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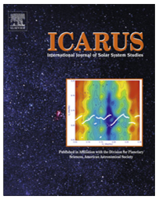

An estimate of the dust pickup current at Enceladus

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ABSTRACT

We demonstrate that the acceleration of submicron dust originating at Enceladus by a reduced co-rotating *E*-field is capable of creating a dust pickup current perpendicular to the magnetic field with values ranging from 3 to 15 kA (depending upon the effective grain charge). Such a current represents a new contribution to the total pickup current in the region. As such, we suggest that dust pickup currents, along with ion and electron pickup currents, are all active within the plume.

1. Introduction

One of the major discoveries of the Cassini mission is the very active space environment in the vicinity of the moon Enceladus. A primary source of this activity is the cometary-like jet of gas (Waite et al., 2006) and dust (Spahn et al., 2006) emitted from the south polar fissures (Porco et al., 2006). The neutral gas emitted at 100 kg/s is believed to undergo photo-ionization and charge exchange to form a substantial southerly-extended ionosphere that mass-loads the passing magnetic field lines (Tokar et al., 2006; Pontius and Hill, 2006). Ion densities on the order of $10^4/\text{cm}^3$ are detected in the proximity of the jet (Shafiq et al., 2011) with evidence of mass loading/plasma slowdown as far as 20 Enceladus radii (R_e) from the body (Tokar et al., 2006; Simon et al., 2011). The electron densities in the plume are not as large as the ion densities, with n_e/n_i dropping below 10% out to as far as $10R_e$ south of the polar fissure (see Fig. 5 of Morooka et al., 2011). This electron density reduction is due to the presence of submicron-sized dust that effectively absorbs most of the electrons (Farrell et al., 2009; Shafiq et al., 2011; Morooka et al., 2011; Jones et al., 2009; Hill et al., 2012). This negatively charged dust becomes the dominant negative charge carrier in the region (Shafiq et al., 2011). In this work, we will assess the strength of the pickup currents of negatively charged dust grains using measurements from the Cassini Langmuir Probe to determine how effective these currents are near the moon.

We focus on the E3 encounter on 12 March 2008, since it is a well-studied event and the north-to-south encounter geometry allows for an estimate of the local radially inward-directed dust current density along the extent of the southern-directed plume. The top panel of Fig. 1 displays the trajectory in Enceladus-centered co-rotation coordinates (X in the plasma co-rotation direction, Y points inward to Saturn, and Z pointing out of the orbital plane). The planetary magnetic field is oriented in the $-Z$ direction (at 320 nT) and the driving co-rotating E-field (of ~12 mV/m) is oriented in the $-Y$ direction. The plasma velocity vector is thus oriented along $+X$ at ~39 km/s in Saturn's frame of reference.

Measurements primarily from the Langmuir Probe (LP) are used in the analysis. This instrument is a key component of Cassini's Radio and Plasma Wave Science (RPWS) package (Gurnett et al., 2004, 2005; Wahlund et al., 2005, 2009) and provides measurements of the local ion density, electron density, ion flow velocity, species temperature, spacecraft potential and ambient potential. We build upon a set of previously-reported observations that include the following:

(1) Analysis of both the LP and the plasma wave upper hybrid emission revealed the presence of a clear and distinct electron density decrease or 'dropout' in the near-vicinity of the moon (Farrell et al., 2009; Shafiq et al., 2011; Morooka et al., 2011). The ratio of electron-to-ion concentration, n_e/n_i, dropped below unity about $5R_e$ north of the moon and remained well below unity for most of the E3 transit, returning to unity about $15R_e$ southward of the moon (Morooka et al., 2011). The n_e/n_i ratio was low, at values of 0.03, even in the plume region (Farrell et al., 2010).

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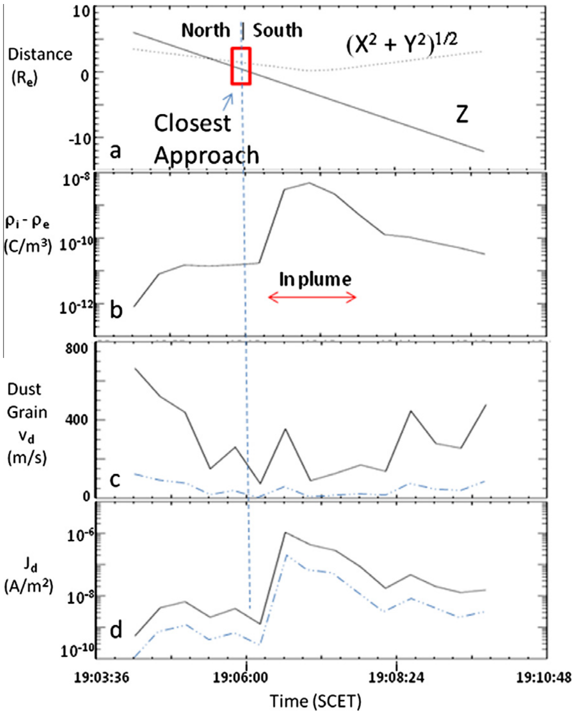

Fig. 1. (a) Cassini trajectory, (b) LP ion and electron charge density difference (dust charge density), (c) speed of 30 nm grain accelerated by E in 100 km distance, and (d) dust grain current.

(2) Shafiq et al. (2011) examined the charge neutrality of the dusty plasma and found it could be maintained only if a substantial concentration of submicron dust grains (10s of nanometers) was in equilibrium with the plasma in the region; thus providing the negative charge required to compensate for the large ion density. In essence, the dust has effectively 'sucked up' the electrons in the near-moon region to become the dominant negative charge carrier. The situation is such that the charge densities are consistent with $e(n_i - n_e) + \rho_d = 0$, with $|\rho_d| \gg |en_e|$. Direct detection of nanograins, the smallest grains, by the Cassini Plasma Spectrometer account for about 10% of the missing negative charge in the plume region (Jones et al., 2009; Hill et al., 2012). For the E3 encounter, the peak nanograin charge content was near 3000 el/cm^3 (Hill et al., 2012) and the Langmuir Probe electron density was near 700 el/cm^3. Since the peak ion density is ~30,000/cm^3, the remaining negative charge should reside on the inferred submicron grains (Shafiq et al., 2011).

(3) Any submicron-sized dust and nanograins will be accelerated by the ambient E-field oriented along the $-Y$ direction (Farrell et al., 2012). In the vicinity of the moon, this E-field is not the full value of the co-rotation E-field but a reduced value due to both the change in frame of reference to the moon's frame and from the shielding of the cross-magnetic field pickup currents. The accelerated dust and any new ions create a perpendicular current and a $J_\perp \times B$ force that slows the plasma down by effectively reducing (shielding) the E-field from its co-rotation value. This pickup current is well-known for ions, with previous applications for Io and Enceladus (Goertz, 1980; Hill and Pontius, 1998; Pontius and Hill, 2006; Tokar et al., 2006, 2009). The negatively-charged dust grains moving in the $+Y$ direction are a newly-appreciated component of the pickup process.

In this work, we will use the previously derived submicron grain charge density (Shafiq et al., 2011) and make an estimate of the shielded E-field in the $-Y$ direction based upon the speed of the ions. We will then calculate the local dust pickup currents based on the charge density and dust velocity under the influence of the driving E-field.

2. Local dust currents

Our approach focuses heavily on the Cassini RPWS/Langmuir Probe measurements. Specifically, we assume the plasma-charged grains get accelerated by the environmental Lorentz forces, especially the existing shielded co-rotational E-field (Pontius and Hill, 2006; Simon et al., 2011) along the $+Y$ direction, E_y. The dust current accelerated by this E-field is $J_d = \rho_d v_d$, where dust charge density, ρ_d, is the LP-measured difference between the ion charge density and electron charge density, and is the dust charge density needed to maintain quasi-neutrality (Shafiq et al., 2011). As discussed in Shafiq et al. (2011), most of this required charge density is carried by grains near 30 nm in size. The quantity v_d is the dust pickup velocity under the influence of the environmental E-field. As described below, we assume this E-field acts coherently on the dust over a distance in the y-direction of $L_y \sim 100$ km. For a 30 nm grain in charge equilibrium with the plasma, the dust pickup velocity is $v_d \sim (q_d E_y L_y / m_d)^{1/2}$, assuming rectilinear motion in a quasi-uniform E-field (i.e., the dust gyroradius is many 10s of R_e, and the E-field component of the Lorentz force dominates over vB (Farrell et al., 2012) near the dust source.

However, Cassini does not have a direct measurement of E_y. LP measurements of the ion flow velocity, U, provide an indirect measurement of E_y since $U \sim E_y/B_z$. In essence, LP's measurement of the plasma flow speed can be treated as a 'poor man's' E-field detector, allowing us to infer the value of the shielded electric field.

Fig. 1 shows the LP measurements and derived dust quantities using the methodology described above. Fig. 1b is the LP measured difference between the ion charge density and electron charge density, $e(n_i - n_e)$, and this difference is a quantification of the dust charge density needed to maintain quasi-neutrality (Shafiq et al., 2011). As indicated in Fig. 5 Shafiq et al. (2011), based on the grain size distribution and equilibrium conditions, this charge difference is consistent with electrons absorbed primarily by 10s of nanometer grains in plasma equilibrium. There are not enough larger grains (~100–1000 nm) in equilibrium to account for the electron-to-ion charge difference. The dust charge density values peak as the spacecraft passes into the southern hemisphere and

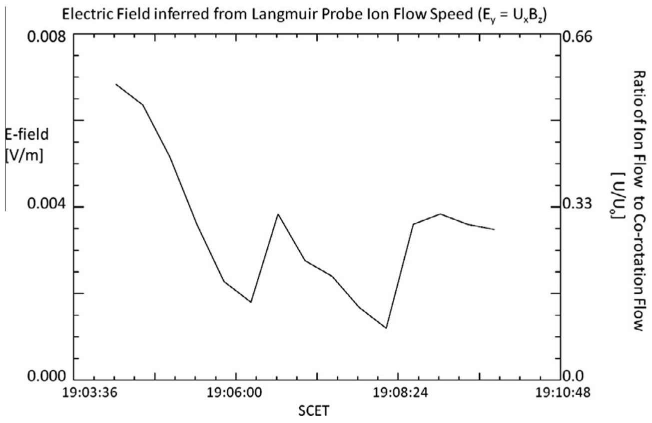

Fig. 2. The inferred E-field along the Cassini trajectory using the ion velocity flow speeds.

becomes immersed within the gas and dust plume. Fig. 1c shows the velocity of 30 nm dust grains after being accelerated by the ambient *E*-field, E_y for L_y = 100 km using the LP-derived ion velocity and *E*-field profile shown in Fig. 2.

We consider dust acceleration only in a distance of ~100 km (about ½ of the Enceladus radius) where the *E*-field can be considered uniform and where we can apply and extend our ρ_d and v_d values at the Cassini observation point with validity. We note that at the edge of the Enceladus flux tube, a substantial E_z may develop (Gurnett et al., 2011), and such an inhomogeneous and abrupt *E*-field should defect grains, changing v_d and spatially dispersing grains, thereby also reducing ρ_d. We thus limit the technique to derive J_d to a region in the near-vicinity of Cassini.

Due to pickup currents from ions, electrons, and dust, the region near the moon exerts a torque on the moon/magnetosphere system that acts to slow the corotating plasma (Hill, 1979; Tokar et al., 2006; Pontius and Hill, 2006), and this effect is clearly evident in Fig. 2. In the plume, the LP measured plasma undergoes a slow down to speeds at $U/U_o \sim 0.1$ near 19:06:30 SCET. The slowdown of the plasma lies below both the rigid co-rotation and Keplerian velocities. The region where the plasma is slowed is not just limited to the southern hemisphere, but is also present in the northern hemisphere (Tokar et al., 2009; Farrell et al., 2012). Using the flow speed to indicate the *E*-field, we find that the value of the driving E_y component is inferred to drop well below co-rotation values during the passage, being as low as ~1.2 mV/m in the vicinity of the plume. This reduced local flow is from the presence of an opposing polarization *E*-field along +*Y* created by ion, electron, and dust pickup separation. The addition of corotation and polarization fields leaves a residual or 'shielded' *E* field that drives ions and dust (Pontius and Hill, 2006).

Given this inferred environmental *E*-field, it is then assumed that this *E* accelerates the submicron grains in the saturnian-system radial direction. Shafiq et al. (2011) found that the LP-observed charge density difference in Fig. 1b could be accounted for by the presence of submicron dust at densities of ~100/cm^3 in equilibrium with the plasma. Such small grains are dominated by environmental electric forces (i.e., electric forces are stronger than gravitational forces) (Farrell et al., 2012). As such, these negatively-charged grains will be accelerated by the shielded *E* field to form a dust pickup current in the −*Y* direction.

In the calculation of the dust pickup velocity, v_d, we also considered the change in the charge state for the 30 nm grains in equilibrium in the dense dusty-plasma environment. Specifically, when many dust grains are found within a Debye sphere, the charge-per-grain, q_d, decreases compared to a grain in the plasma in isolation, q_{do}. This reduction is due to grain–grain mutual capacitance. This effect was quantified by Whipple et al. (1985), who found that the grain potential decreases with the presence of other negatively-charged grains. All the grains absorb a large population of electrons from the plasma, but because of mutual capacitance, the grains in the Debye sphere effectively 'share' the absorbed charge between them. Given a system of ions, electrons, and small dust in charge equilibrium, the change in grain surface potential from grain–grain capacitance can be quantified as a function of the ratio of n_e/n_i (i.e., $q_d = q_d(n_e/n_i)$) as defined in Eq. (31) of Whipple et al. (1985). Since this ratio is measured directly by the LP, $q_d(n_e/n_i)$ is relatively straightforward to incorporate. The value of $q_d = q_d(n_e/n_i)$ including this mutual capacitance effect is shown in Fig. 3.

Given Figs. 2 and 3, we can determine the resulting pickup velocity, v_d, of 30 nm grains being driven by the local *E* field over a distance of 100 km. This pickup velocity is shown in Fig. 1c. The results suggest there is expected to be a dust grain flow between 50 and 300 m/s. This calculation makes the very conservative assumption that the grains at the Cassini observation point have zero radial velocity (i.e., $v_d = 0$). This conservative assumption is required since we have no measurement or observational method for inferring the history of past/previous grain acceleration to the Cassini observation point. With Fig. 1b and c, we can now obtain an estimate of the dust pickup current density in the outward radial direction (−*Y*), $J_d \sim \rho_d v_d$. This dust current density (Fig. 1d) at a distance of 100 km from the Cassini observation point has values possibly peaking around 19:06:50 SCET at 1 μA/m^2 in the plume region. We also note the presence of dust pickup currents in the northern hemisphere region before 19:06:00 SCET at values of ~5 nA/m^2. Hence dust acceleration occurs in a region well away from the plume but where dust is known to be present (Farrell et al., 2012).

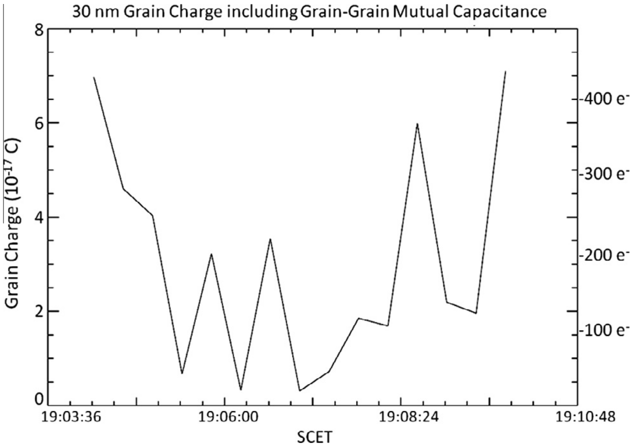

Fig. 3. The 30 nm grain charge during the spacecraft passage through the plume. The grain charge drops substantially near the moon in association grain–grain mutual capacitive effects.

The dust current flow between 19:06:30 and 19:07:30 SCET, within the plume itself, can exceed 0.1 μA/m^2. If we imagine this flow through a surface with a width in the *x*-direction of $1R_e$ and a length in the *z*-direction of $2.5R_e$ (consistent with the spacecraft transit in this 1-min interval), the total dust pickup current in peak regions is approximately 15 kA, which is about 15% of the total pickup current in the region (at 10^5 A, Dougherty et al., 2006). We note that in the northern hemisphere, we can consider J_y of 5 nA/m^2 through a $\sim 1R_e$ by $5R_e$ surface. In this case, the dust pickup current in the north (away from the plume) is ~1.5 kA. As we discuss below, these are initial upper estimates.

3. System-level currents

Goertz (1980) described the pickup currents associated with newly-born photo-ionized ion and electron pairs from Io. As indicated in his Eq. (3), positive ions are driven along the shielded *E*-field direction while the electrons are driven oppositely to the *E*-field vector direction. The guiding center motions of each species are displaced from each other by the sum of their respective gyroradii. In this case, the perpendicular current driven by the shielded *E* field along *y* is expressed as (Goertz, 1980)

$$\mathbf{J}_\perp = (\rho_i^{\prime} r_{ci} - \rho_e^{\prime} r_{ce})\mathbf{E}/|E| \qquad (1)$$

where the current is derived from the generation of new photo-ionized charge, $\rho_{i,e}^{\prime} = d\rho_{i,e}/dt$, with ρ_i transported the length of a cyclotron radius by the shielded *E*-field. This current then exerts a $J_\perp \times B$ force on the flowing plasma that, under conservation of angular momentum, acts to slow down the passing co-rotating magnetoplasma (in a self consistent way reducing *E*) (Hill, 1979; Hill and Pontius, 1998). However, for Enceladus, a large portion of the electrons become attached to the submicron dust grains, and the negatively-charged dust grains then become the dominant negative charge carrier. By analogy, we can then modify the Goertz (1980) expression to include the new pickup current including the dust term as

$$\begin{aligned}\mathbf{J}_{\perp} &= \mathbf{J}_{\perp \mathbf{i}} + \mathbf{J}_{\perp \mathbf{e}} + \mathbf{J}_{\perp \mathbf{d}} \\ &= \rho_i^{\prime} r_{ci}\mathbf{E}/|E| - \rho_e^{\prime} r_{ce}\mathbf{E}/|E| - n_d q_d^{3/2}(E_y L_y/m_d)^{1/2}\mathbf{E}/|E| \end{aligned} \tag{2}$$

where the dust charge density, ρ_d, is defined here as $n_d q_d$ for an assumed relatively narrow size range of submicron dust that can be easily accelerated by E (those grains near 30 nm, Shafiq et al., 2011; Farrell et al., 2012). We note that the ion and electron pickup currents are expressed in terms of their guiding center motion. However, at these spatial scales (100s of km) the dust can be considered unmagnetized, and this pickup current is expressed in terms of the grain's ballistic motion. In essence, in the near-moon vicinity, the vB force acting on the dust grains is not substantial, and the grains will undergo uniform acceleration from $\mathbf{E} = E_y\mathbf{y}$, as $v_d \sim (q_d E_y L_y / m_d)^{1/2}$. This expression is incorporated into the third term of Eq. (2).

There is an apparent paradox that suggests the terms are coupled in complicated ways: The LP consistently measures ion densities on north–south passes E3–E6 with densities exceeding 30,000 ions/cm^3 (see Fig. 5 of Morooka et al., 2011). Such ion densities may be consistent with electron impact ionization with the warm photoelectron populations (Coates et al., 2013). In the case of E3, if we assume that every ion (with content at 30,000/cm^3) gets picked up to co-rotating velocities, the ion pickup current is then 50 μA/m^2. Such a large current density passing through a $1R_e \times 1R_e$ cross-sectional area (consistent with the sharp density peak) would generate an overall cross-plume ion pick-up current of 3 MA, which greatly exceeds the B-field inferred current of 100 kA (Dougherty et al., 2006).

However, we suspect that many of these newly-minted ions remain trapped within the near-grain potential wells, leaving only the most energetic ions (in the high energy tail of the ~2 eV ion thermal distribution) to participate as a component of the ion pickup current. If we use the ratio of the currents (~100 kA/3 MA) to infer the density of 'free' vs 'trapped' ions, then there are two consequences: (1) About 3% of the ions are free to be accelerated by E_y and the ion pickup currents then become consistent with the magnetometer-inferred pickup currents. (2) The remaining 97% stay electrically connected to the near-surface of the grains, trapped in the deep grain potential well (illustrated in Fig. 4 of Goertz, 1989). In doing so, they create a reduced 'effective' charge on the grain, since this ion layer moves with the slowly accelerating dust grains. The net grain charge is then substantially less than that shown in Fig. 3 (closer to 1–2 elementary charges per grain). We would then anticipate the dust pickup velocity and dust pickup current in Fig. 1c and d to be less than that shown. For example, if we assumed the net effective charge on the grain is $q_{eff} = q_d - q_{trapped\_ions} = 0.03q_d$, then v_d and J_d are reduced by about a factor of ~6 (see blue-dashed line in Fig. 1c and d), making the dust pickup current in the plume region closer to 2.5 kA.

The value of the LP-measured electron density in the plume is 300/cm^3 (See Table 1 of Morooka et al., 2011). Assuming that each of these electrons is locally generated to be picked-up, we find that electron pickup current density, $J_{\perp e}$, is about 0.5 μA/m^2. In a $1R_e$ by $1R_e$ cross-section through the flow, this current density creates a 30 kA current, which is less than the ion pickup currents but exceeds the dust pickup currents. Thus, while the negative dust is the dominant 'holder' of the negative charge in the plasma (Shafiq et al., 2011), the more mobile electrons provide a larger pickup current.

Once the dust is accelerated, it will continue to move beyond the Enceladus flux tube, propagating radially-inward for 100s of km. We thus expect the interaction region around Enceladus to possess a radial asymmetry, with the +Y side of the dusty plume being more extended as compared to the $-Y$ side due to the extended acceleration region of the submicron grains. Such an asymmetry was reported by Pontius and Hill (2006), who found that the +Y side of the shielded E field region was nearly 3–5 times more extended in size compared to the $-Y$ region.

4. Discussion

We recognize that the prevalence of a dust pickup current is dependent upon a set of assumptions. It requires (1) that the difference between the LP ion and electron densities is a result of electron-absorbing submicron dust (Farrell et al., 2009; Shafiq et al., 2011; Hill et al., 2012), (2) that the radial E-field can be inferred from the plasma slowdown, and (3) that the E-field in the charged plume has an E_y profile like that quantified here, and does not possess an unusual geometry in the radial direction. Given the three inferences above, the conclusion of dust pickup currents is derivable simply and directly by applying the submicron dust mass, dust charge, and E-field configuration. However, any changes in the assumptions above will alter the resulting conclusions, and as such the model has an element of non-uniqueness, especially given that the presence of submicron dust and value of E_y are inferred quantities.

Regarding the mutual capacitance of the grains (Fig. 3), we find corroborating evidence for collective effects by examining the spacecraft charge in the dusty plasma. As indicated in Fig. 5 of Morooka et al. (2011), the Cassini spacecraft potential can be a proxy for grain charge levels. It is noted that the spacecraft (and thus dust) potentials have their largest negative values in the northern hemisphere where dust densities are lower. In the high-density plume, the spacecraft potentials tend to become overall less negative which is evidence for a low surface charge due to mutual capacitance in the collective dusty plasma.

We have assumed throughout that the grains have obtained equilibrium with the plasma, and are not charging. Just after closest approach, the spacecraft is encountering dust that has been recently ejected by the fissure. The grains have only been in the dusty plasma for about a thousand seconds. For 30 nm grains initially injected in a neutral state into an environment with a dominant electron thermal flux at 4×10^{-5} A/m^2, the grains will come into an equilibrium charge state in 10–20 s (see Eqs. (1) and (2) in Farrell et al., 2008). We thus conclude that 30 nm grains should be mostly in equilibrium in the dusty plasma by the time they reach spacecraft altitudes over the plume. However, many of the smaller nanograins (~2 nm) may not be fully in equilibrium (as suggested by Hill et al., 2012).

In summary, we calculated dust pickup currents in the dense part of the Enceladus plume to have densities between 0.05 and 0.7 μA/m^2. These densities are below both the ion and electron pickup currents. We find that ion pickup currents dominate the environment at a few μA/m^2, and that electron pickup currents at 0.5 μA/m^2 exceed dust pickup currents, even though the dust 'holds' most of the negative charge. The electrons are simply more mobile. The dust currents are <15% of the ion currents and thus should give rise to a B-field perturbation of no more than a few nanoTesla (compared to a ~20 nT overall perturbation like that shown in Fig. 2 of Jia et al., 2010). However, the dust pickup current interaction region should create a radially-asymmetric interaction region extending the magnetoplasma slowdown radially inward toward Saturn. We suggest that the electrodynamics of the dust pickup current is important to consider in the moon/plasma interaction region, possibly providing an extended region of plasma slowdown.

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