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

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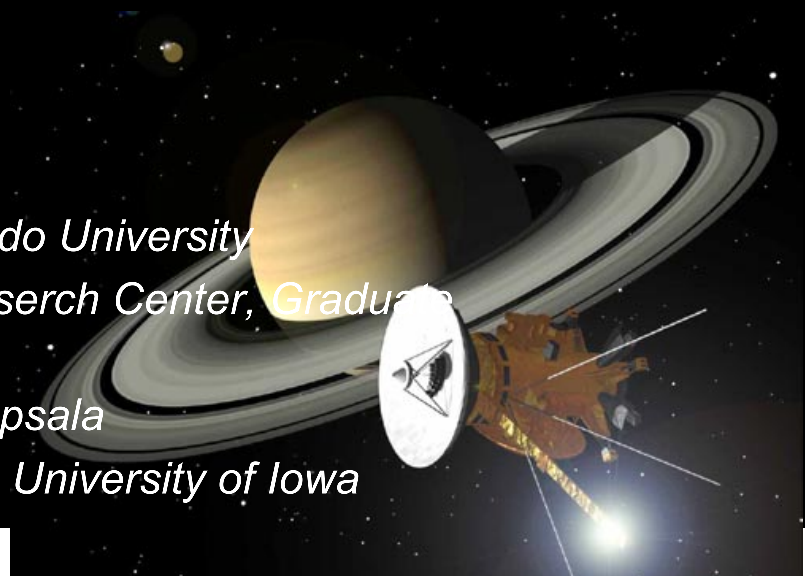
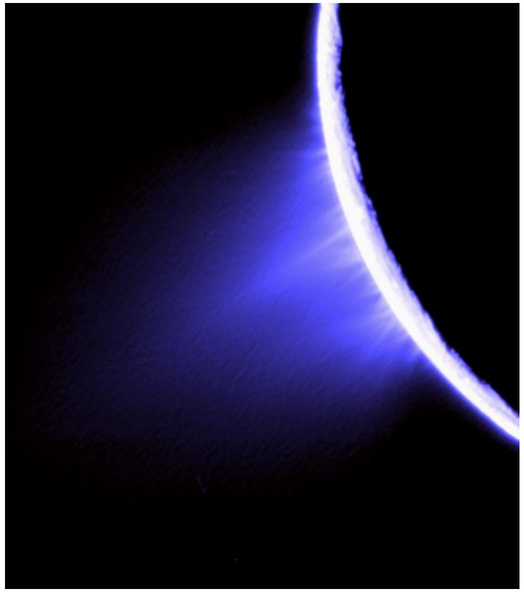
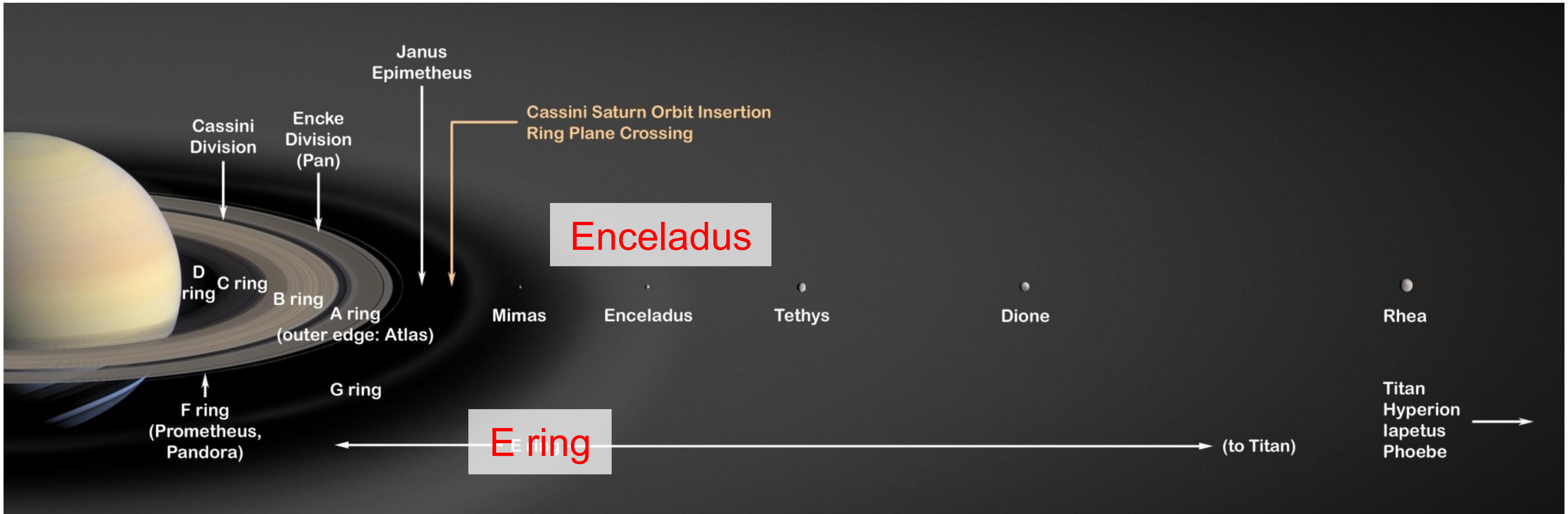


Enceladus plume & E ring

- Enceladus plume (~3.95 Rs)
  - Main component
    - Water gas [*Waite et al.*, 2006]
- E ring
  - Location
    - 3 – 8 Rs
  - Composition
    - H_XO^+ (~80 %) [*Young et al.*, 2005]
    - Dusts [*Kurth et al.*, 2006; *Kempf et al.*, 2008]
  - Source
    - Mainly Enceladus plume



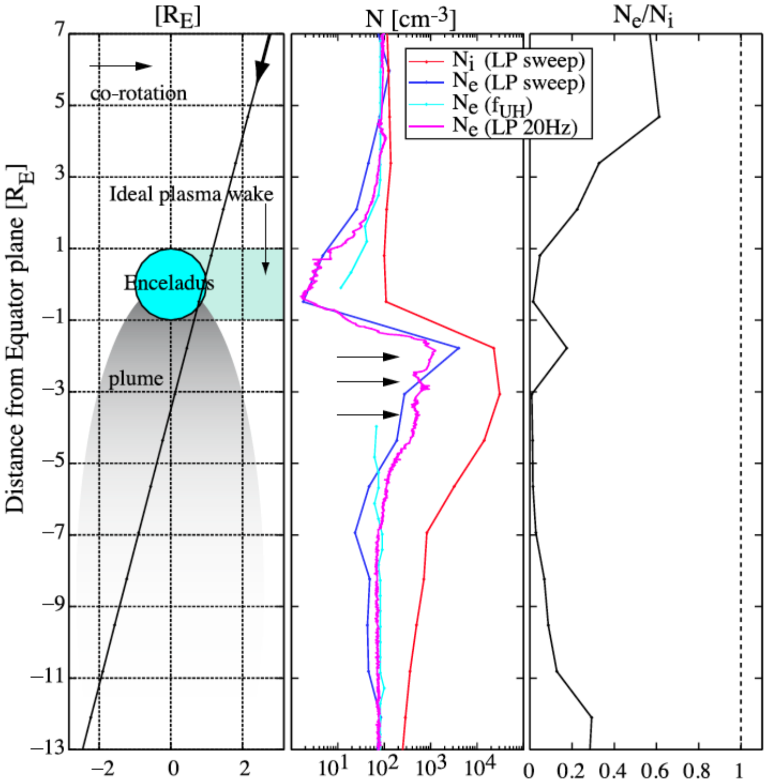
Enceladus plume [NASA/JPL/Space Science Institute]

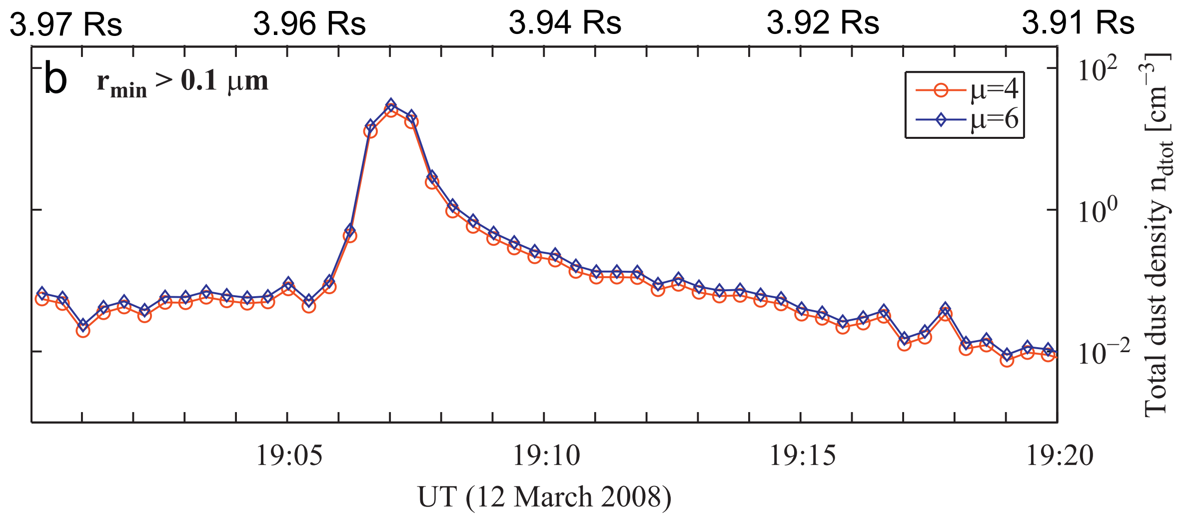


Depletion of electrons

- 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].





Density profile [*Morooka et al.*, 2011], Total dust density [*Shafiq et al.*, 2011]

Co-rotation deviation by dusts?

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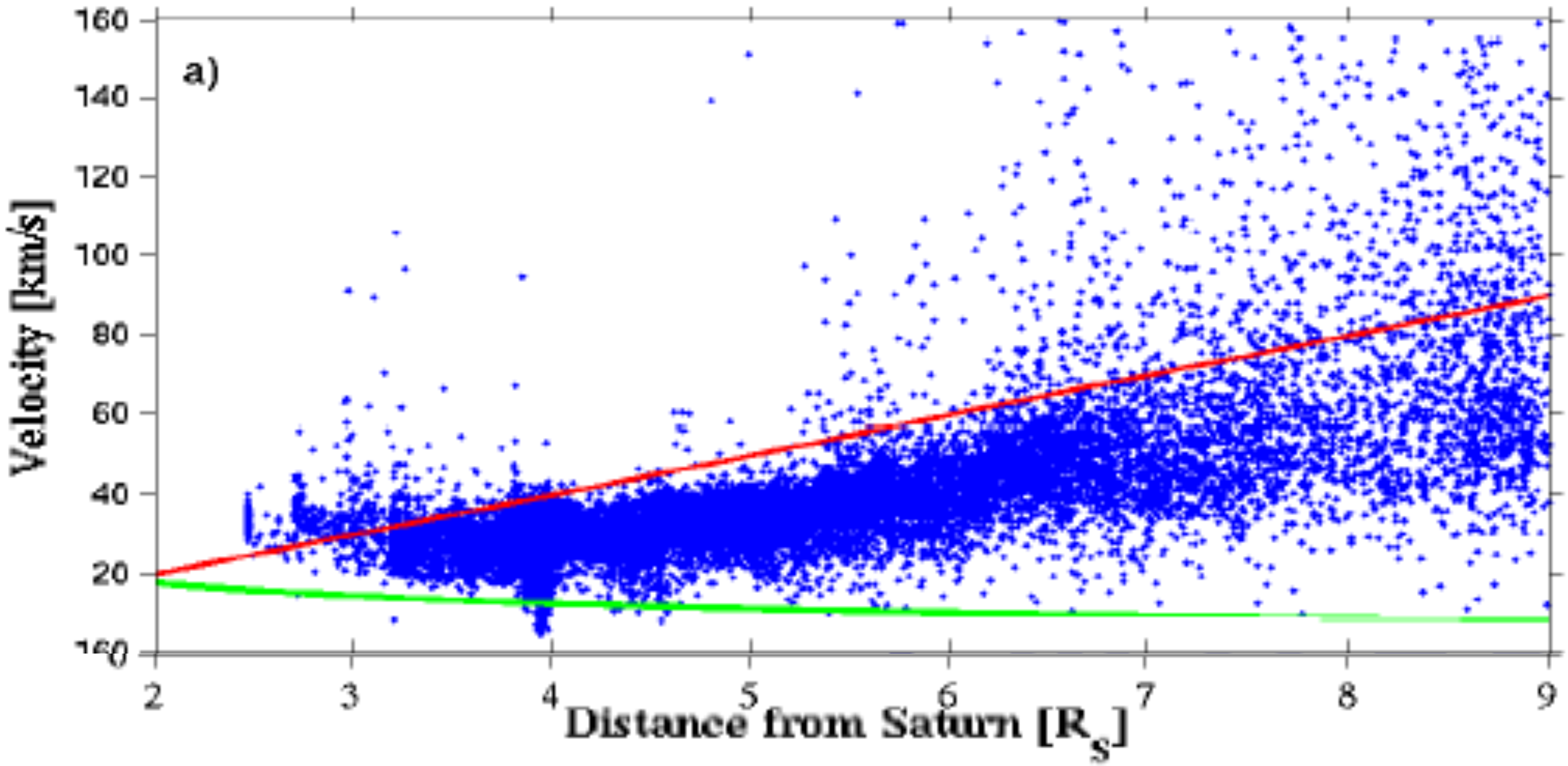
- Observations of inner magnetospheric ion by Cassini RPWS/LP
  - Ion speed is smaller than the co-rotation velocity [*Holmberg et al.*, 2012].
    - May dust affects the motion of ion?



Ion speed [*Holmberg et al.*, 2012]

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

$\mathbf{j}$	Current
$\mathbf{E}_{cor}$	Co-rotational Electric field
Σ_i	Ionospheric conductivity
D	Thickness of dust

- Primitive equations (a multi-fluid equations)

$$\frac{\partial \rho_k}{\partial t} + \nabla \cdot (\rho_k \mathbf{v}_k) = S_k - L_k$$

$$\frac{\partial(\rho_k \mathbf{v}_k)}{\partial t} + \nabla \cdot (\rho_k \mathbf{v}_k \mathbf{v}_k) = n_k q_k (\mathbf{E} + \mathbf{v}_k \times \mathbf{B}) - \nabla p_k - \rho_k \mathbf{g} + \sum_l \rho_k \nu_{kl} (\mathbf{v}_k - \mathbf{v}_l) + \sum_l S_{k,l} \mathbf{v}_l - L_k \mathbf{v}_l$$

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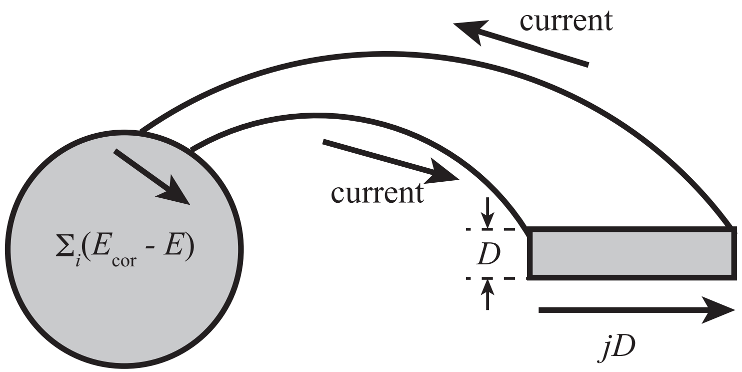
$$\rho_k \frac{\partial \mathbf{v}_k}{\partial t} + \rho_k (\mathbf{v}_k \cdot \nabla) \mathbf{v}_k = n_k q_k (\mathbf{E} + \mathbf{v}_k \times \mathbf{B}) - \nabla p_k - \rho_k \mathbf{g} + \sum_l \rho_k \nu_{kl} (\mathbf{v}_k - \mathbf{v}_l) - \sum_l S_{k,l} (\mathbf{v}_k - \mathbf{v}_l)$$

- M-I coupling

$$\Sigma_i (\mathbf{E}_{cor} - \mathbf{E}) = \mathbf{j} D$$

$$\mathbf{j} = e n_i \mathbf{v}_i - e n_e \mathbf{v}_e - q_d n_d \mathbf{v}_d$$



Collision frequency

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

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

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

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

$$\nu_{en} = \left(5.4 \times 10^{-16} \right) n_n T_e^{1/2}$$

$$\nu_{dn} = n_n \pi r_n^2 \sqrt{\left| v_d - v_n \right|^2 + v_{thd}^2}$$

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

$$\nu_{kl} = \frac{m_l n_l}{m_k n_k} \nu_{lk}$$

Ion production

- Ion production rate

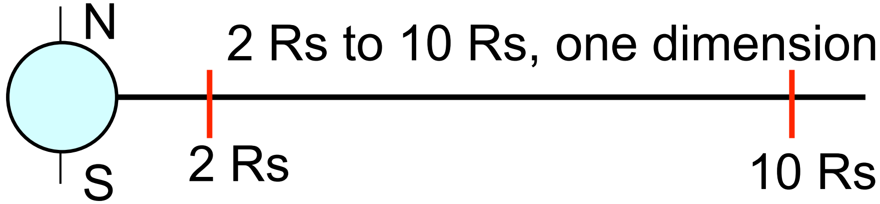
$$S_{k,l} = m_s \kappa n_s n_l + m_k n_l \int_0^\infty \sigma_k F d\lambda$$

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

Reactions	Rates $[m^3\ s^{-1}]$	References
$H^+ + H_2O \rightarrow H + H_2O^+$	2.60×10^{-15}	Burger et al. [2007], Lindsay et al. [1997]
$O^+ + H_2O \rightarrow O + H_2O^+$	2.13×10^{-15}	Burger et al. [2007], Dressler et al. [2006]
$H_2O^+ + H_2O \rightarrow H_2O + H_2O^+$	5.54×10^{-16}	Burger et al. [2007], Lishawa et al. [1997]
$H_2O^+ + H_2O \rightarrow OH + H_3O^+$	3.97×10^{-16}	Burger et al. [2007], Lishawa et al. [1997]
$OH^+ + H_2O \rightarrow OH + H_2O^+$	5.54×10^{-16}	Burger et al. [2007], Itikawa and Mason.[2005]
$H_2O + e \rightarrow H_2O^+ + 2e$		Burger et al. [2007], Itikawa and Mason.[2005]
$H_2O + e \rightarrow OH^+ + H + 2e$	10^{-18} (total)	Burger et al. [2007], Itikawa and Mason.[2005]
$H_2O + e \rightarrow O^+ + H_2 + 2e$		Burger et al. [2007], Itikawa and Mason.[2005]
$H_2O + e \rightarrow H^+ + OH + 2e$	10^{-22}	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



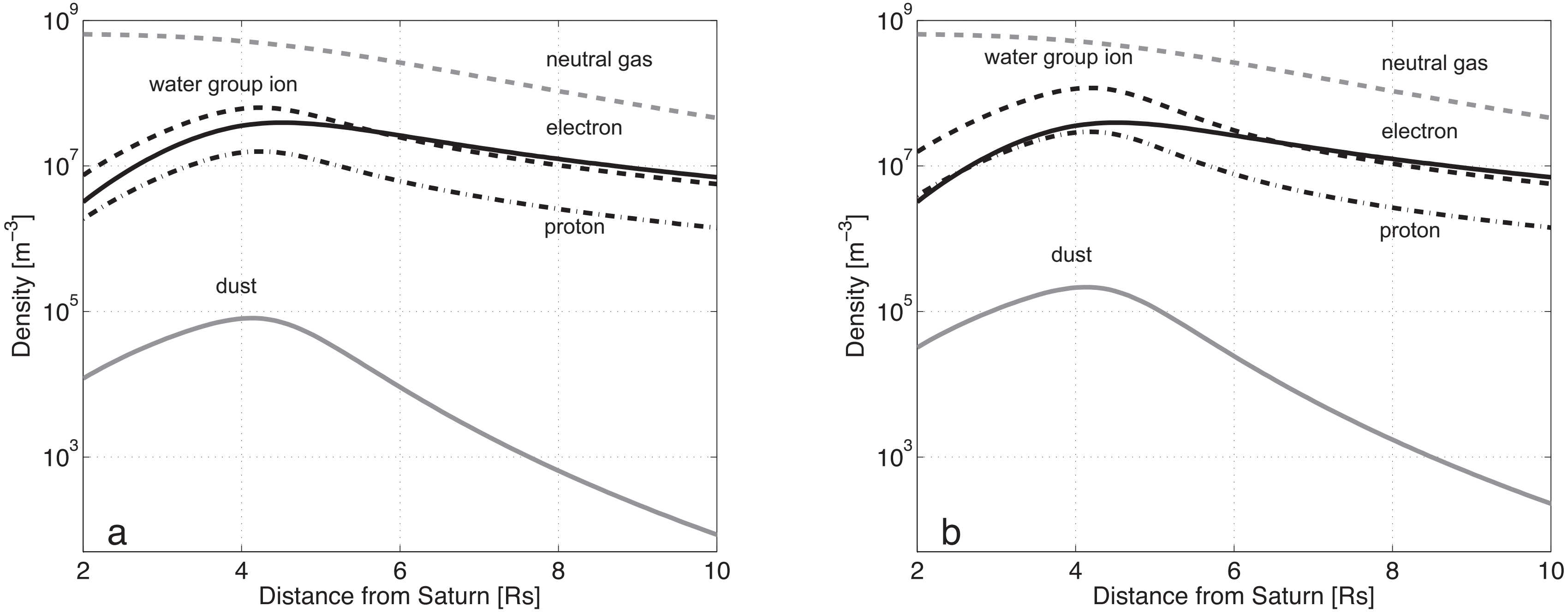
- Initial condition
  - Ion speed: Co-rotation speed
  - Dust speed: Keplerian speed
- Boundary condition
  - Inner boundary
    - Ion speed: Co-rotation speed
    - Dust speed: Keplerian speed
  - Outer boundary
    - Ion/dust speeds: Gradient of speeds is zero.

Density profile & Dust distribution

- Density profile
  - Electron: *Persoon et al.* (2005, 2009)

$$n_w = n_e + \frac{q_d}{e} n_d - n_p$$

$$n_w : n_p = 4 : 1$$



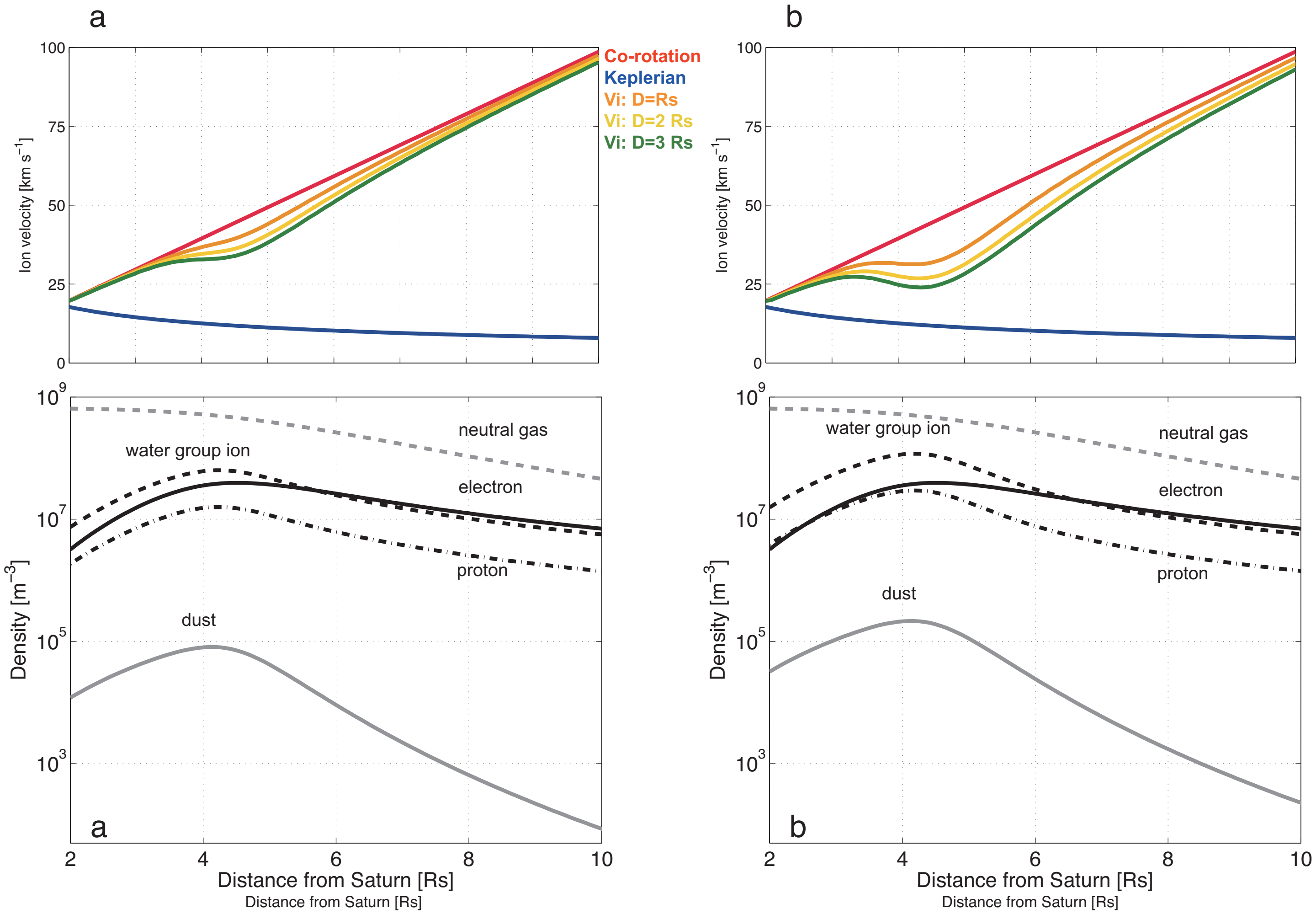
- Thickness of dust distribution *D*
  - $D = R_S$
  - $D = 2\ R_S$
  - $D = 3\ R_S$

Other parameters

- Radius of dusts r_d: 100 nm
- Dust surface potential ϕ: -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 Σ_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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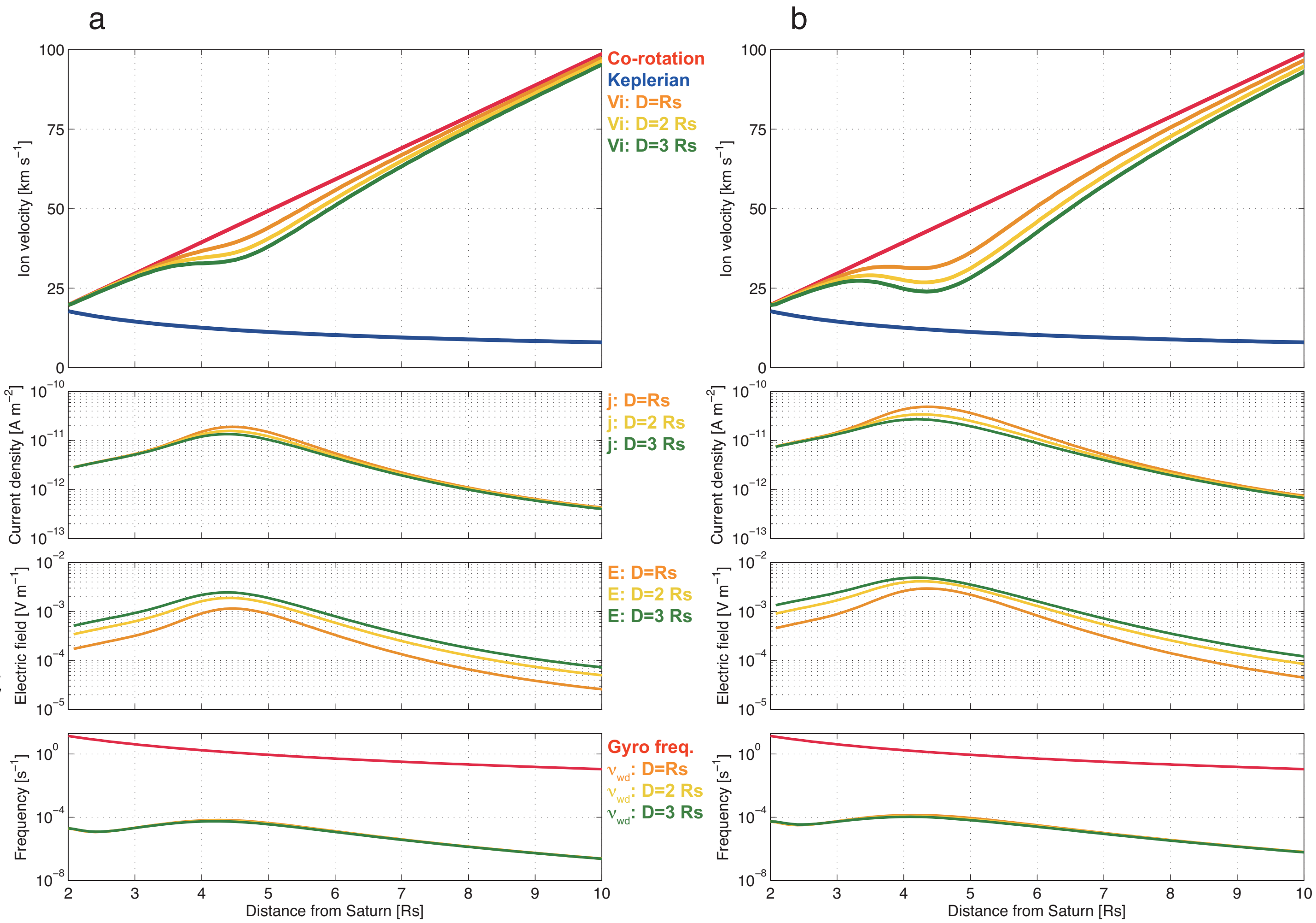

Comparison with LP observation

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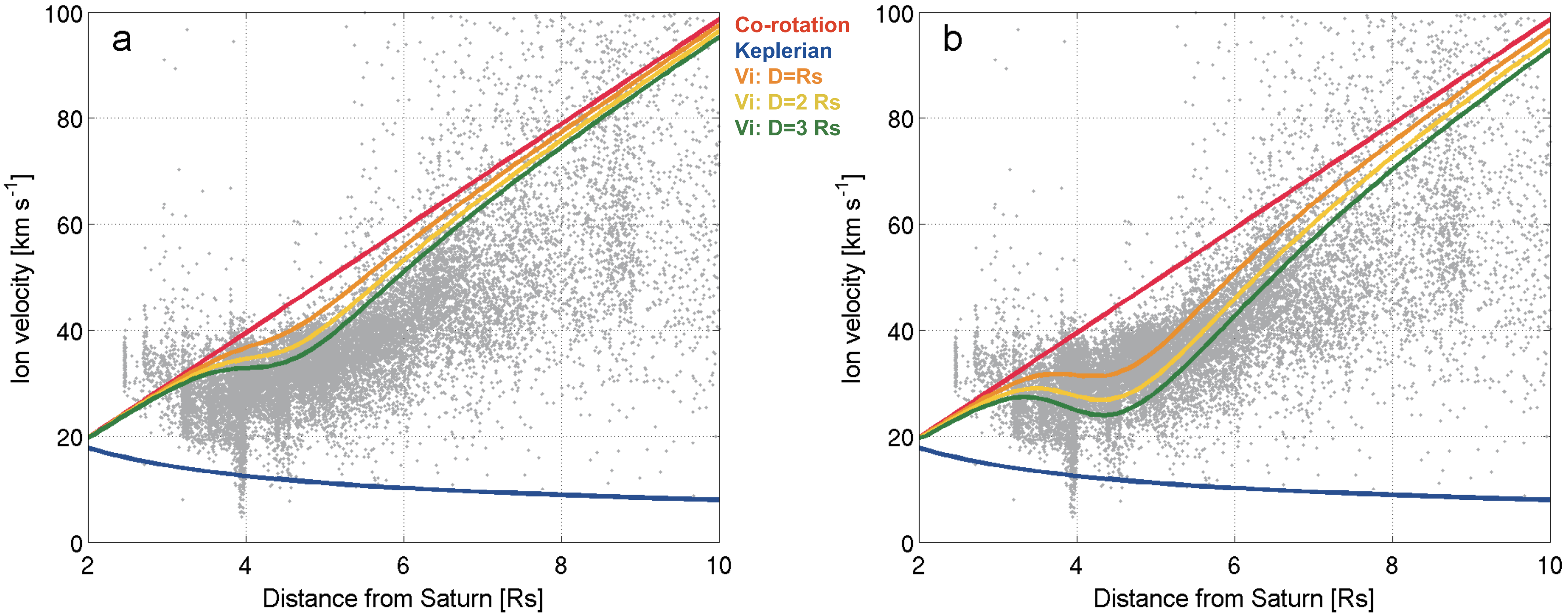

- Ion speeds are 50-90% of the ideal co-rotation speed.
- The modeling is consistent with the LP observations when the dust density and/or the thickness of dust distribution is large.
  - $n_d > \sim 10^5$ m^{-3} and/or $D > 1$ Rs

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.
      - $n_{d\ max} > 10^5\ m^{-3}$
      - $D > 1\ R_S$

- 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".