Charging of ice grains by low-energy plasmas: Application to Saturn’s E ring

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Abstract. The charging of ice grains in planetary plasmas is studied, including the effects of secondary electron emission and backscattering of the incident electrons. It is shown that existing charging models can not be simply extrapolated to the low-energy electron regime (below 30 eV) common in planetary magnetospheric plasmas. We derive expressions for the electrical potential of a grain immersed in a low-energy plasma which more carefully account for electron reflection and the threshold for secondary electron emission. Using plasma parameters from Voyager PLS experiment, we calculate the potential of Saturn’s E ring grains to vary from −5.5 V at 4 Rs to 5 V at 10 Rs.

1. Introduction

The E ring is a diffuse, azimuthally symmetric distribution of small water-ice grains in Saturn’s magnetosphere occupying the region between 3 and 8 Saturnian radii. This ring appears to be composed predominantly of ice grains (1 ± 0.3 μm in radius [Showalter et al., 1991]), which are surrounded by a low-density plasma consisting of electrons, protons, and single-ionized oxygen ions [Richardson and Sittler, 1990]. Three spacecraft have traversed Saturn’s magnetosphere and measured plasma parameters: Pioneer 11, Voyager 1, and Voyager 2. The availability of spacecraft measurements makes the E ring grains excellent candidates for testing aspects of the charging of small grains in space-plasma environments. This is especially relevant since in the near future the Cassini spacecraft will make many passes through the E ring region measuring the plasma energy and composition and the dust particle masses and velocities.

The potential of the E ring grains has been estimated and used as a parameter in recently proposed models for evolution of the E ring particles by Horanyi et al. [1992], Morfill et al. [1993], and Hamilton and Burns, [1994]. Horanyi et al. [1992] calculated the motion of the grains launched from Enceladus (a moon of Saturn which is the presumed source of the E ring material) in the presence of a gravity field, solar radiation pressure, and electromagnetic forces. They showed that micron-sized grains, which are launched over a period of time and which obtain potentials between -5.4 and -5.8 V, would give a grain size and spatial distribution with many of the characteristics of the observed E ring. Morfill et al. [1993] calculated the effect of grain potential on the sputtering rate of the E ring grains. They suggested that the surrounding plasma is produced and maintained by “self-sputtering” of the E ring. That is, the sputtered atoms and molecules are ionized and “picked up” by a planetary magnetic field and accelerated to corotation energies. These ions then bombard the dust resulting in a self-sustained process. Since the secondary electron emission coefficients, which play a crucial role in the grain charging, were not known for water ice, each of these groups of researchers made a parameter study of the effect of interest using a “best guess” for the secondary electron yield and the grain potential. In describing grain erosion, Morfill et al. [1993] used a maximum yield, δm ≈ 1, at energy E m ≈ 1000 eV for the secondary electron emission parameters for energetic electrons incident on water-ice. Applying the grain-charging model described by Draine and Salpeter [1979] this gave E ring grain potentials varying from −40 V at a distance 5 Rs from Saturn to 1 V at 9 Rs from Saturn, where Rs is the radius of Saturn. Horanyi et al. [1992] used the procedure described by Whipple [1981] and three values of δm with E m = 500 eV. They estimated grain potential at the orbit of Enceladus (∼4 Rs) between −8 and +4 V. In the orbit calculations they favored δm = 1.5 which gives the grain potentials varying from -6 V (at 4 Rs) to +3 V (at 8 Rs). Hamilton and Burns [1994] calculated the motion of charged grains in the presence of gravitational forces, Lorentz forces, and solar radiation pressure using -5 V as the grain poten-
tial near Enceladus orbit. They found for this particular potential that the E ring could sustain itself; that is, charged grains comprising the E ring strike Enceladus at high-velocity ejecting new material.

Using laboratory data for secondary electron yields [Maiskevich and Mikhailova, 1960] we recalculate values of the E ring grain potential. We will show that extrapolation procedures for obtaining a grain potential used previously cannot be done for the low-energy plasmas in the Saturnian and other planetary magnetospheres, having electron temperatures usually lower than \( \sim 30 \) eV. For low-energy plasmas, not only "true" secondary emitted electrons but also "reflected" electrons (a distinction based on their respective energies) constitute emitted currents from the grain and significantly influence its equilibrium electrical potential. In addition, the threshold energy for secondary electron emission, determined by the binding energy of the valence electrons, should be taken into account whenever a significant portion of the electron plasma is below this energy, that is, does not produce secondary electrons. In section 2 we review the charging mechanism for a single-grain model surrounded by a plasma with Maxwellian energy distribution commonly used to calculate grain potentials. We emphasize problems that occur when models derived for high energy plasmas (hundreds of eV and higher) are extrapolated to the low energy regime. In section 3 we discuss secondary electron emission and derive the relation for the secondary electron current appropriate for small incident energies. In section 4 we discuss the importance of the reflection coefficient for elastically and inelastically reflected primary electrons, especially for low-energy (cold) electrons below 20 eV. We then obtain the charging contribution due to the reflected current and apply the results to Saturn’s E ring examining the relative importance of the contributions to the charging current to find equilibrium grain potentials. The plasma parameters based on the Voyager measurements are given in section 5. Results with applications to the other E ring evolution models are given in sections 6 and 7.

2. Charging mechanism

The potential of a grain depends on the energy distribution of the surrounding plasma as well as on the properties of the grain itself, and it is determined by a balance between various charging currents. Assuming that the main charging mechanism comes from the fluxes of the incoming electrons and ions, the equilibrium potential of the grain is obtained from the current balance equation

\[
J_i - J_e + J_{sec} + J_{ref} + J_{hv} = 0 \tag{1}
\]

where \( J_i \) and \( J_e \) are electron and ion fluxes incident on a grain, \( J_{sec} \) is the escaping flux of secondary electrons, \( J_{ref} \) the outgoing flux of reflected primary electrons and \( J_{hv} \) the photo electron current. Distinction between secondary emitted electrons and reflected primary electrons used for calculating the grain potential has been made based on electron energy measurements as will be discussed. The secondary electron energy distribution shows a peak around \( E_{sec} = 3 \) eV almost independent of the incident electron energy, while a peak which occurs around the incident electron energy is attributed to elastically reflected electrons.

The secondary electron current induced by the electron impact usually determines the charging of a grain. Assuming spherical grains immersed in a plasma with Debye screening length much larger than the grain’s radius and that the fluxes of incoming and escaping particles are orbital-motion limited [Lafraimboise and Parker, 1973], the incoming fluxes of electrons (e) and ions (i) have the form

\[
J_{e,i} = \int_{\max(0, \pm \varphi)}^{\infty} [1 \pm \left(\frac{e\varphi}{E}\right)] \frac{d\varphi}{E} dE \tag{2}
\]

where minus (plus) corresponds to electrons (ions), \( E \) is the incident electron (ion) kinetic energy, \( \varphi \) is the grain’s surface potential and the factor \( [1 \pm (-e\varphi/E)] \) accounts for the change in the geometrical cross section due to Coulomb attraction and repulsion [Spitzer, 1941]. Although the electron energy distribution function in the planetary environments is closer to a kappa distribution [Rosenberg and Mendis, 1992], it can be reasonably fitted using two Maxwellsians [Sittler et al. 1983b]. Consequently, for calculating Saturn’s E ring grain potential we evaluate (2) using two Maxwellians for the incident electron current: a thermal (“cold”) component with temperature \( T_c \) and a suprathermal (“hot”) component with temperature \( T_h \).

Using a Maxwellian flux distribution for incident electrons, (2) yields the well known result

\[
J_e = \begin{cases} 
      J_0 \exp\left(\frac{e\varphi}{kT_c}\right) & \varphi \leq 0 \\
      J_0 \left(1 + \frac{e\varphi}{kT_c}\right) & \varphi \geq 0 
\end{cases} \tag{3}
\]

with

\[
J_0 = \frac{1}{4} n_e \overline{v_e}, \quad \overline{v_e} = \sqrt{\frac{8kT_c}{\pi m_e}} \tag{4}
\]

where \( n_{e,i} \) is the electron or ion density and \( \overline{v}_{e,i} \) is the average thermal velocity.

For bodies with \( \varphi < 0 \) the secondary emitted flux is obtained based on (2) as

\[
J_{sec(\varphi<0)} = \int_{-\infty}^{\infty} (1 + \frac{e\varphi}{E}) \frac{d\varphi}{E} \delta(E + e\varphi) dE \tag{5}
\]

where \( \delta(E) \) is the secondary electron yield. On the other
hand, when $\varphi > 0$ not all secondary electrons will escape. Assuming that the velocity distribution of secondary electrons can be approximated by a Maxwellian with peak energies $E_{\text{sec}} = kT_{\text{sec}} \ (2-5 \ \text{eV})$, regardless of the form of the incident velocity distribution, Prokopenko and Laframboise [1980] found that the escaping secondary electron flux is

$$J_{\text{sec}(\varphi>0)} = \left(1 + \frac{e\varphi}{kT_{\text{sec}}}\right) \exp\left(-\frac{e\varphi}{kT_{\text{sec}}}\right) \cdot \left[ \int_{0}^{\infty} \left(1 + \frac{e\varphi}{E}\right) \frac{d\varphi}{dE} \delta(E + e\varphi) \, dE \right]$$  

(6)

where the factor $\left[1 + (e\varphi/kT_{\text{sec}})\right] \exp(-e\varphi/kT_{\text{sec}})$ in front of the integral represents the fraction of the total electron flux emitted from the grain surface which is able to overcome the grain's potential.

While this charging scheme works for incident electron energies of the order of hundreds of eV, it is not appropriate when energies approach tens of eV. First, at low incident energies, elastic and inelastic reflection becomes the dominant process governing the electron loss from a grain. Also, secondary electron emission starts at some threshold energy (usually between 5 and 10 eV for insulators), not at zero energy which is often assumed in relations for the secondary electron yield $\delta(E)$ derived from the measurements at higher energies. Finally, in the low-energy regime the escaping electron flux cannot be approximated by a Maxwellian independent of the incident electron energy because that assumption implies that for small incident energies a significant portion of the secondary electrons escape with energies greater than the incident energy. Therefore the charging calculation needs to be modified, when the electron temperature is tens of eV or less.

Secondary electron ejection can also be induced by ion or photon impact. The measured ion fluxes are substantially smaller than the electron fluxes and the ion current contribution to the charging is much smaller than the electron contribution. In addition, the ion-induced secondary electron yield below 1 keV is small, so the secondary electron current induced by ion impact can generally be ignored. The secondary electron yield is expected to be smaller than 0.1 for ion energies in the order of a 100 eV [Whipple, 1981]. Therefore the main contribution to charging is the direct ion current.

For a nonstationary grain (2) should be modified if the grain velocity is comparable to the plasma velocity [Whipple, 1981; Havens et al., 1987]. This is the case for ions whose measured velocities in the inner edge of the $E$ ring are comparable to the grain's Keplerian velocity. For the cold ion current we note that the corotating component of velocity is substantially larger than the thermal velocity and the average ion flux to a grain is roughly

$$J_i \approx \left(1 - \frac{2 \ e \varphi}{m_i (v_i - v_{\text{kep}})^2}\right) \frac{n_i}{4} (v_i - v_{\text{kep}})$$  

(7)

where $v_i$ is the measured corotating component of ion velocity and $v_{\text{kep}}$ is the grain speed. We will show later that the ion current contribution to the total current to a grain is substantially smaller than the electron contribution.

The photoelectron flux is also low. We use the relation given by [Wallis and Hassan, 1983]

$$J_{he} = \frac{3}{4} \times 10^{14} \ \frac{X}{r_{AU}} \ \exp\left(-\frac{\max[e\varphi, 0]}{1.3 \ eV}\right)$$  

(8)

to estimate it with the photoelectric efficiency $\chi = 0.1$ for icy grains and Saturn's distance $r_{AU} = 9.6$.

### 3. Secondary electron emission

On the basis of the energy spectra of the emitted electrons, the total electron yield, the mean number of ejected electrons per incident electron, is often written as a sum

$$\sigma = r + \eta + \delta$$  

(9)

do elastically ($r$) and inelastically ($\eta$) backscattered primaries (sometimes added together as "reflected" primaries $R = r + \eta$) and "true" secondary electrons ($\delta$). For incident electrons with energies in the range where secondary electron emission dominates (for example, from approximately 100 eV to few keV for ice, Figure 2) elastically and inelastically backscattered primaries constitute only a small fraction of the total yield. In that case the total yield is often approximated by the secondary electron yield. However, for small incident energies elastically and inelastically backscattered primaries constitute a dominant fraction of all outgoing electrons and in that case reflected electrons cannot be neglected.

The secondary electron yield curve $\delta(E)$ is often described by a "universal" shape characterized by two parameters: the maximum yield $\delta_m$ and the energy at which it occurs, $E_m$. Typically, the maximum electron yield $\delta_m$ is greater for insulators and semiconductors (1-10) than for metals (0.5-2). In the energy range where the total electron yield of a material is greater than one, the electron current (like an incoming ion current) contributes to positive charging.

Here we use the empirical relation for the dependence of the secondary electron yield given by Draine and Salpeter [1979]

$$\delta(E) = \delta_m \ \frac{4(E - E_m)}{(1 + (E - E_m)^2)}$$  

(10)

This relation approximates the secondary electron yield for normal incidence. Since the grain is surrounded by plasma with isotropic flux distribution an angle averaged yield is needed. On the basis of expressions given by Dionne [1973, 1975], Katz et al. [1977] derived an angular dependence based on the range and energy loss.
rate for penetrating electrons which reads

\[ \delta(E, \theta) = 2.54 \frac{\delta_m E}{Q \cos \theta E_m} \{1 - \exp[-Q \cos \theta]\} \]  

(11)

where \( \theta \) is the angle of incidence of the electron and \( Q = 2.28 (E/E_m)^{1.35} \). This expression gives an approximation for energies below 4 \( E_m \) and for an isotropic primary electron distribution it may be integrated to give an angle averaged yield [Whipple, 1981]:

\[ \delta(E) = 5.08 \frac{\delta_m E}{E_m} Q^{-1} + \exp(-Q) \frac{Q^2}{Q^2} \]  

(12)

3.1. Secondary Electron Flux for Low Incident Energies

The secondary electron energy distribution emitted from a material is almost independent of the incident energy \( E \) for energies above a hundred eV and is often approximated by a Maxwellian with a temperature of about 3 eV [Prokopenko and Laframboise, 1980] which is in reasonable agreement with measurements [Murashov et al., 1991]. This is done for mathematical convenience and does not imply a thermal origin of secondary electron emission. For incident energies of the order of tens of eV or less, we assume that it can still be approximated as a Maxwellian with a peak at \( E_{sec} = kT_{sec} \), but we require a cutoff at the incident electron energy. Therefore the velocity distribution of the escaping secondary electrons at the surface of a charged grain, with the required cutoff at the incident electron velocity \( v \), is

\[ f(v, v_s)_{sec} = c(v) \exp(-\frac{mv_s^2}{2kT_{sec}})H(\sqrt{\frac{2}{m}(\frac{mv_s^2}{2} + \varphi v_s) - v_s}) \]  

(13)

where \( v_s \) is the velocity of the emitted secondary electron at the surface of a grain, \( H \) is Heaviside step function and \( c(v) \) a normalization constant determined at \( \varphi = 0 \). For grains at negative potentials all secondary electrons can escape, but for positive grain potentials only those electrons for which \( \frac{1}{2}mv_s^2 - \varphi > 0 \) can escape. In order to calculate \( J_{sec} \) for a positively charged grain, we find the ratio \( \Lambda(E, \varphi) \) between escape fluxes from a grain at a potential \( \varphi \) and a noncharged grain (\( \varphi = 0 \))

\[ \Lambda(E, \varphi) = \frac{\int [\frac{3}{2} (m \varphi^2 + \varphi)]^{1/2} f(v, v_s)_{sec} v_s \cdot n \, d^3v_s}{\int_0^\infty f(v, v_s)_{sec} v_s \cdot n \, d^3v_s} = \frac{(1 + \frac{\varphi}{kT_{sec}}) \exp(-\frac{\varphi}{kT_{sec}}) - (1 + \frac{E + \varphi}{kT_{sec}}) \exp(-\frac{E + \varphi}{kT_{sec}})}{1 - (1 + \frac{E + \varphi}{kT_{sec}}) \exp(-\frac{E + \varphi}{kT_{sec}})} \]

where \( v_s \cdot n \) is the secondary electron velocity component in the outward normal direction. This ratio represents a fraction of secondary electrons which are able to overcome the grain potential, that is, escape from a grain. The total secondary electron flux for \( \varphi > 0 \) in (6) becomes

\[ J_{sec,(\varphi>0)} = \int_0^\infty \Lambda(E, \varphi) (1 + \frac{e\varphi}{E}) \frac{dJ}{dE} \delta(E + e\varphi) \, dE \]  

(14)

When the incident energy is substantially larger than the grain potential, the factor \( \Lambda(E, \varphi) \) reduces to \( [1 + (e\varphi/kT_{sec})] \exp(-e\varphi/kT_{sec}) \) which can be pulled in front of the integral so that (14) becomes equivalent to the result in (6).

3.2. Secondary Electron Emission for H2O - Ice

Unfortunately, very few measurements have been made of the secondary electron yield for water-ice, or for other molecular ices of interest in the outer solar system, especially for low incident energies. Therefore modelers have used different parameters, \( \delta_m \) and \( E_m \), as well as different energy dependencies, \( \delta(E) \), inferred from the yields measured for other materials.

Recently, Suszcynsky et al. [1992] measured the secondary electron yield of an H2O ice film at normal incidence using a scanning electron microscope. Incident electron energies were between 2 and 30 keV, far above the maximum-yield energy \( E_m \). Suszcynsky et al. [1992] used the Sternglass universal curve to extrapolate measured values in the low-energy range, predicting the secondary electron emission parameters for water-ice of \( \delta_m = 6.8 \) and \( E_m = 142 \) eV. These authors were apparently unaware of an earlier measurement of the secondary emission yield by Matskevich and Mikhailova [1960] for electron energies from 100 to 2500 eV at normal incidence, using a single pulse method.

Both measurements are plotted in Figure 1 together with the numerical fit to the data using functional dependences given by (11) with \( \theta = 0 \) (curve a) and (10) (curve b), for the secondary electron coefficients \( \delta_m = 2.35 \) and \( E_m = 340 \) eV. The widely used Sternglass formula [Meyer-Verte, 1982] is also plotted in the same figure (curve c) for comparison. Above 1 keV the different fitting formulas give significantly different yields with (10) giving the best approximation to the measurements. For the low-energy portion of the secondary electron yield curve, which is most important in the E ring since the surrounding plasma temperature is low, the fitting formulas do not differ greatly, but the data is very different from the “best guesses” of \( \delta(E) \) used by Morfill et al. [1993] and Horanyi et al. [1992] to calculate the grain potential (Figure 1). We use (11) and, as a check (10), both used in recent models [Morfill et al., 1993; Horanyi et al., 1992] to see how much the calculated grain potential is affected by the different functional relationships for \( \delta(E) \).
As the "temperature" of the secondary emitted electrons, we use the peak energy $\sim 3$ eV of the secondary electrons emitted from quartz (which has secondary electron parameters $\delta_m$ and $E_m$ similar to mica, glass and water-ice), measured by Murashov et al. [1991].

3.3. Threshold Energy for Secondary Electron Production

When dealing with low-energy electrons inside the solid, it is important to notice that only those absorbing sufficient energy from an incoming electron, ion or photon can leave the surface and contribute to the secondary current. The surface barrier for insulators is determined by the electron affinity ($E_A$) which is the energy difference between the vacuum level and the bottom of the conduction band. Only those electrons for which the component of kinetic energy perpendicular to the surface is greater than $E_A$ will escape from the material. In addition, electrons from the valence band need to absorb at least the band gap energy, which is 7.8 eV for cubic ice. Since the electron affinity is 0.9 eV, the valence band edge lies about 8.7 eV below the vacuum level for cubic ice [Baron et al., 1977] or about 9 eV for amorphous ice [Williams et al., 1974]. The primary electron also gains $\sim 0.9$ eV (electron affinity) when entering the material, so we put the threshold energy for secondary electron production at $E_{th} = 8$ eV. In Figure 2 we plot the functions in both (10) and (11), starting at $E_{th} = 8$ eV which corresponds to replacing $E$ with $E - E_{th}$ and $E_m$ with $E_m - E_{th}$ in (10) and (11).

A lower threshold may result for the excitation of electrons in trap states in the band gap with binding energies $\sim 1 - 2$ eV [Haas et al., 1983]. If the grain is negatively charged, then, of course, the excess electrons must reside in traps, which are likely to be near the surface. Although these electrons can be more easily removed from the grain, they constitute an extremely small fraction of the electrons involved in determining the current balance. That is, for a 1 micron radius grain at -10 V there are only $5 \times 10^{-5}$ excess electrons per surface molecule. Therefore we will use the threshold value given above for all secondary electrons.

3.4. Secondary Electron Emission for Isotropic Incidence

The measurements described above were for normal incidence. Morfill et al. [1993] used a multiplying factor of 2 for secondary electron yield to account for both the assumed spherical shape of a dust particle and isotropic incidence [Draine and Salpeter, 1979]. Measurements show [Salehi and Flinn, 1981] that the enhancement of the secondary electron yield due to isotropic incidence has a different energy dependence and cannot be accounted for by a simple multiplying factor. It was observed that the secondary electron emission increases with incident angle and that the value of $E_m$ shifts toward higher energies, approximately proportional to $(\cos \theta)^{-1}$. The enhancement in the secondary electron yield due to the small particle effect [Chow et al., 1993], which can be significant for a grain size of order 0.1 $\mu m$ and smaller, can be ignored in the case of the $E$ ring grains.

First, we use (11) as a fit for the normal incidence yield and find the angle averaged yield from (12). In Figure 3 the dash-dot lines represent normal incidence...
old energy. The reflected yield measured by Figure 2. Measured secondary electron yield given by 

tion yields from (a) equation (11) with \( \theta = 0 \) and (b) equation (10), both starting at \( E_{th} = 8 \text{ eV} \) as the threshold energy. The reflected yield measured by Bader et al. [1988] (squares) and Matskevich and Mikhailova [1960] (pluses) is shown together with our fit to the actual functional dependence \( R(E) = 103.9 E^{0.23} / (1 + 1.93 \ E)^{5.66} \) (dashed line).

yield from (11) (lower line) and the corrected yield for isotropic incidence given by (12) (upper line). As a check, we also find an angle averaged yield using (10) as the normal incidence yield. For this we use angular dependent measurements [Salehi and Flinn, 1981] for \( V_2O_5-P_2O_5-C_5O_4 \) glass which has secondary emission parameters close to ice. We numerically integrated those measurements over all incident angles and find an angle averaged yield which we can scale to ice, assuming that parameters \( E_m \) and \( \delta_m \) for ice and glass in the case of the isotropic incidence are shifted by the same factor from the normal incidence parameters. We plot in Figure 3 as solid lines the normal incidence yield given by (10) (lower line) and the calculated angle averaged yield based on (10) (upper line).

4. Reflection Coefficient

A typical ejected electron flux distribution, measured by Harrower [1956] for tungsten target at the incident electron energies of 10 and 20 eV, is shown in Fig. 4 (solid lines). The first peak at \( \sim 3 \text{ eV} \) corresponds to secondary electrons while the second peak at the incident energy corresponds to the reflected electrons. The maximum is elastic reflection while inelastic reflected electrons, which lose some of their energy in the inter-

action with the target, correspond to energies below the elastic maximum. To model such flux distributions at other incident electron energies we use two curves: one for the secondary electrons and the other for reflected electrons and calculate these two current contributions \( J_{sec} \) and \( J_{ref} \) independently. The distinction between the inelastically scattered electrons and the secondary electrons is somewhat arbitrary, but both contributions, \( J_{sec} \) and \( J_{ref} \), enter into the total charging current as a sum. The outgoing energy only determines whether the electron can escape from a grain's potential well, that is, how it contributes to the charging.

For negative grain potentials \( (\varphi \leq 0) \) all emitted electrons can escape regardless of their energy and the reflected flux can be calculated using (5), where \( \delta \) is replaced by \( \eta + \varphi = R \), and where we add both elastically and inelastically reflected electrons in the reflection coefficient.

For positive grain potentials only electrons with sufficient energies escape, that is, all elastically reflected electrons and those inelastically emitted with energies \( \frac{1}{2} m v_i^2 > \varphi \). To see how the energy distribution of reflected electrons influences the current to a grain, and consequently the grain potential, we present a simple model for reflected current from a charged grain. For the sake of simplicity, we approximate all reflected electrons from an uncharged grain with a half-Gaussian velocity distribution up to the elastic peak at incident electron velocity \( v \)

Figure 3. Secondary electron yield for ice for normal incidence from equation (11) (lower dashed-doted line) and the corrected yield for isotropic incidence given by equation (12) (upper dashed-doted line). Solid lines represent the normal-incidence yield given by equation (10) (lower line) and the calculated angle averaged yield based on measurements on glass (upper line).
\[ f_{\text{ref}}(v, v_r) = c'(v) \exp\left(-\frac{m(v^2 - v_r^2)}{2 k T_{\text{ref}}}\right) H(v - v_r) \] (15)

where \(v_r\) is the velocity of the reflected electrons at the surface, \(T_{\text{ref}}\) measures the spread of the distribution around the elastic peak, while \(H(v - v_r)\) introduces the cut-off at the incident electron energy and \(c'(v)\) is a normalization constant. We also assume that the electrons are reflected from the small surface element isotropically [Whipple and Parker, 1969; Whipple, 1981], which means that reflected flux measured from the surface normal follows the experimentally known "cosine law." We use the same procedure as that to obtain (14) for the secondary electron emission flux to estimate reflected electron contribution \(J_{\text{ref}}\) in (1). The total reflected flux for \(\varphi > 0\) is

\[ J_{\text{ref}}(\varphi > 0) = \int_0^\infty \left[ 1 + \frac{\varphi}{k T_{\text{ref}}} - 1 \right] \left[ 1 - \exp\left(-\frac{E+\varphi}{k T_{\text{ref}}}\right) - \frac{E+\varphi}{k T_{\text{ref}}} \right] \cdot \left(1 + \frac{E+\varphi}{E} \right) \frac{dJ}{dE} R(E + \varphi) dE \] (16)

where \(R\) is a measured reflection coefficient. The dashed lines in Figure 4 represent our approximation for the flux distribution which includes the secondary electron flux (with peak at \(k T_{\text{sec}} = 3\) eV) and the reflected flux with our choice for \(k T_{\text{ref}} = 1\) eV. Because of the finite resolution of the energy analyzer, the measured energy spreads around the incident energies (10 and 20 eV) are overestimated [Harrower, 1956], and, consequently, our choice for the parameter \(k T_{\text{ref}}\) represents the upper limit for the actual spread around the elastic peak. However, the change in the equilibrium grain potential introduced by this choice does not exceed 0.1 V, which is less than other estimated uncertainties. It can be concluded that when the elastic peak is sharp (which is the case for ice, Michaud and Sanche, 1987b), the shape of the reflected electron energy distribution does not significantly influence the charge balance.

From measurements of the reflection coefficient for various insulators at low incident electron energies [Bronstein and Novitskii, 1978; Nemchenok et al., 1976; Khan et al., 1963; Fridrikov and Shul'man, 1959] it is known that the reflection coefficient approaches zero as \(E \to 0\); reaches a maximum below \(\sim 20\) eV, and decreases slowly at higher energies. Typically, for metals the maximum value reaches 0.1 - 0.4, whereas for dielectrics it attains 0.5 - 0.8 [Dobretsov and Gomoyunova, 1971].

Measurements of the elastic electron reflectivity of amorphous films of ice have been done by Michaud and Sanche [1987a,b] for various thicknesses (1-40 monolayers) and for incident electron energies from 1 to 20 eV at 14° incidence. Using the same experimental arrangement as Michaud and Sanche [1987a,b], Bader et al. [1988] measured the transmitted current on a 50-layer \(H_2O\) film for incident electron energies from 0.1 to 4 eV. Matskevich and Mikhailova [1960] measured reflection coefficients for ice in the energy range from 100 eV to 2.5 keV. In Figure 2 we show both measurements together with a least squares fit to the measurements (dashed line) using for \(R(E)\) a form similar to that in (10). This fit should be considered only as a rough approximation to the actual functional dependence \(R(E)\) in the range of interest, below 1 keV.

![Figure 4. Total electron fluxes from tungsten for 10 and 20 eV primary electrons at normal incidence measured by Harrower [1956] (solid lines) and modeled flux distribution (dashed lines) using velocity distributions in equation (13) for secondary electrons and that in equation (15) for reflected electrons.](image-url)
5. Plasma Parameters

For equatorial plasma parameters around Saturn’s E ring we use the model given by Richardson and Sittler [1990], which is based on Voyager measurements. The electron energy distribution is fitted by two Maxwellian distributions: thermal (“cold”) component with temperature $T_e$ and suprathermal (“hot”) component with temperature $T_h$. The high-energy tail is not well fit using two Maxwellians, but it does not play an important role in our calculation, since the electron fluxes and the secondary electron yields are low in this region. For the proton and oxygen ion densities, we use values extrapolated to the equatorial plane using the Richardson and Sittler [1990] model. A summary of the plasma parameters used are given in Table 1, where $T_{ec}$, $T_{eh}$, $n_{ec}$, and $n_{eh}$ represent temperatures and densities of the cold and hot electrons respectively. There are, of course, considerable uncertainties in this model, which involved extrapolation of the measured plasma densities to the equatorial plane, and indeed the plasma parameters probably vary in time somewhat. Both the ion and electron temperatures recorded during the Voyager 1 and 2 traverses vary substantially along the same dipole $L$ shell. Consequently, the distribution of temperatures and densities can be considered a parameter study for grain charging because the distance from Saturn affects the result only via changes in electron temperature and density. Since Voyager 1 crossed the equatorial plane at $L \approx 6$ Saturnian radii, equatorial plasma parameters can be determined there and are also given in Table 1.

6. Results: Potential of the E ring Grains

Using (8), (3) and (7) for the photon, electron and ion currents, (5) and (14) for the secondary electron currents and (5) and (16) for the reflected current, a grain potential can be found for which the current balance equation (1) is satisfied. As an example, in Figure 5 we give all currents to a micron-sized ice grain at radial distance $L = 6 R_s$, incident electron current to a grain, secondary electron current, reflected current, sum of the photon and ion currents for H$^+$ and O$^+$ ions and, finally, total current to a grain. Current balance is obtained in this case for the grain potential -2 V. As one can see the combined photoelectron current and the ion current (due to the small ion velocities) to a grain is substantially smaller than other contributing currents; consequently, the equilibrium potential primarily results from balancing different electron currents.

In Figure 6 we show the calculated potential for a spherical grain as a function of radial distance from Saturn for both relationships used for the secondary electron emission (a, b in Figures 1 and 2). The resulting potential using (11) for normal incidence yield (and, consequently, (12) for the isotropic yield) gives an average $\sim 1$ V more negative than that based on (10), since the secondary emission yield in that case rises more rapidly up to $E_m$ (Figure 3). The potential in Figure 6 is seen to rise from 4-8 $R_s$ and stays almost constant between 8 and 10 $R_s$. The potential increases in going from Enceladus (4 $R_s$) to 8 $R_s$ due to increasing electron temperatures (both hot and cold) and increasing densities of the hot electrons. The almost constant potential near and beyond Rhea (8.7 $R_s$) arises from the fact that, when the positive potential becomes greater than the secondary electron temperature, $kT_{sec} = 3$ eV, the number of secondaries (which constitutes the major part of the positive current to the grain) sharply decreases. These results are also compared to the best guess of Morfill et al. [1993] and three models from Horanyi et al. [1992]. Agreement is seen to be best with model H2 in which $\delta_m = 2$. In their calculation of E ring grain orbits Horanyi et al. [1992] used $\delta_m = 1.5$ and $E_m = 500$ eV, whereas Morfill et al. [1993] used $\delta_m = 1$ and $E_m = 1000$ eV to describe E ring grain ero-

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Table 1. Equatorial Plasma Parameters

<table>
<thead>
<tr>
<th>$L$</th>
<th>$T_{ec}$</th>
<th>$n_{ec}$</th>
<th>$T_{eh}$</th>
<th>$n_{eh}$</th>
<th>$T_{O^+}$</th>
<th>$n_{O^+}$</th>
<th>$T_{H^+}$</th>
<th>$n_{H^+}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>2.7</td>
<td>90</td>
<td>100</td>
<td>0.2</td>
<td>40</td>
<td>70</td>
<td>12</td>
<td>20</td>
</tr>
<tr>
<td>5</td>
<td>3.5</td>
<td>45</td>
<td>120</td>
<td>0.4</td>
<td>80</td>
<td>40</td>
<td>14</td>
<td>3.7</td>
</tr>
<tr>
<td>6</td>
<td>5.0</td>
<td>27</td>
<td>150</td>
<td>0.4</td>
<td>100</td>
<td>25</td>
<td>16</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>6.8</td>
<td>15</td>
<td>170</td>
<td>0.4</td>
<td>120</td>
<td>15</td>
<td>18</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>11</td>
<td>4.5</td>
<td>200</td>
<td>0.4</td>
<td>170</td>
<td>4</td>
<td>20</td>
<td>0.8</td>
</tr>
<tr>
<td>9</td>
<td>13.5</td>
<td>2.7</td>
<td>250</td>
<td>0.3</td>
<td>220</td>
<td>2.3</td>
<td>22</td>
<td>0.65</td>
</tr>
<tr>
<td>10</td>
<td>17</td>
<td>1.9</td>
<td>300</td>
<td>0.2</td>
<td>260</td>
<td>1.6</td>
<td>24</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Plasma parameters from Richardson and Sittler [1990]: temperatures $T$ (eV) and densities $n$ (cm$^{-3}$) for electrons ("cold" and "hot") and ions (O$^+$ and H$^+$) in equatorial plane versus distance $L$ in Saturnian radii. To indicate uncertainties in plasma parameters we used Voyager 1 measurements [Sittler et al., 1983] averaged over a 2-h period covering the ring plane crossing between 5 $< L < 6.7$. The proper electron density is determined from ion density requiring the charge balance. These parameters are $T_{ec} = 12.3 \pm 2.9$, $n_{ec} = 24.3 \pm 6.2$, $T_{eh} = 99 \pm 50$, $n_{eh} = 1.0 \pm 0.4$. 

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The best fit of the experimental yield is obtained with the equilibrium potential, which from Figure 5 is clearly seen to be important at almost all potentials shown. While all currents to a grain and ion currents for ice at low incident energies suffer small energy losses, all reflected electrons can be considered as having reflected elastically, introduces a change in the grain potential of the order of 0.1 V. Further uncertainties may result from the effects of irregular shapes and roughness of ice grains, impurities in the ice and radiation induced defects which introduce electron states in the band gap, thereby affecting the yields and threshold energies. Using the Voyager 1 ring plane crossing data only (Table 1) the grain potential at 6 $R_S$ would be +3 V as compared to -2 V for value b in Figure 6. Therefore the plasma parameters are the largest uncertainty in this calculation.

### 7. Conclusion

In this paper we calculated the charging of an ice grain in Saturn’s magnetosphere where the plasma electron temperatures are low. These calculations were based on extrapolations of the complete set of available secondary electron and reflected electron data, taking into account the physics of the secondary electron yields and electron reflection coefficients. We assumed that the grains are one micron solid water-ice spheres, as suggested by most of the measurements [Showalter et al., 1991]. However, the calculated potentials are not sensitive to the grain size as long as the grains are not much smaller than ~ 0.1 μm and the secondary electron yield parameters for other materials possibly present in the E ring probably do not differ significantly from that of water ice. We show that for low incident electrons energies the calculation of the grain potential requires consideration of electron reflection and of the secondary electron production threshold. In fact, for the potentials calculated here for Saturn’s inner magnetosphere, varying from about -5.5 V at 4 $R_S$ to 5 V at 10 $R_S$, reflection is always important, as it is in the case whenever the electron temperature is < 20 eV or less. Therefore the charging calculations developed here can be used when the plasma parameters in Saturn’s inner magnetosphere are more firmly established and in calculations for other planetary plasmas environments in which a cold electron component is dominant.

Our calculation of the E ring grain potential versus distance from Saturn using the plasma data of Richardson and Sittler [1990], which is an average of Voyager data with ion densities extrapolated to the equatorial plane, is seen to be in rough agreement with curve H2 (Figure 6) in Horanyi et al. [1992], who described the spatial distribution of the E ring. Therefore our results appear to support this aspect of the hypothesis of the formation and evolution of the E ring grains. On the other hand, our results differ significantly from the best guess of Morfill et al. [1993] for describing a plasma source by low energy ion sputtering of E ring grains. However, sputtering of the E ring grains by keV ions does contribute significantly to the plasma formation near Enceladus [Johnson et al., 1993].

Horanyi et al. [1992] and Hamilton and Burns [1994] concluded that the spatial distribution and grain size
occurs because they also neglected the electron reflection coefficient. Hamilton and Burns [1994] found that micron-sized grains charged to -5 V would obtain the required orbital eccentricity to account for the spatial extent of the E ring. That is, they would cross the orbit of Tethys during their life in Saturn’s inner magnetosphere. Such potentials are close to those found here at 4 Rs, but the fact that the potential changes with distance from Enceladus must be considered. Therefore calculations presented here appear to confirm aspects of the E ring hypothesis, if the plasma parameters used are reasonable. These results can now be used for more detailed determination of the physics of the E ring.

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Figure 6. Calculated grain potential as a function of the radial distance in Saturnian radii. Solid lines show the potential determined in this paper using $E_m$ =340 eV and $\delta_m$ =2.35. Two different extrapolations for the secondary electron yield lead to slightly different potentials: line (a) based on equation (11) and line (b) based on equation (10). The dashed-dotted line represents the potential favored by Morfill et al. [1993] with estimated secondary electron parameters $E_m$ =1000 eV and $\delta_m$ =1. Dashed lines show potentials given by Horanyi et al. [1992] using $E_m$ =500 eV and three different values for the maximum yield: $\delta_m$ =0 (H0), $\delta_m$ =1 (H1), and $\delta_m$ =2 (H2). Their "best guess," based on the observed E ring characteristics, is $\delta_m$ =1.5.
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