Charging Processes for Dust Particles in Saturn’s Magnetosphere

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We investigated the electrostatic charging behavior of submillimeter-sized dust particles located in Saturn’s magnetosphere. The charging effects we considered included electron/ion capture from the magnetospheric plasma, electron/ion capture from the solar-wind plasma, the photoelectric effect from solar radiation, and secondary electron emission from energetic electrons. In our results, we show charging times and equilibrium potentials for particles located in different regions of Saturn’s magnetosphere. We find that charging in Saturn’s magnetosphere is not particularly sensitive to the dust particle’s material properties. The equipotential ranges from \(\sim-2\) V at \(3.5\) \(R_S\), decreasing to \(\sim-5\) V at \(6\) \(R_S\), and then increasing to \(\sim-1.5\) V at \(10\) \(R_S\). The charging time for one micron-sized particles is a few minutes, and for 0.01 micron-sized particles the charging time is 6 hours (or more). The latter is a significant fraction of Saturn’s rotation period.

The dynamics of dust, submillimeter-sized dust grains, is a fascinating area of study of our solar system’s dynamical evolution. Small particles, especially charged particles, respond to other forces than gravitational, in particular, electromagnetic forces. The dust particle’s properties and dynamics fall into a complex regime between nuclear physics and electromagnetic physics and gravitational physics. In order to calculate charges on a dust particle around a planet, we must characterize:
The planet’s magnetospheric features: its magnetic field and plasma,

The physical processes onto the dust particle that generate currents, and

The material properties of the dust particle.

In this paper, we make reference to results of charging of dust particles in Earth’s magnetosphere ([2],[3]). Earth is an interesting charging environment for dust particles, in part, because the dynamic magnetospheric plasma shows steep changes in the electron and ion energies and densities, therefore, the electron energy can be quite high (e.g. a few thousand eV). Table 1 lists some basic parameters comparing Saturn’s and Earth’s magnetosphere.

| Parameters                  | Saturn     | Earth       |
|-----------------------------|------------|-------------|
| Rotation Period (day)       | 0.44       | 1.0         |
| Dipole Moment (Gauss-cm$^3$)| 2.4 $10^{28}$ | 7.9 $10^{28}$ |
| Field at Equator (Gauss)    | 0.22       | 0.305       |
| Dipole Axis (deg)           | 0.0        | +10.8       |
| Magnetopause Distance       | 20 $R_S$  | 10 $R_E$    |
| Plasma Source               | Solar Wind, Atmosphere, Rings, Moons | Solar Wind, Atmosphere |

Data from [4].

1. Saturn’s Plasma Environment

The electrostatic potential of a dust particle not only depends on the physical properties of the particle, but also on the plasma environment, such as the plasma number density, temperature (energy), velocity distribution of the plasma particles, intergrain distance, and the relative motion between the dust particles and the plasma ([1]).

Inside of Saturn’s plasmasphere, the plasma density increases towards the planet from $\sim 1$ electron per cm$^{-3}$ at Saturn radius $10 R_S$ to $\sim 100$ electrons per cm$^{-3}$ at $3 R_S$, and the electron energy $kT_e$ decreases from $\sim 100$ eV to $\sim 10$ eV.

To characterize Saturn’s plasma, we utilized plasma data from M. Horányi. This plasma data is a four component plasma (hydrogen, oxygen, hot electrons, and cold electrons) fit to the Voyager data described in [6]. The Debye screening length is the distance that the Coulomb field of an arbitrary charge of the plasma is shielded. We
Table 2
Saturn Plasma Representative Numbers

| Component       | Location (R_S) | Energy (eV) | Density (cm^{-3}) | Debye Length (m) |
|-----------------|----------------|-------------|-------------------|------------------|
| Cold electrons  | 10             | 8.6         | 1                 | 22               |
|                 | 3              | 0.005       | 52                | 0.073            |
| Hot electrons   | 10             | 862         | 0.6               | 280              |
|                 | 3              | 27          | 0.6               | 50               |
| Hydrogen ions   | 10             | 17          | 0.3               | 56               |
|                 | 3              | 6           | 6                 | 7.4              |
| Oxygen ions     | 10             | 250         | 0.9               | 120              |
|                 | 3              | 31          | 46                | 6.1              |

can calculate the charge for an isolated grain if we have only one grain within a sphere of radius Debye length. Figures 1 and 2 show the energy, density our plasma data, and we state, in Table 2, some representative plasma values for our plasma data.

2. Charging Processes

We calculate the time-varying charge due to currents acting on a dust particle in a planetary magnetosphere using the following expression:

\[ \sum_k I_k = I_{i,e,moving} + I_{sec} + I_\nu \]  

(1)

where \( I_k \) is the current of the \( k \)-th charging processes. We consider 3 charging currents. The first charging current is: \( I_{i,e,moving} \), which is the collection of ions and electrons onto the dust particle from the ambient plasma. The second current: \( I_{sec} \), the secondary electron current, occurs when a high energy electron impacts the dust particle, some of the dust material is ionized, and electrons are ejected from the particle. The third current, \( I_\nu \), photoelectron emission current, occurs when a UV photon impacts the dust particle and photoelectrons are released. For a more complete treatment, one should add reflected electrons from the secondary electron emission and the small particle effect.

The secondary electron current is dependent on the dust particle material. If one wants to characterize different dust material properties, then one applies the secondary electron emission maximum yield \( \delta_m \) and the primary energy \( E_m \) at which the maximum yield occurs, acquired from laboratory measurements. The yield is the ratio of the secondary current to the primary current, given the energy of the impacting electron or ion. Example yield and energy values for relevant solar system material is shown in Table 3.
Table 3
Examples of Dust Particle Material Properties

| Material   | density (g-cm\(^3\)) | \(\delta_m\) | \(E_m\) (eV) |
|------------|-----------------------|--------------|--------------|
| Graphite   | 2.26                  | 1            | 250          |
| SiO\(_2\)  | 2.65                  | 2.9          | 420          |
| Mica       | 2.8                   | 2.4          | 340          |
| Fe         | 7.86                  | 1.3          | 400          |
| Al         | 2.70                  | 0.95         | 300          |
| MgO        | 3.58                  | 23           | 1200         |
| Lunar dust | 3.2                   | \(\sim1.5\) | 500          |

Data from [5].

3. Charging Results

We choose, as our canonical example, a hybrid dust particle with material properties similar to a conducting graphite particle \(\delta_m=1.5\), \(E_m=250\) eV, but with photoelectron yield properties similar to a dielectric particle (in Horányi et al.’s, modeling work, the photoelectron yield is denoted \(\chi\) and ranges from \(\chi=1.0\) for conducting magnetite dust particles to \(\chi=0.1\) for dielectric olivine particles). These properties were chosen in order to compare with charging results we have obtained for a dust particle in Earth’s magnetosphere.

For our canonical dust particle, we calculated the equilibrium potential (“equipotential”), the charging time, and examined the dominant currents for a particle at Saturn radii locations of 3 \(R_S\) to 10 \(R_S\). Equilibrium potential for the dust particle is reached when the sum of the charging currents is zero. The charging time is the time for a particle’s potential to reach an equilibrium. The currents that we examined are the electron and ion collection currents, the photoelectron current and the secondary electron current. Figures 3a,b,c display the results for the equilibrium potential, the charging time, and the dominant currents for our canonical case, 1 \(\mu\)m dust particle. Here, the equipotential ranges from \(\sim2\) V at 3.5 \(R_S\), decreasing to \(\sim5\) V at 6 \(R_S\), and then increasing to \(\sim1.5\) V at 10 \(R_S\). The charging time for the starred positions is \(\sim1\) minute. If we perform the same calculations for a 100 times smaller particle with the same material properties, then we find charging times on order of a few hours, which is a significant fraction of Saturn’s rotation period. Also, for a 100 times smaller particle, the secondary electron emission current will be more efficient, causing the smaller particle to charge more positively than for the larger (1 \(\mu\)m-sized) dust particle.

For an identical dust particle in a geostationary location in Earth’s magnetosphere, we calculated dramatic differences in the equipotential values and the charging times when we applied plasma conditions appropriate to “disturbed” and “quiet” Earth
magnetosphere conditions, and when we slightly varied the material properties from \( \delta_m = 1.5, E_m = 250 \text{ eV}, \chi = 0.1 \) to \( \delta_m = 1.4, E_m = 180 \text{ eV}, \chi = 0.1 \). For the first set of material properties in quiet Earth plasma conditions, the equilibrium potential was \( \sim +5 \text{ V} \). However, for the second set of material properties in disturbed Earth plasma conditions, the equilibrium potential was \( \sim -3000 \text{ V} \). The charging time was about 10 seconds for a 1 \( \mu \text{m} \) dust particle in quiet Earth plasma conditions, and one-third that time for a 1 \( \mu \text{m} \) dust particle in active Earth plasma conditions. The charging time generally increases with decreasing particle radii.

What happens when we vary the material properties \( \delta_m, E_m, \) and \( \chi = 0.1 \) for a 1 \( \mu \text{m} \) dust particle in the same way in Saturn’s magnetosphere, using the same charging processes as we applied for a particle in Earth orbit? Surprisingly, we find very little change in the resulting potentials, charging times, and currents, as seen in Figures 4 and 5. Removing each of the currents, one by one, however, does have an effect, in particular the secondary electron emission. If we calculate equipotentials without the secondary electron emission current, then the dust particle potential stays negative throughout the magnetosphere, and doesn’t reach positive potentials beyond 8 \( R_S \).

On the other hand, removing the photoelectron emission current doesn’t alter the equilibrium potentials in a significant way.

The charging time for a 1 \( \mu \text{m} \) dust particle is on the order of a few minutes, while for a 0.01 \( \mu \text{m} \) dust particle, the charging time is on the order of \( \gtrsim \) few hours.

4. Summary

- Charging in Saturn’s magnetosphere is not particularly sensitive to the dust particle’s material properties. This is a large contrast to dust particles in Earth’s magnetosphere, where small material property changes can have a big effect on the equilibrium potential.

- The charging time for one micron-sized particles is a few minutes, and for 0.01 micron-sized particles the charging time is 6 hours (or more). The latter is a significant fraction of Saturn’s rotation period.

Acknowledgements. We are very grateful to M. Horányi, Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, for his Saturn plasma data and helpful guidance on dust particle charging mechanisms.

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Figure 1: Saturn plasma energies of our four component plasma: hot electrons, cold electrons, oxygen ions, and hydrogen ions.

Figure 2: Saturn plasma densities of our four component plasma: hot electrons, cold electrons, oxygen ions, and hydrogen ions. The highest energy and density components are the oxygen ions and hot electrons.

Figure 3: a) Equilibrium potential (V), b) Charging time (sec), and c) Currents ($e s^{-1} cm^{-2}$) for a 1 $\mu$m dust particle of material properties $\delta_m=1.5$, $E_m = 250$ eV, $\chi=0.1$.

Figure 4: a) Equilibrium potential (V), and b) Currents ($e s^{-1} cm^{-2}$) for a 1 $\mu$m dust particle of material properties $\delta_m=2.4$, $E_m = 400$ eV, $\chi=0.1$.

Figure 5: a) Equilibrium potential (V), and b) Currents ($e s^{-1} cm^{-2}$) for a 1 $\mu$m dust particle of material properties $\delta_m=1.4$, $E_m = 180$ eV, $\chi=0.1$. 
Saturn Radii ($r/R_S$)

Saturn Plasma Energies

- O ions
- Hot electrons
- H ions
- Cold electrons

$T$ (°K)

Saturn Radii ($r/R_S$)
Saturn Radii ($r/R_S$)

**Equilibrium Potential**

$E_{max} = 250$ eV, $d_{sec} = 1.5$, $\chi = 0.1$

**Charging Time**

**Currents**

1. Electron current
2. Ion current
3. Photoelectron current
4. Secondary electron current
Equilibrium Potential

Potential (V)

Saturn Radii ($r/R_s$)

Emax = 400 eV, delsec = 2.4, chi = 0.1

Currents

Current (e s$^{-1}$ cm$^{-2}$)

Saturn Radii ($r/R_s$)

(1) Electron current
(2) Ion current
(3) Photoelectron current
(4) Secondary electron current
Equilibrium Potential

Potential (V)

Saturn Radii (r/Rₕ)

Currents

Current (e s⁻¹ cm²)

Saturn Radii (r/Rₕ)

Emax = 180 eV, delsec = 1.4, chi = 0.1

Potential (V)

Saturn Radii (r/Rₕ)

Current (e s⁻¹ cm²)

Saturn Radii (r/Rₕ)