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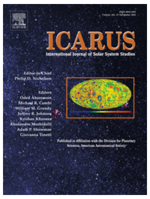

Transport and electrodynamical coupling of nano-grains ejected from the Saturnian rings and their possible ionospheric signatures

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ABSTRACT

Besides oxygen-bearing neutral gas and ions, the Saturnian rings could be a source of small dust particles of nano-meter size range. Electrostatic charging effect by photoemission and/or electron impact could lead to ejection of the nano-grains out of the ring plane by electromagnetic force. The orbital motion of low-velocity charged dust generated by mutual collision of the ring particles has been considered in previous work (Liu and Ip, [2014], ApJ, 786, 34.). In the present parametric study, the dust component produced by meteoroid bombardment is modelled. Depending on the plasma environment in the vicinity of the rings and the condition of electrostatic charging at the ring plane, the transport mechanism could be modulated by the sunlit angle on the ring plane. It is found that, besides negatively charged dust, positively charged nano-grains could play a potentially important role in transporting water into the mid-latitude region of the Saturnian ionosphere in both hemispheres. Positively charged tiny grains could be injected into low-inclination escape trajectories away from Saturn. In addition to the modification (depletion) of Saturn's ionospheric electron content, this gravito-electromagnetic mass transport effect might modulate the water loading mechanism associated with the quasi-periodic formation of the Great White Spots and the planet-circling storms in the northern hemisphere. The present sets of simulations also suggest that the correlation the H_3+ emission pattern with the ring opacity distribution could be a consequence of a source mechanism in addition to quenching by the so-called "ring rain" effect.

1. Introduction

The Saturnian ring system provides a natural laboratory to study the formation of small bodies in the dust disk of the primordial solar nebula (Charnoz et al., 2010; Ohtsuki, 1993; Hyodo and Ohtsuki, 2014) as demonstrated by the Cassini observations of the "propeller" features (Tiscareno et al. 2013a) and outgrowth at the outer edge of the A ring (Murray et al. 2014). The interaction of the planetary magnetosphere and the ring particle might also be an important channel for mass exchange between the rings and the ionosphere as demonstrated by the formation of the sharp boundary between the B and C ring (Northrop and Hill, 1982, 1983; Ip, 1983a, 1984a; Northrop & Connerney, 1987). In addition, the injection of water and oxygen ions and charged grains of nano-meter size could play a significant role in depleting the ionospheric electron content (Connerney and Waite, 1984; Moses & Bass, 2000, Moore et al. 2006; Tseng et al., 2010). Because of the combined effect of the planetary gravitational force and Lorentz force constrained by the axially symmetric dipole field with center-offset by 0.04 R_s in the northern direction (Connerney et al., 1982), the precipitation pattern is asymmetrical. That is, ions or charged nano-grains with charge-to-mass ratio (q/m) smaller than 10^{-5} e/amu (or electronic charge to atomic mass unit), if launched initially in Keplerian motion at the ring plane with radial distance inside the orbital instability limit of 1.53 R_s, will move along the magnetic field line until hitting the planetary surface at mid-latitute in the southern hemisphere (Bouhram et al., 2006; Luhmann et al., 2006; Tseng et al., 2010; Liu and Ip, 2014). This theoretical prediction is inconsistent from the radio occultation measurements that a significant electron density bite-out occurs near the equatorial region (Moore and Mendillo, 2007). Even though a significant fraction (~ 17%) of the water-group neutrals in the neutral gas cloud of Enceladus origin will impact on the rings (Jurac and Richardson, 2005, 2007), it is noted that they would not be directly injected into the equatorial region of the

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Saturnian atmosphere. Instead, most of the water molecules will recondense on the surfaces of the ring particles in the outer A ring (Jurac and Richarcdson, 2007) and be recycled into the ring atmosphere. The final impact sites on Saturn's surface would still be guided by the magnetic field as described earlier.

This might be indicative of a new pathway for equatorial injection of positively charged icy nano-grains as discussed in Liu and Ip (2014). In this scenario, a population of small grains is constantly generated by mutual low-velocity (~ a few m s^{-1}) collisions among the ring particles. The main source region is distributed between the inner edge of the B ring and the synchronous orbit at 1.87 R_S. Because of the absorption effect of the ring particles, the ambient plasma density is very low thus resulting in predominantly positive charge of the dust grains (Ip, 1984b).

Because the ring plane is subject to hypervelocity impact by interplanetary meteoroids (Morfill et al., 1983, Tiscareno et al. 2013b), a component of high velocity ejecta should exist. Nano-grains could be created in the impact process or generated by recondensation of the expanding hot vapor cloud. What would be their corresponding trajectories and how might they interact with the planetary ionosphere are topics of importance to the unique investigation of the Cassini Proximal Mission in 2016–2017. The present work is organized as follows. Section 2 will describe the model and calculations. The results will be presented in Section 3. A summary and discussion will be given in Section 4.

2. Trajectory calculation

The impact velocity (v_i) of interplanetary meteoroids of micron-size at the Saturnian rings varies according to their orbital distribution in the outer solar system and the locations of ring plane crossing (Ip, 1995). With a range of v_i between 25 and 40 km/s, the expectation is that a volume of impact vapor of high temperature will be created. For example, from laboratory experiments of hyper-velocity impact of submicron particles on metallic surfaces, it was found that the temperature of the expanding vapor could be of the order of 2500–5000 K (Eichhorn, 1976; Collette et al, 2013). In the impact plume, smoke particles of nano-meter size could form during its adiabatic expansion. Because of the icy composition, the temperature of the vapor plumes of the Saturnian ring particles from micro-meteoritic bombardment might be lower. Taking the vapor temperature to be 2500 K, the outflow speed of these recondensed grains can be estimated to be on the order of 1.5 km/s.

Because the particle motion in the direction perpendicular to the ring plane will be least subject to collisional scattering and absorption, we can first consider the nano-grains of impact origin to have an initial velocity in the vertical direction. It is further assumed that the grains will be electrostatically charged to a charge-to-mass ratio in the range between 10^{-5} and 10^{-7} e/amu, either positively or negatively.

The subsequent trajectory of the charged dust grain is described by the equation of motion:

$$\frac{d\mathbf{v}}{dt} = \frac{q}{m}(\mathbf{E} + \mathbf{V} \times \mathbf{B}) - \frac{GM}{r^2}\hat{\mathbf{r}}$$

where G ($=6.7 \times 10^{-11}$ $m^3 s^{-2} kg^{-1}$) is the gravitational constant, M is the mass of Saturn, m is the mass of the dust grain, q is the charge, r is the radial distance from the planetary center, V is the grain velocity, the corotational electric E= $-V_c$ xB, with B as the planetary magnetic field and V_c as the corotation velocity. We further assume that the density of the dust grain is $\rho = 1000$ kg m^{-3}. From $q/m = 1.683 \times 10^{-9}$ $\phi_v/a_\mu{}^2$ [e/amu] with ϕ_v in volts and the grain radius a_μ in microns, we find $q/m = 10^{-5}$ (ϕ_v/6 V) [e/amu] if $a_\mu = 0.013$ (i.e., $a = 13$ nm).

3. Results

Fig. 1 is a summary of the particle trajectories for negatively charged grains with q/m between 10^{-5} and 10^{-7} e/amu, emitted upward with an initial vertical velocity of $v_z = 1.5$ km s^{-1}. The magnetic field model used in the present calculations has its dipole moment aligned with Saturn's spin axis and the dipole center has an offset of 0.04 R_S (Saturn radius) in the upward direction. The magnetic field strength at the magnetic midplane is $B_o = 0.21$ G. The panels from (a) to (c) describe the motion of the charged grains. The trajectories in the ϱ-z projection plane where ϱ is the perpendicular distance to the central axis and those projected onto the x–y plane of the rotating coordinate system of Saturn are given in the upper and lower panels, respectively. Because of the vertical shift of the magnetic moment, for launching site inside the Northrop-Hill instability limit of 1.53 R_S, the nano-grains would generally reverse its direction after the initial upward movement (see Fig. 1a). Once crossing the equatorial plane the particle with $q/m = 10^{-5}$ e/amu will continue to move along the magnetic field line until hitting the planetary surface. For those emitted outside the Northrop-Hill instability limit, they will be confined to bounce motion in the vicinity of the mid-plane. As is well known, the B-ring with its inner edge at 1.53 R_S has large optical depth ($\tau > 1$) according to radio science and UV occultation measurements (Esposito et al, 1983; Tyler et al., 1983), these charged grains will soon be re-absorbed by the ring particles. When the charge-to-mass ratio is reduced by a factor of 10 and more, all particles will be kept in oscillatory motion (see Fig. 1b and c)

Fig. 2 are for positively charged grains emitted in the same (upward) direction. The group with $q/m \sim 10^{-5}$ e/amu is divided into two components (see Fig. 2a). The population with launching sites inside the synchronous radius (1.866 R_S) – where the velocity of the Keplerian orbit is the same as the corotation velocity – will all move away from the ring plane with their trajectories ending at the planetary surface. The other population of charged grains will be ejected outward becoming interplanetary dust particles. When the charge-to-mass ratio is reduced to 10^{-6} e/amu (see Fig. 2 b), the particle motion will be confined to equatorial region even though the bifurcation of the orbits into inward and outward trajectories is still evident. If $q/m > 10^{-7}$ e/amu, electromagnetic force is much less than the gravitational force, the motion of the charged particles will be mainly Keplerian orbits accompanied by oscillation in the vertical direction. In this case, except for those created in the C ring, the dust particles emitted in the A and B rings will quickly be re-aborbed as they move across the optically thick ring plane.

Fig. 3 and 4 are trajectories of the same sets of charged particles with an initial velocity of 1.5 km s^{-1} but in the downward direction. The patterns of the corresponding orbital dynamics are basically the mirror images of their counterparts with v_z in the upward direction.

If we now consider the dynamics of the charged nano-grains according to the sign of their surface electrostatic potential (ϕ), the positively charged grains with q/m between 10^{-5} and 10^{-6} e/amu and launch sites within the synchronous orbit will be injected into the hemisphere in the same direction of the initial ejection velocity, namely, northern hemisphere for $v_z > 0$, and southern hemisphere for $v_z < 0$.

On the other hand, for negatively charged grains, they tend to follow the effect first pointed out by Northrop and Hill (1983) that only those launched inside the planetocentric distance of 1.53 R_s from the planetary center will reach the southern hemisphere; those ejected at larger radial distances will remain in oscillatory motion above and below the ring plane (see Fig. 1a and 3a). Because the C-ring inside the Northrop-Hill instability limit contains very little mass, it is expected that the corresponding mass