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# Polarization electrostatic field and ambipolar diffusion in the presence of negatively charged grains near Saturn's F ring: case study using RPWS/LP data

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## Abstract

It is well known that in the magnetosphere of Saturn, even in the absence of an electric current, a polarization electrostatic field develops along the field lines to maintain the charge neutrality of the plasma. It is also well established that certain regions of the Saturnian system (ionosphere, moons, rings) are populated by significant amount of nm and $\mu$m charged grains. Hence, in order to estimate this electric field ($\mathbf{E}_{||}$), it is important to take into account the dusty plasma as well. In the present work, we derive a more general form of $\mathbf{E}_{||}$ by including the presence of negatively charged nm-sized grains. Moreover, using the Cassini RPWS/LP data, we calculate $|\mathbf{E}_{||}|$ from one case study near the F ring, by integrating over 1 nm-100 nm grains. We show that in the region close the ring plane ($|Z| < 0.1\,\mathrm{Rs}$) the additional dust diffusion and gravitational terms of the momentum equation amplify $|\mathbf{E}_{||}|$ to $\sim 6\times10^{-6}$ V/m, at least one order of magnitude larger than the case without the charged grains ($\sim 2\times10^{-7}$ V/m). Eventually we discuss how this has a direct consequence on confining the electrons to the ring plane.

## 1. Introduction

A dusty plasma consists of electrons, ions and charged dust particles. It is widely present in the universe and known to play a major role in the star and the planet formation [1]. In our solar system, the dusty grains populate some of the most beautiful features of the cosmos, the planetary rings [5]. Thanks to the availability of the Cassini spacecraft measurements, we could detect and study in-situ the characteristics of the dusty plasma around and within Saturn's rings [3]. In addition to its spectacular main rings, nm to tens of $\mu$m sized grains were observed in its more diffuse rings: the E ring, originating from Enceladus' plumes, was shown to be dominated by negatively charged grains [6, 2] and more recently during the F ring-grazing orbits, [4, 7] have reported the dominance of nm to $\mu$m negatively charged grains near the Janus/Epimetheus ring, outside the F ring ($\sim$ 2.5 Rs). Since these small particles are charged, beside the gravitational force, they are also strongly affected by the electromagnetic forces. As a consequence, the presence of the negatively charged grains may significantly influence various physical processes such as the ambipolar diffusion process of the plasma along the magnetic field lines.

## 2. Theory

Assuming diffusive equilibrium, single charged electrons, ions, and dust ($q_d$), cold and magnetized dust and considering the **motion along the B field** and predominantly negatively charged grains ($n_e = n_i - z_d n_d$), the polarization electrostatic field can be expressed in terms of pressure gradient, gravity and ambipolar diffusion:

$$\mathbf{E}'_{\|} = \frac{1}{2en_e}\Big[\nabla_{\|}(P_i - P_e) - (n_d m_d + n_i m_i)\mathbf{g}_{\|} + (n_e m_e \nu_{ed} - n_i m_i \nu_{id})(\mathbf{u}_d - \mathbf{u}_i)_{\|}\Big]$$

where the ambipolar diffusion term is given by:

$$(\mathbf{u}_d - \mathbf{u}_i)_{\|} = \frac{2k_B T_p}{m_i\nu_{id} + m_e\nu_{ed}}\left[\frac{1}{n_i}\nabla_{\|}n_i - \frac{1}{2n_i T_p}\nabla_{\|}\Big(n_d z_d T_e\Big) - \Big(\frac{m_i + \frac{n_d}{n_i}m_d}{2k_B T_p}\Big)\mathbf{g}_{\|}\right]\left[1 - \frac{z_d\frac{n_d}{n_i}}{\Big(\frac{m_i\nu_{id}}{m_e\nu_{ed}} + 1\Big)}\right]^{-1}$$

The red terms are the ones that depend on the negatively charged dust. Considering only ions and electrons, we have:

$$\mathbf{E}_{\parallel} = \frac{1}{2en_e}\left[\nabla_{\parallel}(P_i - P_e) - n_i m_i \mathbf{g}_{\parallel}\right] \quad (1)$$

Since the dust grains have different sizes ($r_d$), we integrate over $r_d = [r_{min}; r_{max}]$ in order to obtain the total polarization electrostatic field:

$$\mathbf{E}'_{\parallel} = \int_{rmin}^{rmax} \frac{1}{2en_e}\Big[\nabla_{\parallel}(P_i - P_e) + (n_e m_e \nu_{ed} - n_i m_i \nu_{in})(\mathbf{u}_d - \mathbf{u}_i)_{\parallel} - (n_d m_d + n_i m_i)\mathbf{g}_{\parallel}\Big] dr_d \quad (2)$$

where:

$$n_d(r_d) = K r_d^{-\mu} \ \ (K = \frac{(2-\mu)e(n_i - n_e)}{4\pi\epsilon_0 \alpha U_{sc}[r_{min}^{2-\mu} - r_{max}^{2-\mu}]})$$

$$m_d(r_d) = C_m r_d^3 \ \ (C_m = \frac{4}{3}\pi\rho)$$

$$z_d(r_d) = C_z r_d \ \ (C_z = \frac{-\alpha 4\pi\epsilon_0 U_{sc}}{e})$$

$$\nu_{ed}(r_d) = 54.6\frac{C_z^2 K r_d^{2-\mu}}{T_e^{3/2}}$$

$$\nu_{id}(r_d) = 1.27\frac{C_z^2 C_m^{1/2} K r_d^{3.5-\mu}(C_m r_d^3 + m_i)}{m_i^{1/2}(m_i T_d + C_m r_d^3 T_i)^{1.5}}$$

# 3. Case study: Rev 254

In order to compute $\mathbf{E}'_{||}$, we consider the same case study analyzed by [4, 7] (Rev 254) and integrate equ. 2 from $r_{min} = 1$ nm to $r_{max} = 100$ nm and for $\mu = 5$. The result is presented Figure 1. The polarization electric field in the presence of negatively charged dust, $|E'_{||}|$ is shown in red, and the case without including the dust $|E_{||}|$ is shown in black. As one can see, very close to the ring plane for $|Z| < 0.1$ Rs (area in yellow, where the nanometer negatively charged grains dominate [4]), $|E'_{||}| \approx 6 \times 10^{-6}$ V/m, whereas in the absence of the dust, $|E_{||}| \approx 2 \times 10^{-7}$ V/m.

# 4. Discussion and Conclusion

This study highlights the important role of the negatively charged nanometer-sized grains on amplifying the polarization electrostatic field at least one orders of magnitude larger than the normal case with no dusty plasma. This has a direct consequence on the motion of the plasma along the field lines. In fact, in this new scenario where negatively charged grains are present, the grains and the ions take the same role that the ions and the electrons play in the normal case. More explicitly, owing to the small ion mass relative to the grains, gravity causes a slight charge separation, with the lighter ions tending to settle on top of the heavier negatively charged grains (with respect to the ring plane). This charge separation results in a polarization electrostatic field, which hence prevents a further charge separation. To conserve the charge neutrality, the electrons would also be attracted by the ions. As a consequence, the presence of the dusty grains and so the relatively strong ambipolar electrostatic field confines the electrons to the ring plane and inhibit their diffusion upward along the field lines.

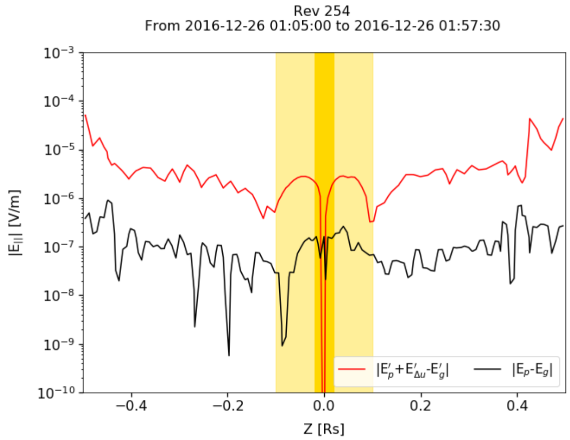


Figure 1: $|\mathbf{E}_{||}|$ in the presence (red) and absence (black) of negatively charged grains.

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