation of this phenomenon in dust aggregates is the “recapturing” of electrons that are emitted along blocked lines of sight. A complicating factor such as this could increase the time it takes for the current to the aggregate to reach equilibrium and therefore could cause the charging history to reverse.

Over 500 aggregates were studied. The aggregates studied range in size from 2-20 monomers, and the compactness factors range from 0.4569-0.9880. The aggregates were charged using the OML_LOS program with a variety of UV photon fluxes. The accepted range of photon fluxes at 1 AU used for this study is 5e12 – 1.5e13 $m^{-2}s^{-1}$ [8]. Each aggregate was charged under seven different fluxes in this range (Table 1). The aggregates were charged for 375 seconds initially, followed by extended charging if the characteristics of the charging history were unclear.

For all aggregates, the plasma density is 6×10^6 m^{-3} and the plasma temperature is 2×10^5 K, conditions which are commonly found at 1 AU [4].

Table 1
Values for Photon Flux

Value
5×10^{12} $m^{-2}s^{-1}$
6×10^{12} $m^{-2}s^{-1}$
7×10^{12} $m^{-2}s^{-1}$
8×10^{12} $m^{-2}s^{-1}$
9×10^{12} $m^{-2}s^{-1}$
1×10^{13} $m^{-2}s^{-1}$
1.5×10^{13} $m^{-2}s^{-1}$

The aggregates included in the study where charged seven times, using the above values for the photon flux of the UV radiation.

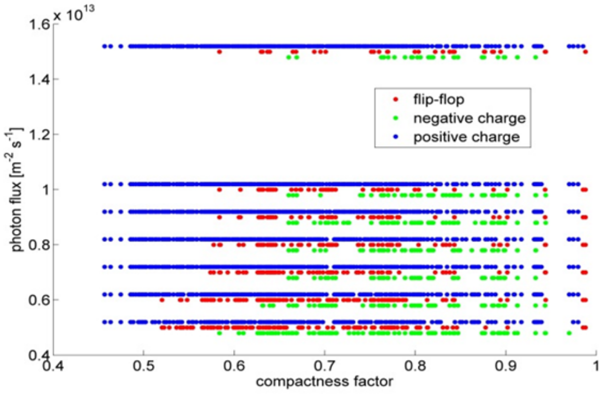

Fig. 3. The aggregates charged are separated by charging history, offset in the y-direction. The photon flux of the UV radiation is plotted against the compactness factor of the individual aggregate.

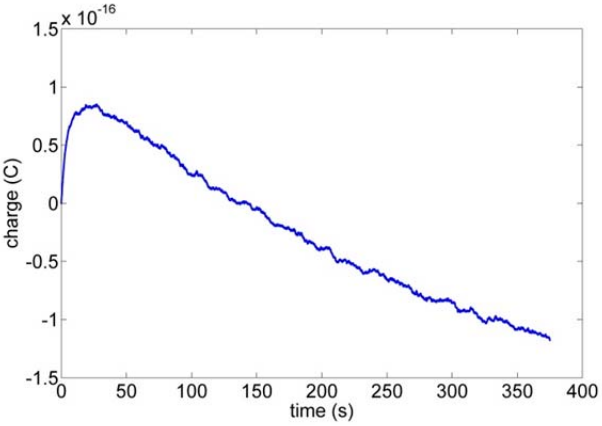

Fig. 4. The charging history for this aggregate of size 15 monomers and compactness factor 0.5823 exhibits the flip-flop effect. The photon flux of the UV radiation is 5×10^{12} $m^{-2}s^{-1}$

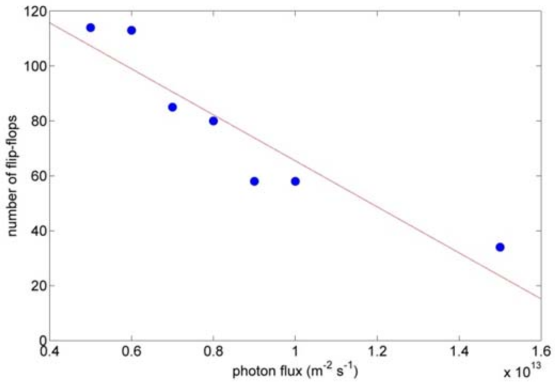

Fig. 5. The frequency of the flip-flop effect demonstrates a negative relationship with the photon flux of the UV radiation.

III. RESULTS AND DISCUSSION

The results of the charging are presented in Fig. 3. The charging history of the aggregate depends mostly on the compactness factor of the aggregate and the photon flux of the environment.

A. *Relationship to Photon Flux*

The "flip-flop" effect is much more common at lower values than at higher values for the photon flux of the UV radiation. Fig. 5 demonstrates this relationship. There is a definite negative correlation between the photon flux of the UV radiation and the frequency of the flip-flop effect for aggregates charged.

As the aggregates that exhibit the flip-flop eventually charge negatively, it is to be expected that the flip-flop would be more common at a lower value for the photon flux. A higher photon flux corresponds to more positive current to the dust aggregate, so aggregates under this higher flux condition should be less likely to charge negatively at any point in their histories. Our results reflect this.

B. *Relationship to Compactness Factor*

A perfectly compact aggregate has a compactness factor of 1, and, as would be expected, there is a negative correlation between size of the aggregate (by number of monomers) and compactness factor of the aggregate. Fig. 6 shows all of the aggregates included in the study plotted according to compactness factor and size. The aggregates that exhibited the flip-flop are in the upper portion of the cluster. This corresponds to aggregates that are larger and more compact, or some combination of the two.

If the flip-flop effect is somehow a result of electrons being "recaptured" by aggregates when they are emitted due to UV radiation, this trend is to be expected. Aggregates would need to be sufficiently large and "folded in" on themselves to maximize blocked lines of sight and enable "recapturing."

C. *Single Sign Charging Histories*

Many aggregates did not exhibit the flip-flop effect and had a charging history that was all positive or all negative. This in itself is not surprising, but the trends are notable.

The most significant trend among the single sign charging histories is the prevalence of the all-positive charging history. As discussed, in an isolated plasma environment, dust aggregates will generally come to a negative charge equilibrium, and any aggregates that come to a positive equilibrium are considered the exception. However, in this study, an all-positive charging history was the most common result, occurring in 71% of cases.

The flip-flop and the all-negative charging history had similar frequency. The flip-flop, the second most common occurrence, was present in 15% of cases. An all-negative charging history was present in only 13% of cases.

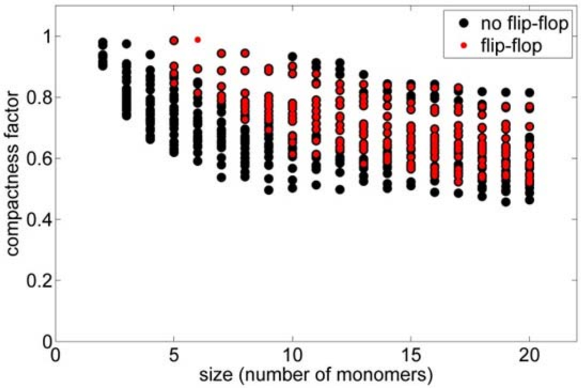

Fig. 6. Aggregates that exhibit the flip-flop effect tend to be of larger size and have a higher compactness factor, corresponding to a more compact aggregate.

IV. FUTURE WORK

There is the possibility for future study in this field. Previous research has shown that the charge on a dust grain is important in its growth and coagulation. The growth rate, in turn, can affect the development of a protoplanetary disk. Therefore, it would be interesting to study the effects of a mixed charging history on the coagulation and growth rates of dust in a plasma.

Additionally, it may be worthwhile to conduct a study similar to this one on aggregates that are made up of all ellipsoidal monomers or a mix of spherical and ellipsoidal monomers. Ellipsoidal monomers may be more physically accurate than spherical monomers.

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