Dust-plasma interaction through magnetosphere-ionosphere coupling in Saturn’s plasma disk

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Enceladus plume & E ring

- Enceladus plume (~3.95 Rs)
  - Main component
    - Water gas [Waite et al., 2006]
  - Source
    - Mainly Enceladus plume

- E ring
  - Location
    - 3 – 8 Rs
  - Composition
    - $H_2O^+$ (~80 %) [Young et al., 2005]
    - Dusts [Kurth et al., 2006; Kempf et al., 2008]
Depletion of electrons

- Electron density is smaller than ion density [Wahlund et al., 2009, Yaroshenko et al., 2009, Morooka et al., 2011]
  - 50 – 70 cm$^{-3}$ less

→ Wahlund et al. [2009] suggested that a large amount of negatively dusts are existent [Wahlund et al., 2009].

![Graph showing electron and ion densities](image)

Density profile [Morooka et al., 2011], Total dust density [Shafiq et al., 2011]
• Observations of inner magnetospheric ion by Cassini RPWS/LP
  • Ion speed is smaller than the co-rotation velocity [Holmberg et al., 2012].
  • May dust affects the motion of ion?
Purpose of this study & method

• Investigation of a dust-plasma interaction in Saturn’s system
  • What is a role of dusts in Saturn’s inner magnetosphere?
  • It is possible that the dust-plasma interaction occurs the proto-star/planetary disk.
  • We estimate dust density or thickness (z-direction) from ion velocity in this study.

• Methods
  • Numerical model
    • Using a multi-fluid model
    • Including Coulomb collision and mass loading
    • Considering magnetosphere-ionosphere coupling
Inner magnetospheric model

- **Primitive equations (a multi-fluid equations)**

\[
\frac{\partial \rho_k}{\partial t} + \nabla \cdot (\rho_k v_k) = S_k - L_k \\
\frac{\partial (\rho_k v_k)}{\partial t} + \nabla \cdot (\rho_k v_k v_k) = n_k q_k (E + v_k \times B) - \nabla p_k - \rho_k g + \sum_l \rho_k v_{kl} (v_k - v_l) + \sum_l S_{kl} v_l - L_k v_l
\]

- **M-I coupling**

\[
\Sigma_i \left( E_{cor} - E \right) = jD \\
j = en_i v_i - en_e v_e - q_d n_d v_d
\]
Collision frequency

\[ \nu_{id} = n_d \left\{ 4\pi \left[ \frac{q_d e}{4\pi \varepsilon_0 m_i \left( |v_i - v_d|^2 + v_{thi}^2 \right)} \right]^2 + \pi r_d^2 \right\} \sqrt{|v_i - v_d|^2 + v_{thi}^2} \]

\[ \nu_{ed} = \frac{2\sqrt{2\pi}}{3} n_d \nu_{th} r_d^2 \left( \frac{e\phi_S}{k_B T_e} \right)^2 2 \ln \left( \frac{2k_B T_e}{e\phi_S r_d \lambda_D} \right) \]

\[ \nu_{ei} = 54.5 \times 10^{-6} \frac{n_i}{T_i^{3/2}} \]

\[ \nu_{in} = (2.6 \times 10^{-15}) (n_n + n_i) A^{-1/2} \]

\[ \nu_{en} = (5.4 \times 10^{-16}) n_n T_e^{1/2} \]

\[ \nu_{dn} = n_n \pi r_n^2 \sqrt{|v_d - v_n|^2 + v_{thd}^2} \]

\[ \nu_{wp} = 1.27 \frac{\mu}{M_w} \frac{n_p}{T_i^{3/2}} \]

\[ \nu_{kl} = \frac{m_i n_i}{m_k n_k} \nu_{lk} \]
Ion production

- Ion production rate

\[ S_{k,l} = m_s k n_s n_l + m_k n_l \int_0^\infty \sigma_k F d\lambda \]

\[ \int_0^\infty \sigma_k F d\lambda = 1.184 \times 10^{-8} \text{ [s}^{-1}] \]

<table>
<thead>
<tr>
<th>Reactions</th>
<th>Rates [m$^3$ s$^{-1}$]</th>
<th>References</th>
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<tbody>
<tr>
<td>$\text{H}^+ + \text{H}_2\text{O} \rightarrow \text{H} + \text{H}_2\text{O}^+$</td>
<td>$2.60 \times 10^{-15}$</td>
<td>Burger et al. [2007], Lindsay et al. [1997]</td>
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<td>$\text{O}^+ + \text{H}_2\text{O} \rightarrow \text{O} + \text{H}_2\text{O}^+$</td>
<td>$2.13 \times 10^{-15}$</td>
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<td>$\text{H}_2\text{O}^+ + \text{H}_2\text{O} \rightarrow \text{H}_2\text{O} + \text{H}_2\text{O}^+$</td>
<td>$5.54 \times 10^{-16}$</td>
<td>Burger et al. [2007], Lishawa et al. [1997]</td>
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<td>$\text{H}_2\text{O}^+ + \text{H}_2\text{O} \rightarrow \text{OH} + \text{H}_3\text{O}^+$</td>
<td>$3.97 \times 10^{-16}$</td>
<td>Burger et al. [2007], Lishawa et al. [1997]</td>
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<td>$\text{OH}^+ + \text{H}_2\text{O} \rightarrow \text{OH} + \text{H}_2\text{O}^+$</td>
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Burger et al. [2007], Lindsay et al. [1997], Burger et al. [2007], Dressler et al. [2006], Burger et al. [2007], Lishawa et al. [1997], Burger et al. [2007], Itikawa and Mason.[2005], Burger et al. [2007], Itikawa and Mason.[2005], Burger et al. [2007], Itikawa and Mason.[2005], Burger et al. [2007], Itikawa and Mason.[2005].
Model settings

• We find a steady solution of ion velocity.
• 1 dimension (radial direction), 2 $R_S$ to 10 $R_S$
• Grid size
  • 0.1 $R_S$
• Initial condition
  • Ion speed: Co-rotation speed
  • Dust speed: Keplerian speed
• Boundary condition
  • Inner boundary
    • Ion speed: Co-rotation speed
    • Dust speed: Keplerian speed
  • Outer boundary
    • Ion/dust speeds: Gradient of speeds is zero.
Density profile & Dust distribution

• Density profile
  • Electron: Persoon et al. (2005, 2009)
    
    \[ n_w = n_e + \frac{q_d}{e} n_d - n_p \]
    
    \[ n_w : n_p = 4 : 1 \]

• Thickness of dust distribution \( D \)
  • \( D = R_S \)
  • \( D = 2 \, R_S \)
  • \( D = 3 \, R_S \)
Other parameters

- Radius of dusts $r_d$: 100 nm
- Dust surface potential $\phi$: -2 V
- Temperature: 2 eV
- Quantity of dust charge: $q_d = \beta 4 \pi \varepsilon_0 r_d \phi$
  - $\beta = 3.66$
- Ion mass: 18 $m_p$
- Dust mass: $4 \pi \rho r_d^3/3$
  - $\rho = 10^3$ kg/m$^3$
- Ionospheric conductivity $\Sigma_i$: 1 S
Results

- Ion velocity is smaller when dust density is large.
- Ion velocity is also smaller when $D$ is large.
- The inner magnetospheric total current weakens the electric field in Saturn’s ionosphere.
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Comparison with LP observation

- Ion speeds are 50-90% of the ideal co-rotation speed.
- The modeling is consistent with the LP observations when the dust density and/or the thickness of dust distribution is large.
  - $n_d > \sim 10^5 \text{ m}^{-3}$ and/or $D > 1 \text{ Rs}$
Summary

• Co-rotation deviation
  • Dust-plasma interaction
    • The inner magnetospheric total current along a magnetic field line weakens the electric field in Saturn’s ionosphere.
    • The ion speeds approach Keplerian due to the large total current when the ion and dust densities are large.
    • The dust–plasma interaction is significant when the thickness of the dust distribution is large and/or the density of ions and dusts is high.
      • $n_d \max > 10^5 \text{ m}^{-3}$
      • $D > 1 \text{ R}_S$

• Detail is shown by “Sakai et al., 2013, Dust-plasma interaction through magnetosphere-ionosphere coupling in Saturn’s inner magnetosphere, Planet. Space Sci., 75, 11–16, doi:10.1016/j.pss.2012.11.003”.