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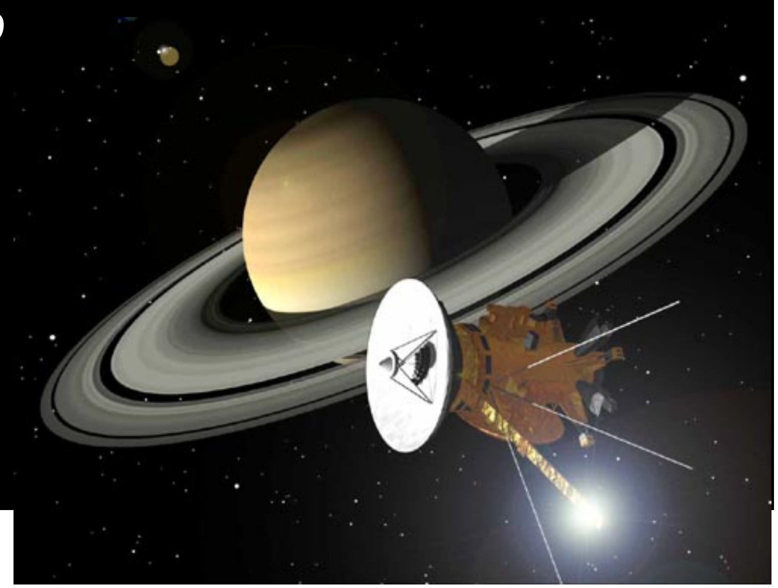
Studies on dust-plasma interaction in Saturn's inner magnetosphere and its magnetosphere-ionosphere coupling

Shotaro Sakai

Planetary and Space Group



Outline of my thesis

Structure of my doctoral thesis

1. General Introduction
2. Enceladus plume observed by Cassini RPWS/LP
3. Modeling of the inner magnetosphere
4. Modeling of the ionosphere
5. Magnetosphere-ionosphere coupling
6. Summary

Outline of my thesis

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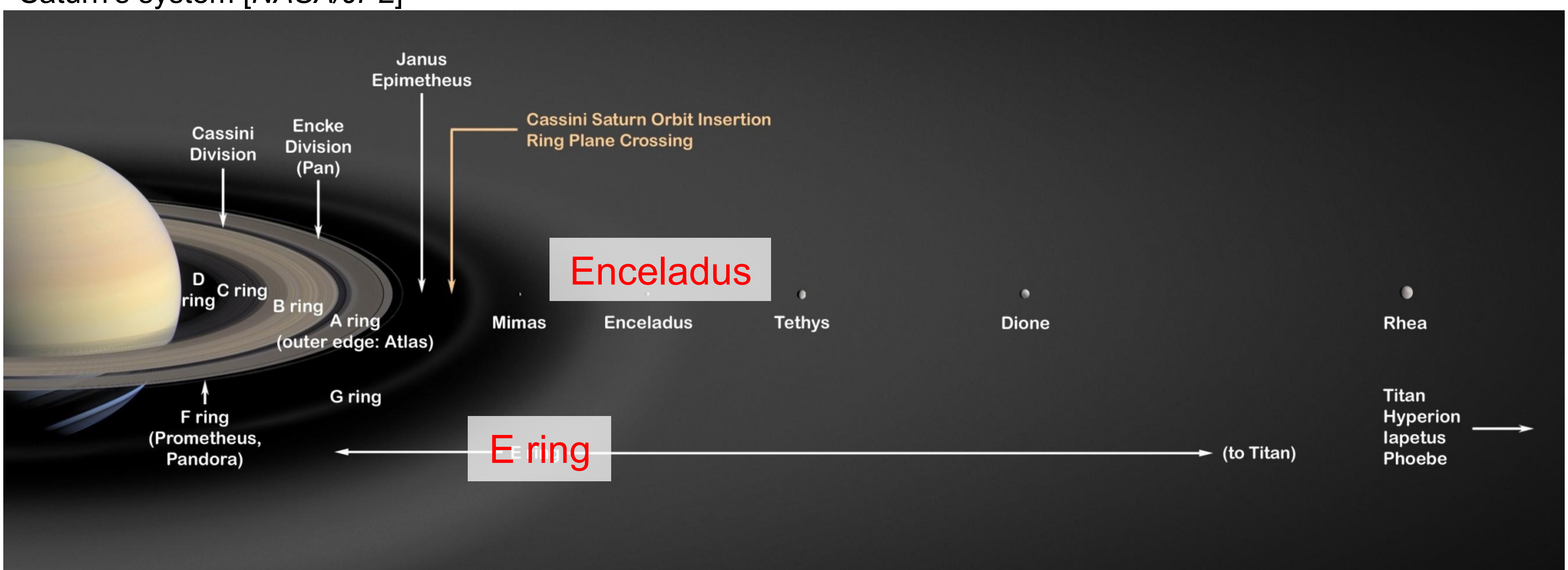
Introduction

Saturn’s system

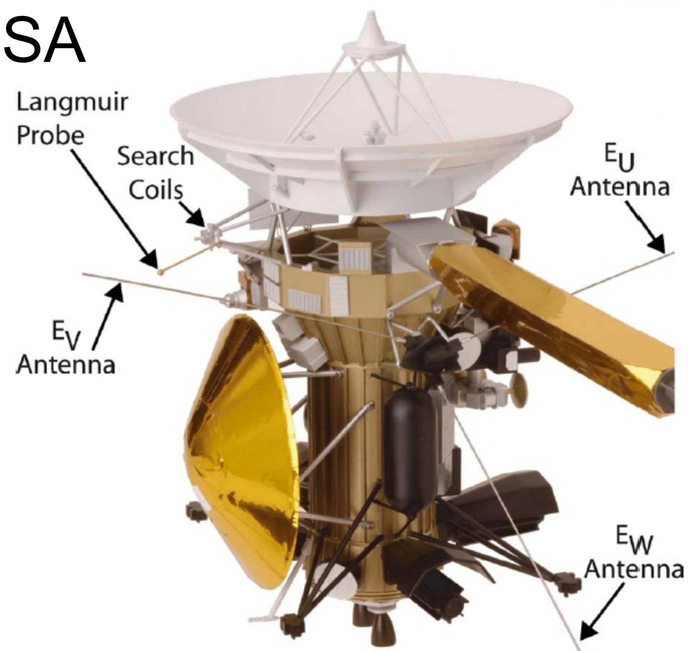
- Equatorial radius: 60,268 km (1 Rs)
- Mass: 5.68×10^{26} kg
- Equatorial gravity: 10.44 m/s^2
- Rotation period: 0.436 day
- Revolution period: 29.46 year
- Magnetic moment: 4.6×10^{18} T/m^3
- Tilt of magnetic axis respect to rotational axis: < 1°
- Satellites#: 64
- Rings: D, C, B, A, F, G and E
- Exploration of Saturn: Pioneer 11, Voyager 1 and 2, Cassini

Saturn’s system [*NASA/JPL*]



Cassini

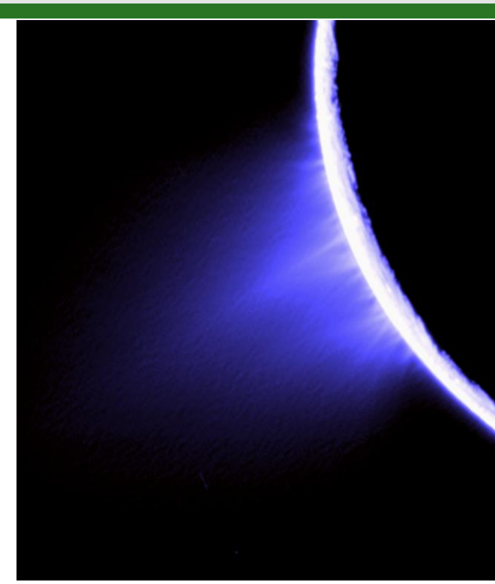
- Outline
  - Launch date: 15 Oct. 1997
  - Development & Operation: NASA, ESA
  - Orbit Insertion: Dec. 2004
  - Now Operating!
    - Until Sep. 2017
- Instruments (3 major)
  - Optical remote sensing
  - Electric-magnetic field, particles and wave observation
  - Microwave remote sensing



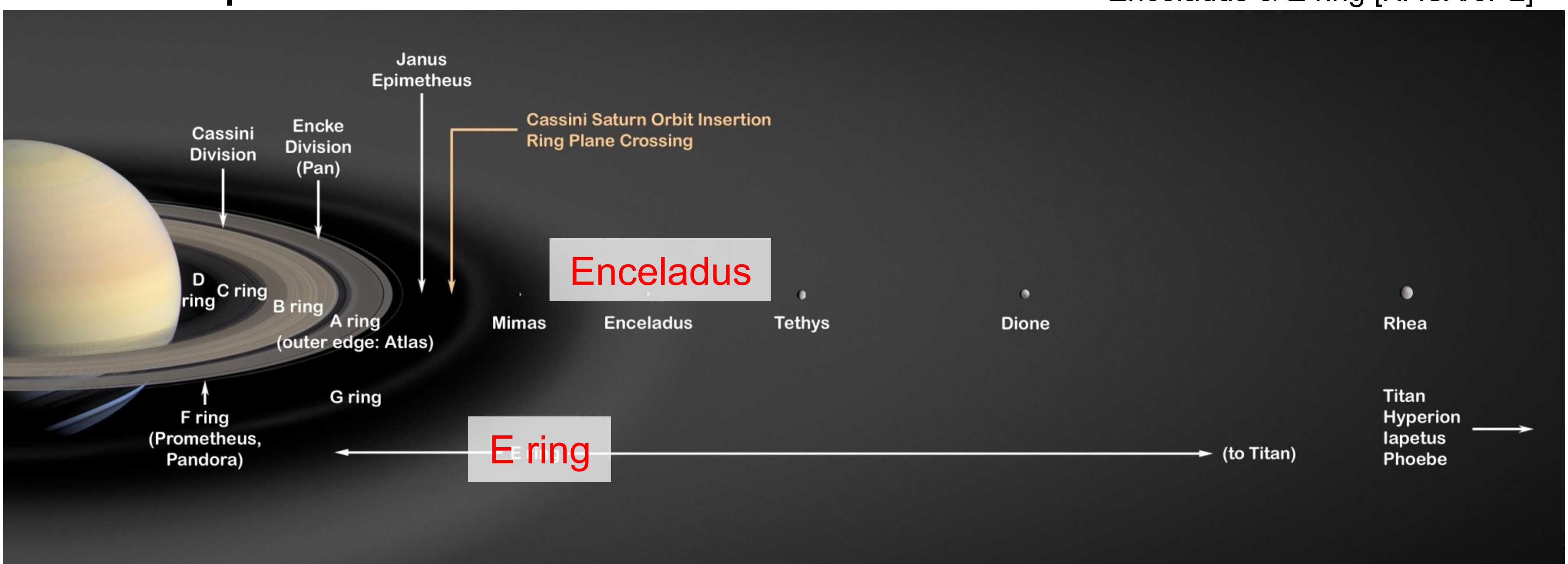
Cassini [*Gurnett et al.*, 2004]

Enceladus plume & E ring

- Enceladus plume (~3.95 Rs)
  - Water gas
- E ring
  - 3 – 8 Rs
  - Water group ion
  - Dust
  - Source: Mainly Enceladus plume
  - Kepler motion

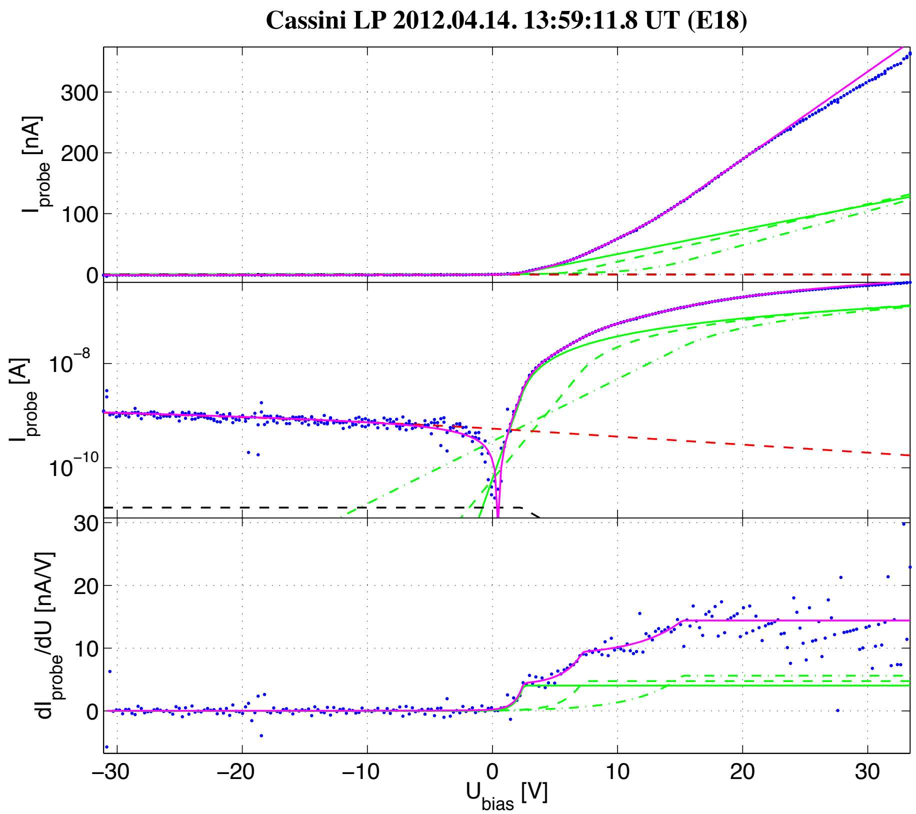


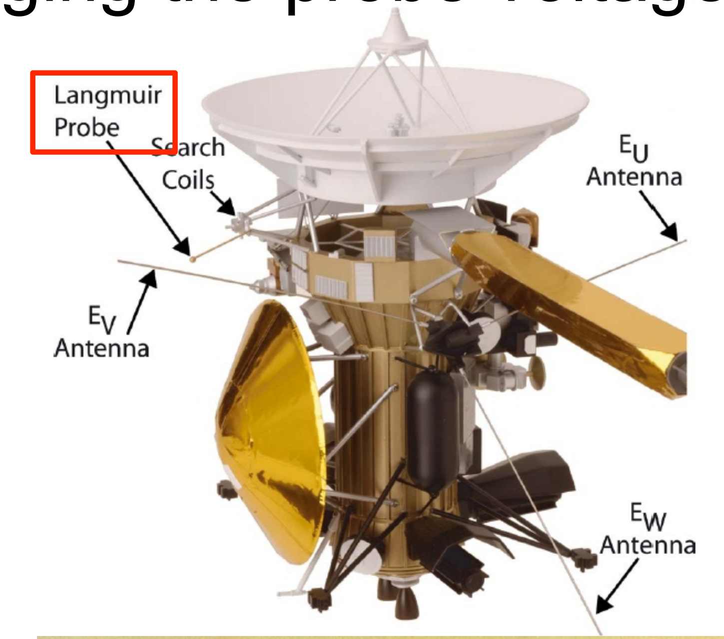
Enceladus & E ring [*NASA/JPL*]

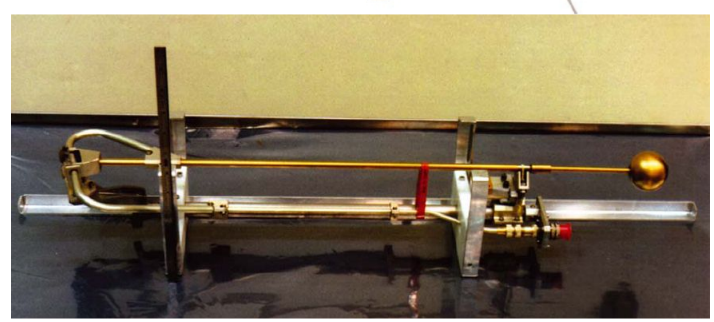


Cassini Langmuir Probe (LP)

- Length: 1.5 m, Diameter: 50 mm
- Titanium
- LP measures currents by changing the probe voltage from -32 to 32 V.



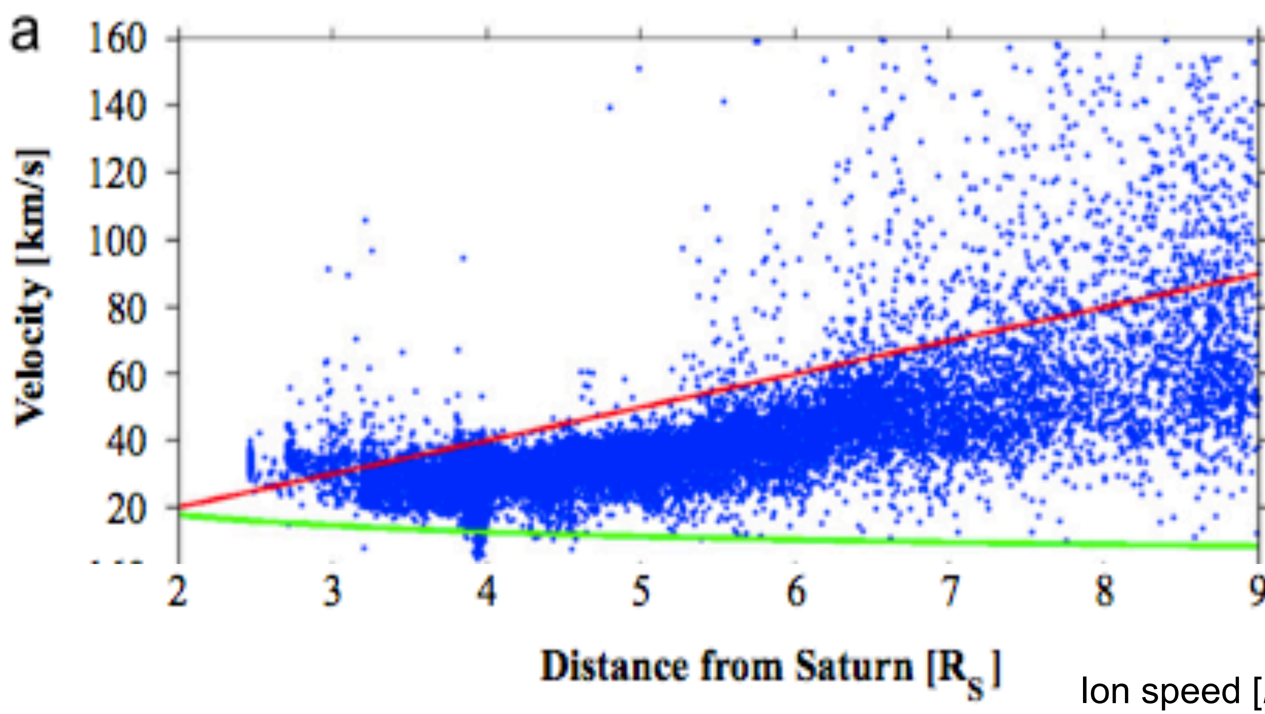




Cassini & Cassini LP [*Gurnett et al.*, 2004]

Co-rotation deviation by dusts?

- Ion observations from the Cassini RPWS/LP in Saturn's magnetosphere
  - Ion has slower speed than the co-rotation [*Wahlund et al.*, 2009; *Morooka et al.*, 2011; *Holmberg et al.*, 2012].



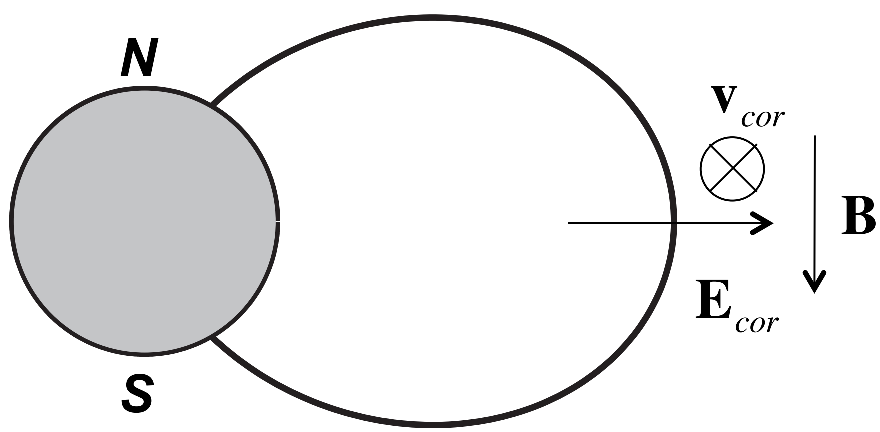
Ion speed [*Holmberg et al.*, 2012]

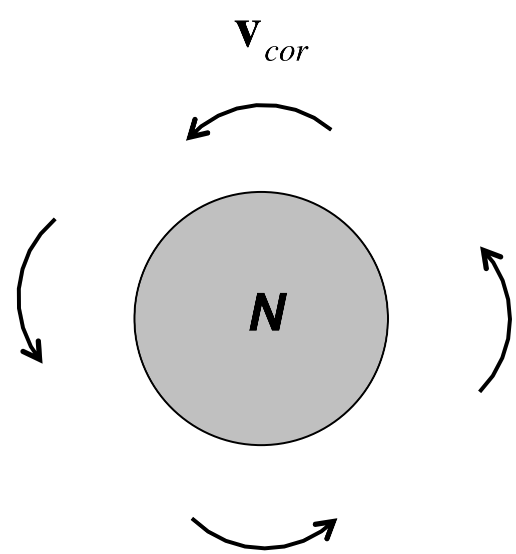
Co-rotation

- Magnetospheric plasma should be co-rotating.

Co-rotation velocity: $$\mathbf{v}_{cor} = \frac{\mathbf{E}_{cor} \times \mathbf{B}}{B^2}$$

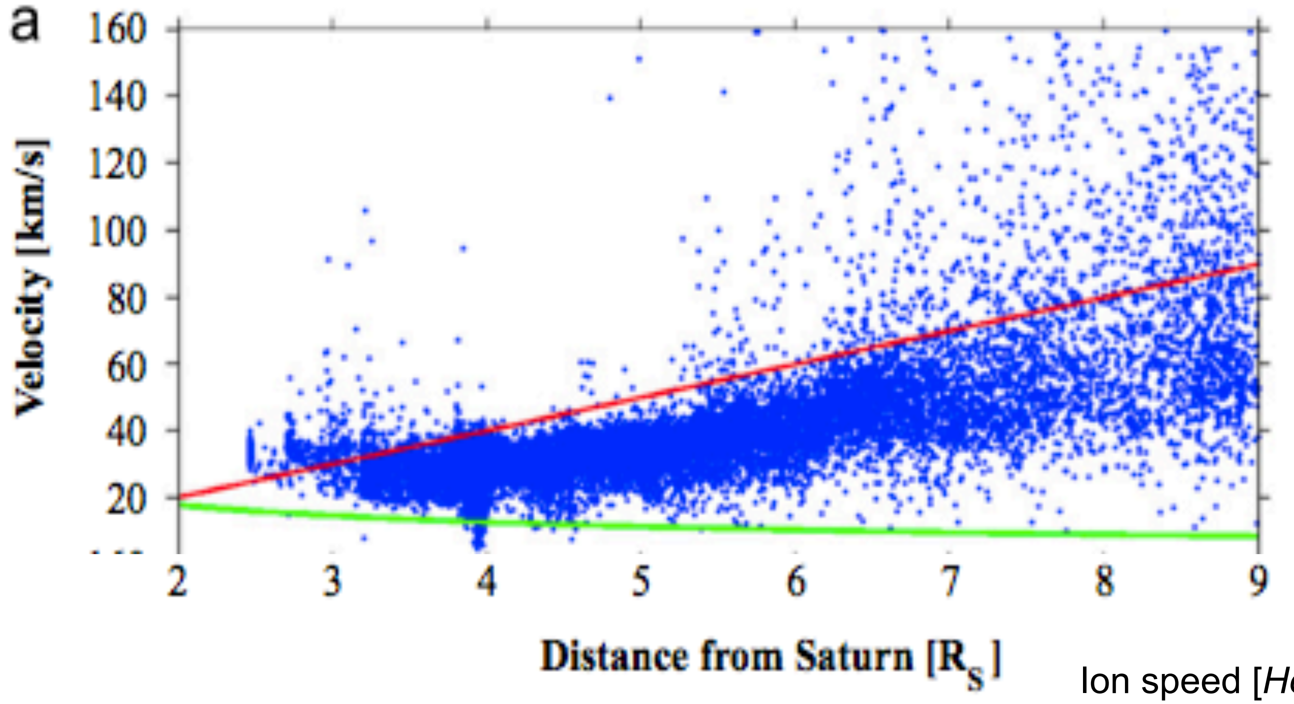
Saturn's case





Co-rotation deviation by dusts?

- Ion observations from the Cassini RPWS/LP in Saturn's magnetosphere
  - Ion has slower speed than the co-rotation [*Wahlund et al.*, 2009; *Morooka et al.*, 2011; *Holmberg et al.*, 2012].
    - Do dusts affect the ion velocities in the inner magnetosphere?



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

Purpose of this thesis

- Investigation of dust-plasma interaction and magnetosphere-ionosphere coupling in the Saturn's inner magnetosphere
- Understanding of generation process for magnetospheric current, electric field and ion-dust collision
- Understanding of relationship of ionospheric conductivity with the magnetospheric ion speed

Plasma in the plume

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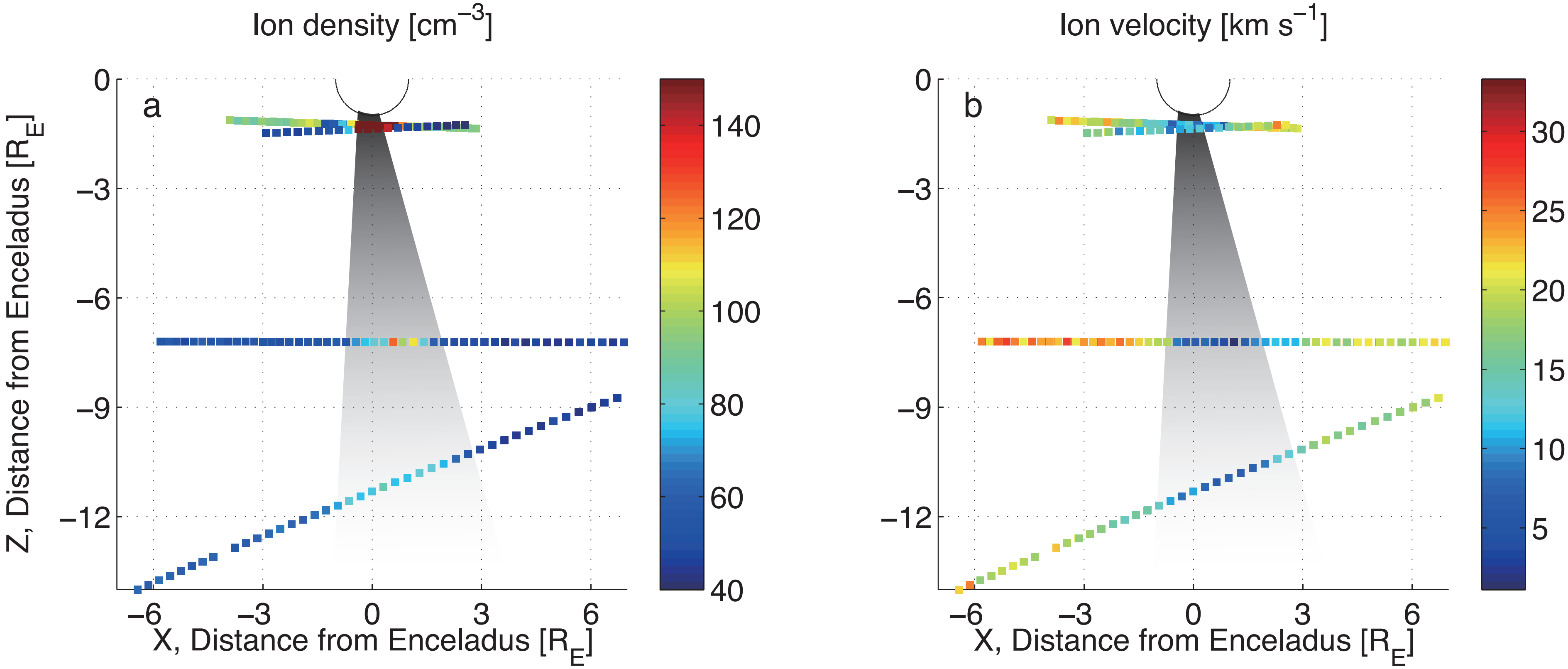


- Density
  - $N_e/N_i < 0.01$ at 1.3 R_E

    ~ 0.7 at 11 R_E
- Ion speed
  - $V_i \sim V_{Kepler}$

Ion density and speed in plume [*Sakai et al.*, in prep.]

Charged dust in the plume

- Dust density

~1.3 R_E

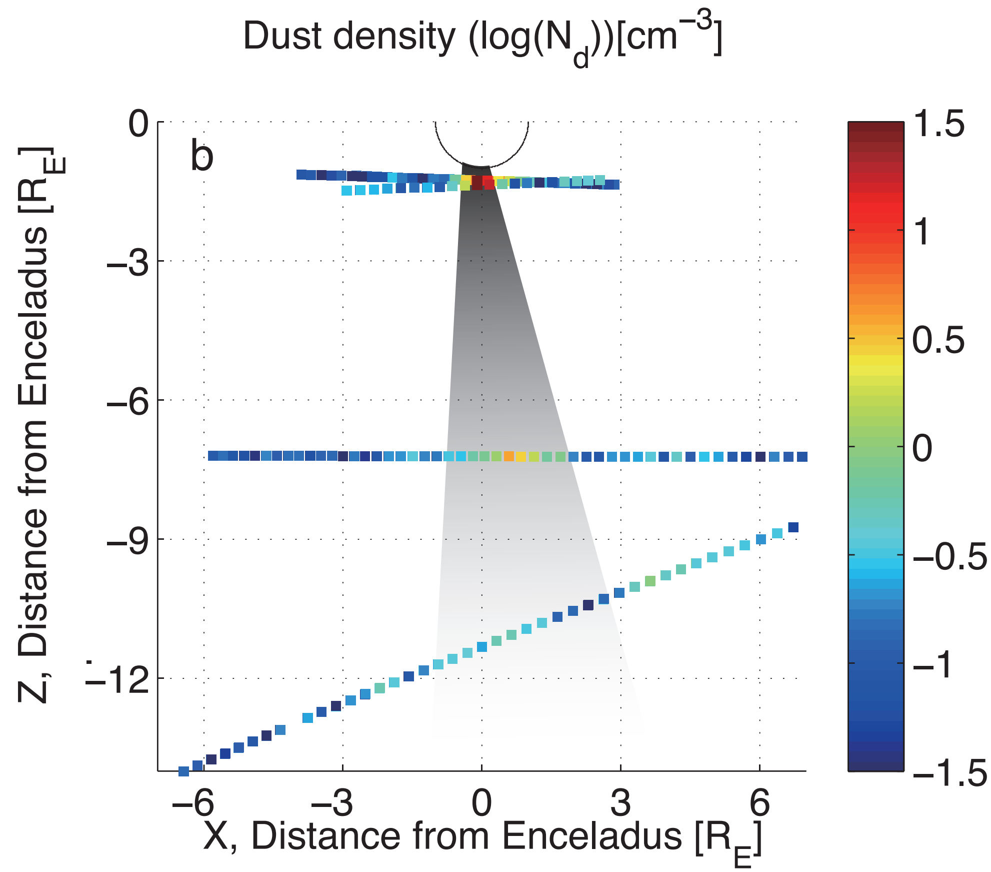
N_{dmax} > 10 cm^{-3}

~7 R_E

N_{dmax} ~ 1 cm^{-3}

~11 R_E

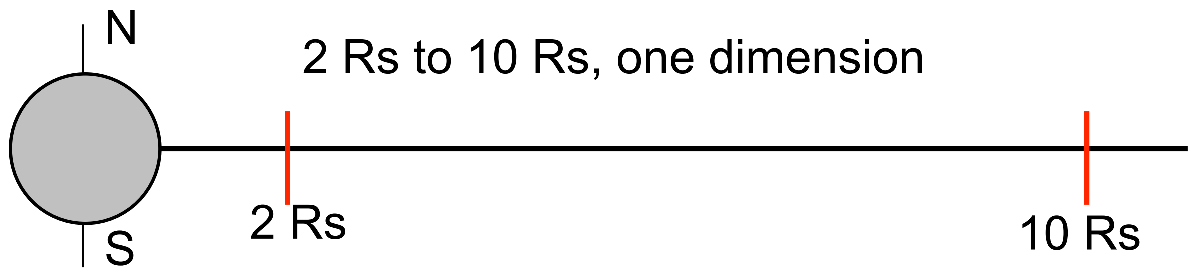
N_{dmax} ~ 0.1 cm^{-3}



Modeling of the inner magnetosphere

Model

- Multi-fluid model (H^+, H_2O^+, dust, e^-)
- 1 dimension (radial direction), 2 R_S to 10 R_S
  - V_r, V_ϕ are calculated.



- Initial condition
  - Ion speed: Co-rotation speed; Dust speed: Keplerian speed
- Boundary condition
  - Inner boundary
    - Ion speed: Co-rotation speed; Dust speed: Keplerian speed
  - Open outer boundary

Inner magnetospheric model

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- Momentum equations
  - H^+, H_2O^+, e^- and dust

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

Chemical term

- Dust: $q_d = 4\pi\varepsilon_0 r_d \phi$
  - r_d = 100 nm; ϕ = -2 V

S_k	Production rate
n_k	Number density
$\mathbf{B}$	Magnetic field
q_d	Charge quantity of dust
r_d	Dust radius
ϕ	Dust surface potential
ε_0	Permittivity

$\mathbf{V}_k$	Velocity
$\mathbf{E}$	Electric field
$\mathbf{g}$	Gravity
ρ_k	Mass density
p	Pressure
e	Charge quantity
ν_{kl}	Collision frequency

Chemical reactions

- For ion production rate
  - Water group ion and H^+
  - 9 reactions

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]

Inner magnetospheric model

- Momentum equations
  - H^+, H_2O^+, e^- and dust

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

Electric field — Collision term — Chemical term

- Dust: $q_d = 4\pi\varepsilon_0 r_d \phi$
  - r_d = 100 nm; ϕ = -2 V

S_k	Production rate
n_k	Number density
$\mathbf{B}$	Magnetic field
q_d	Charge quantity of dust
r_d	Dust radius
ϕ	Dust surface potential
ε_0	Permittivity

$\mathbf{V}_k$	Velocity
$\mathbf{E}$	Electric field
$\mathbf{g}$	Gravity
ρ_k	Mass density
p	Pressure
e	Charge quantity
ν_{kl}	Collision frequency

Electric field

- M-I coupling for deriving electric field, E

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

$$\mathbf{j} = en_i\mathbf{v}_i - en_e\mathbf{v}_e - q_d n_d \mathbf{v}_d$$

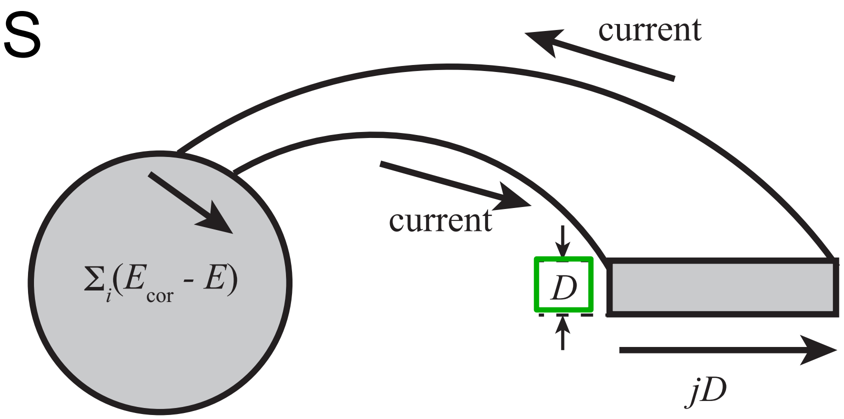
↓ ↓ ↓

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

D: Thickness of dust distribution

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

- Ionospheric conductivity Σ_i: 1 S



Density profile & Thickness of dust

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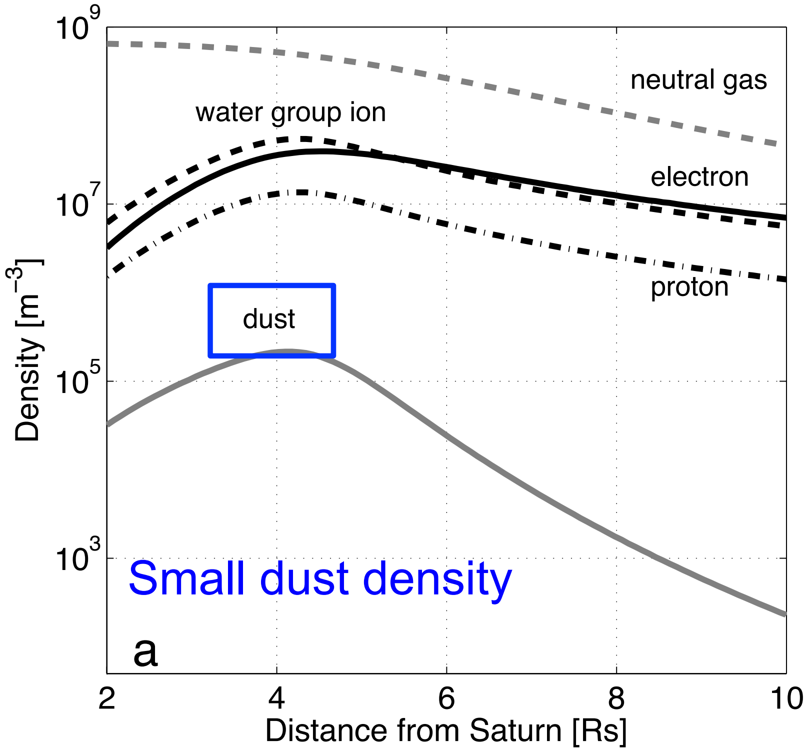
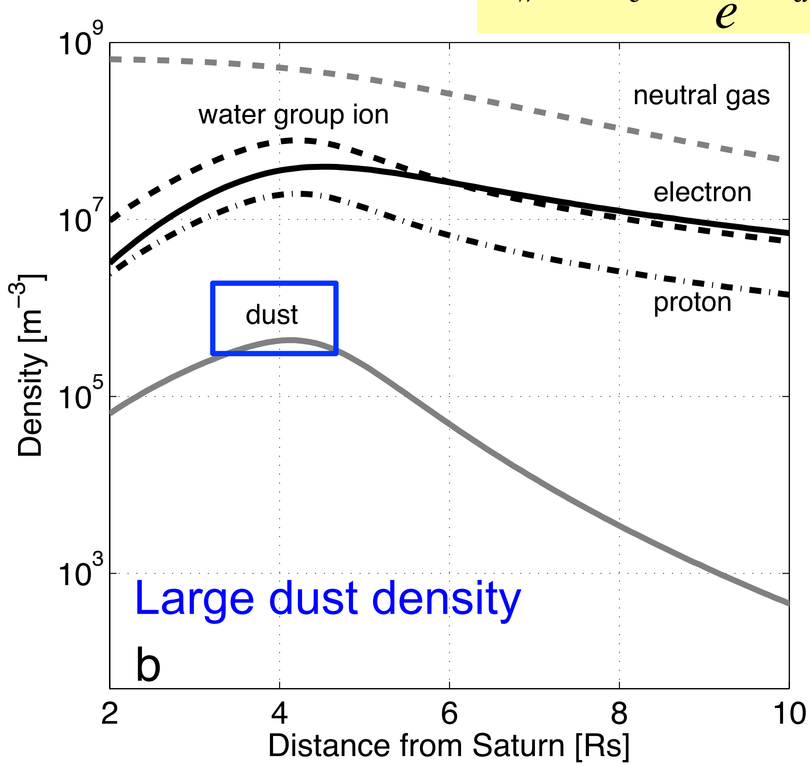
- 2 cases for dust density N_d

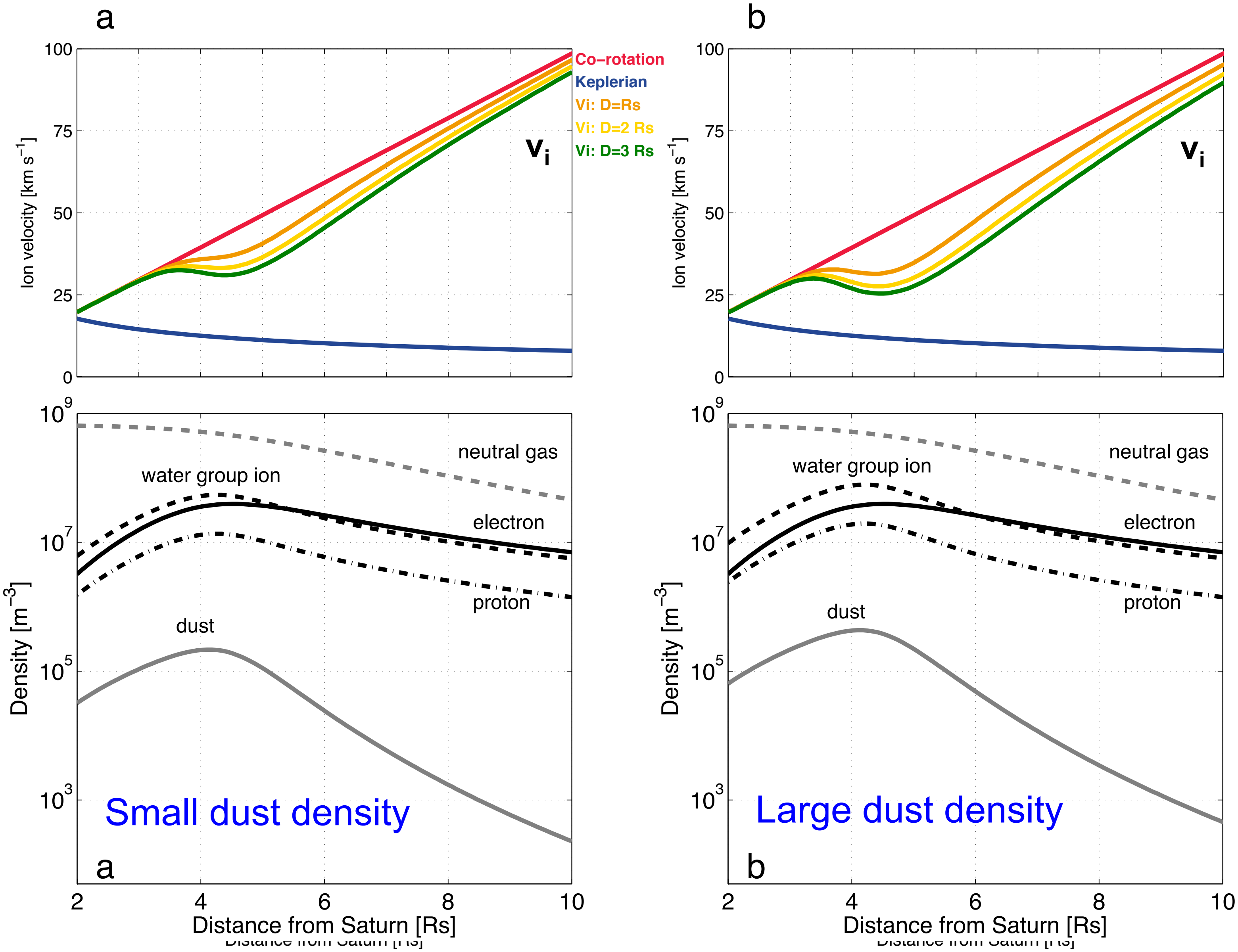
$$n_w = n_e + \frac{q_d}{e} n_d - n_p$$





- 3 cases for thickness of dust distribution *D*
  1. $D = R_S$
  2. $D = 2\ R_S$
  3. $D = 3\ R_S$

Results: Ion velocity

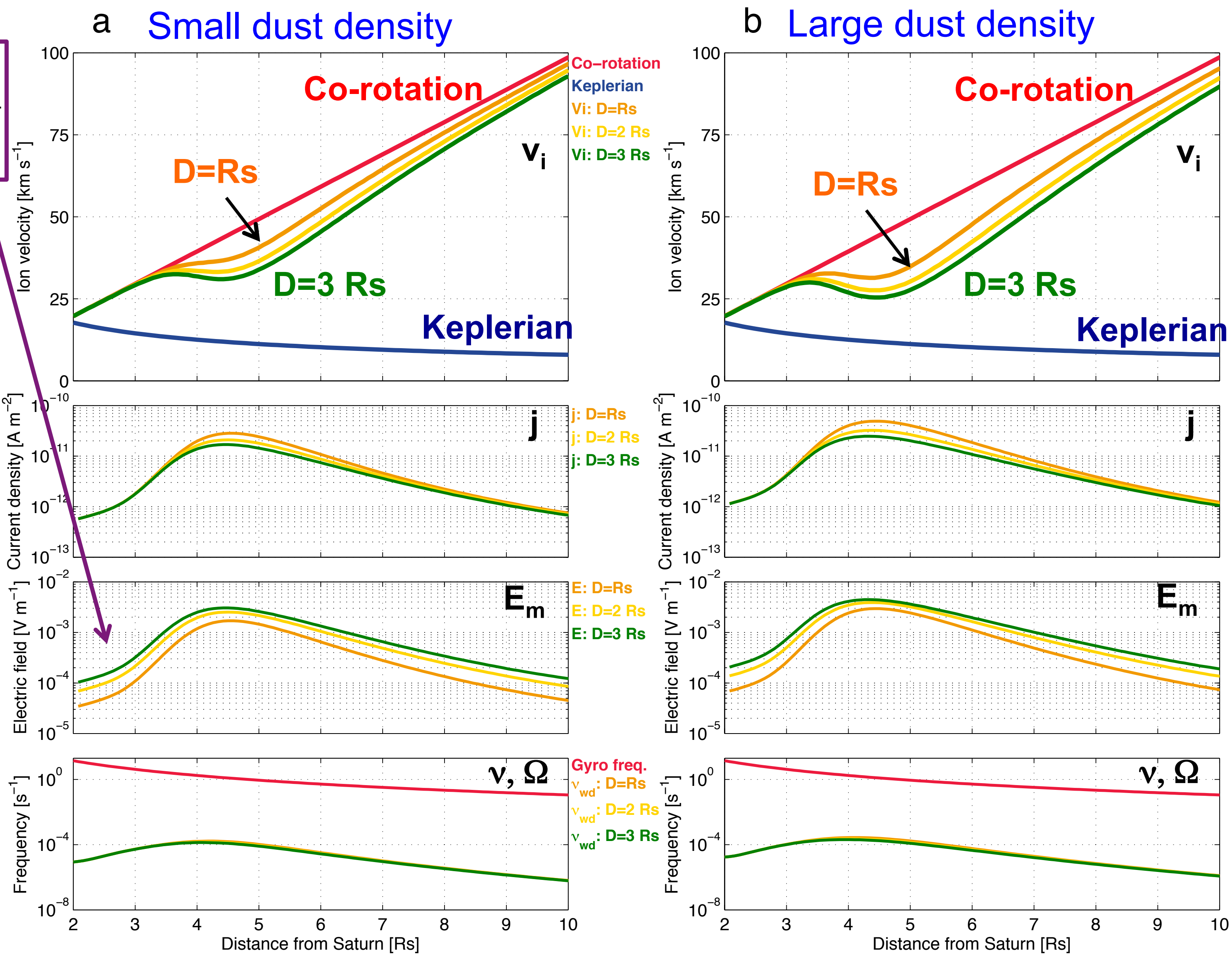


Results: Ion velocity

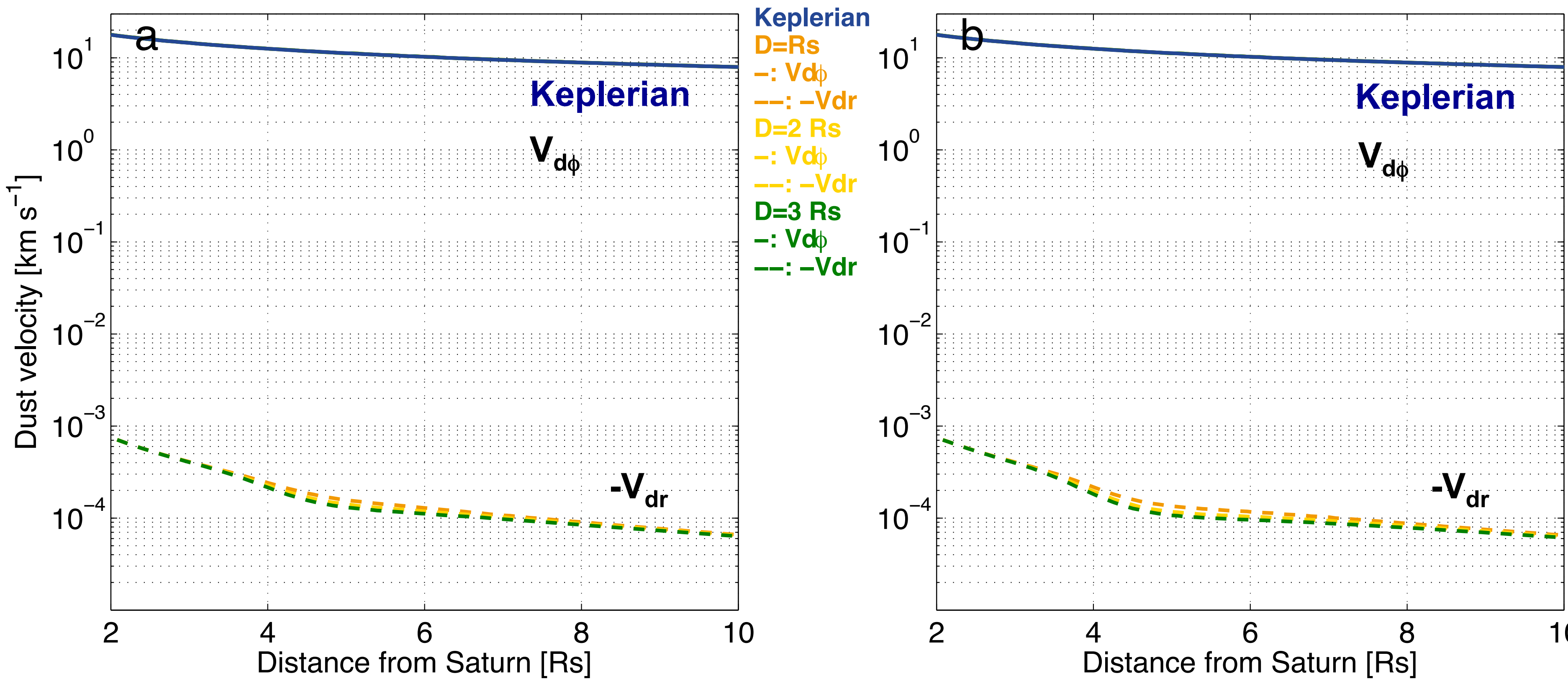
$$\mathbf{E} = \mathbf{E}_{cor} - \frac{\mathbf{j}D}{\Sigma_i}$$

$$\mathbf{v}_i \approx \frac{\mathbf{E} \times \mathbf{B}}{B^2}$$

$$< \mathbf{v}_{cor}$$



Results: Dust velocity



Small dust density

Large dust density

- V_d is almost Keplerian.
  - However, dusts are slightly affected by the electric field.

Comparison with LP observation

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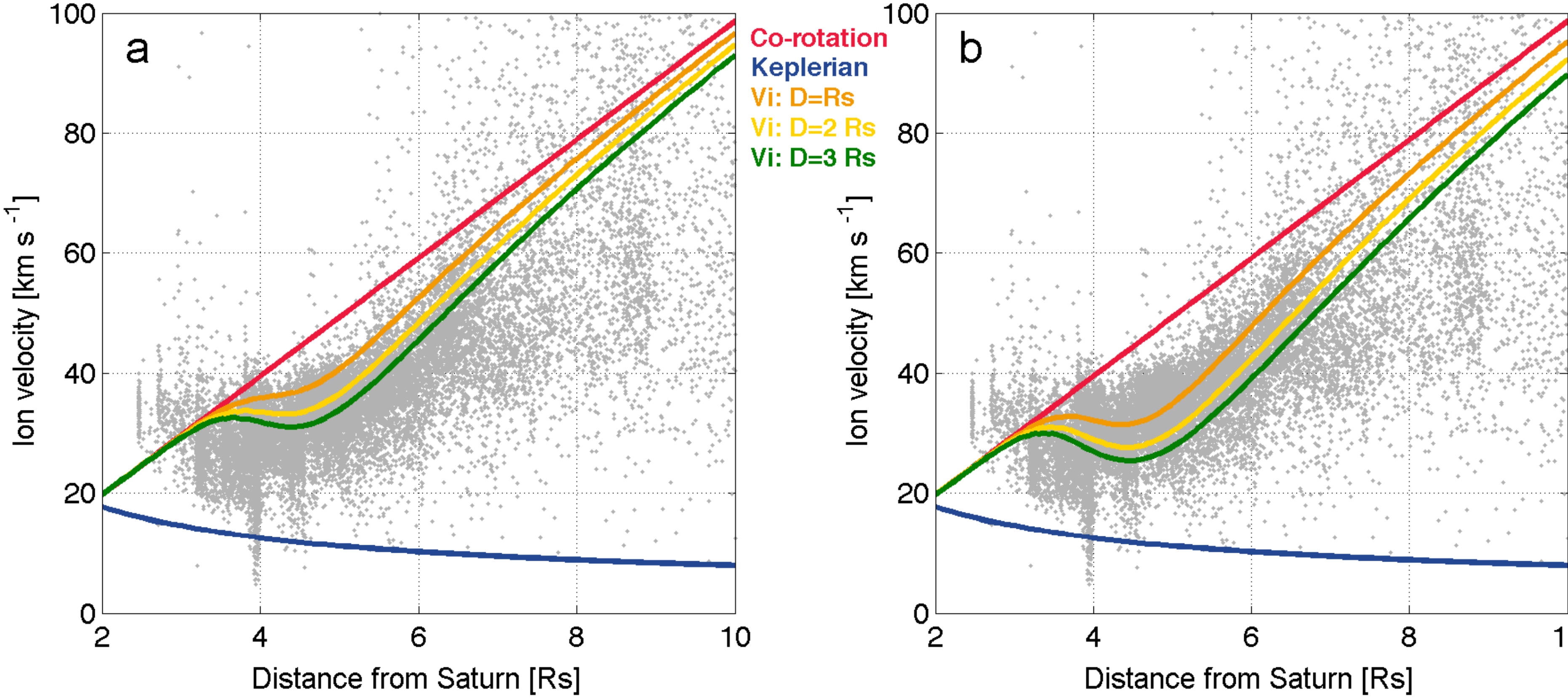


Small dust density

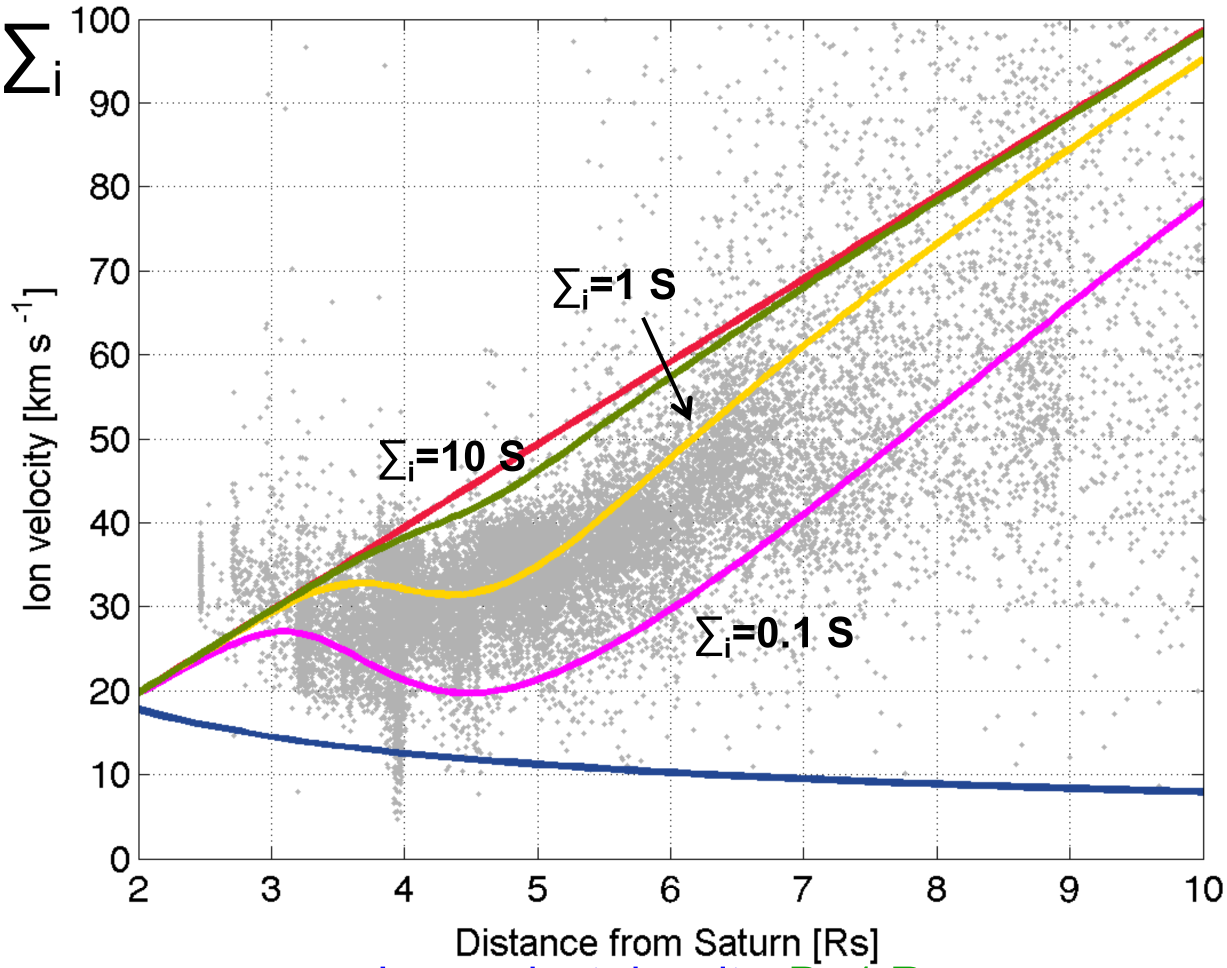
Large dust density

- Consistent with observations in $N_d > \sim 10^5\ m^{-3}$ and/or $D > 1\ R_S$.

Comparison with LP observation

- Change $\sum_i$
  - 0.1 S
  - 1 S
  - 10 S

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



Large dust density, D=1 R_S

- V_i is slower when $\sum_i$ is smaller.
- V_i strongly depends on $\sum_i$.

Summary

- Co-rotation lag
  - Dust-plasma interaction
    - The dust–plasma interaction is significant when *D* is large and/or N_d is high.
      - $N_{d\ max} > \sim 10^5\ m^{-3}$
      - $D > 1\ R_S$
    - The inner magnetospheric total current along a magnetic field line weakens E.
    - V_d is almost the Keplerian.
      - However, dusts are slightly affected by this interaction.
- Ionosphere and magnetosphere are strongly coupled.
  - V_i depends on $\sum_i$.

Modeling of the ionosphere & Magnetosphere-ionosphere coupling

Co-rotation deviation by dusts?

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- Ionospheric Pedersen conductivity
  - E depends on the conductivity.

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

Electric field

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

Pedersen conductivity

$$\sigma_p = \sum_i \frac{\nu_i}{\nu_{in}^2 + \omega_{ci}^2} \frac{n_i e^2}{m_i} + \frac{\nu_e}{\nu_{en}^2 + \omega_{ce}^2} \frac{n_e e^2}{m_e} \qquad \Sigma_i = \int_{z_1}^{z_2} \sigma_p ds$$

- However, it is one of the open questions.
  - ~0.1-100 S [*Connerney et al.*, 1983; *Cheng and Waite*, 1988]
  - ~0.02 S [*Saur et al.*, 2004]
  - 1--10 S [*Cowley et al.*, 2004; *Moore et al.*, 2010]
- We find the ionospheric N_i for deriving $\sum_i$.

Saturn's ionosphere

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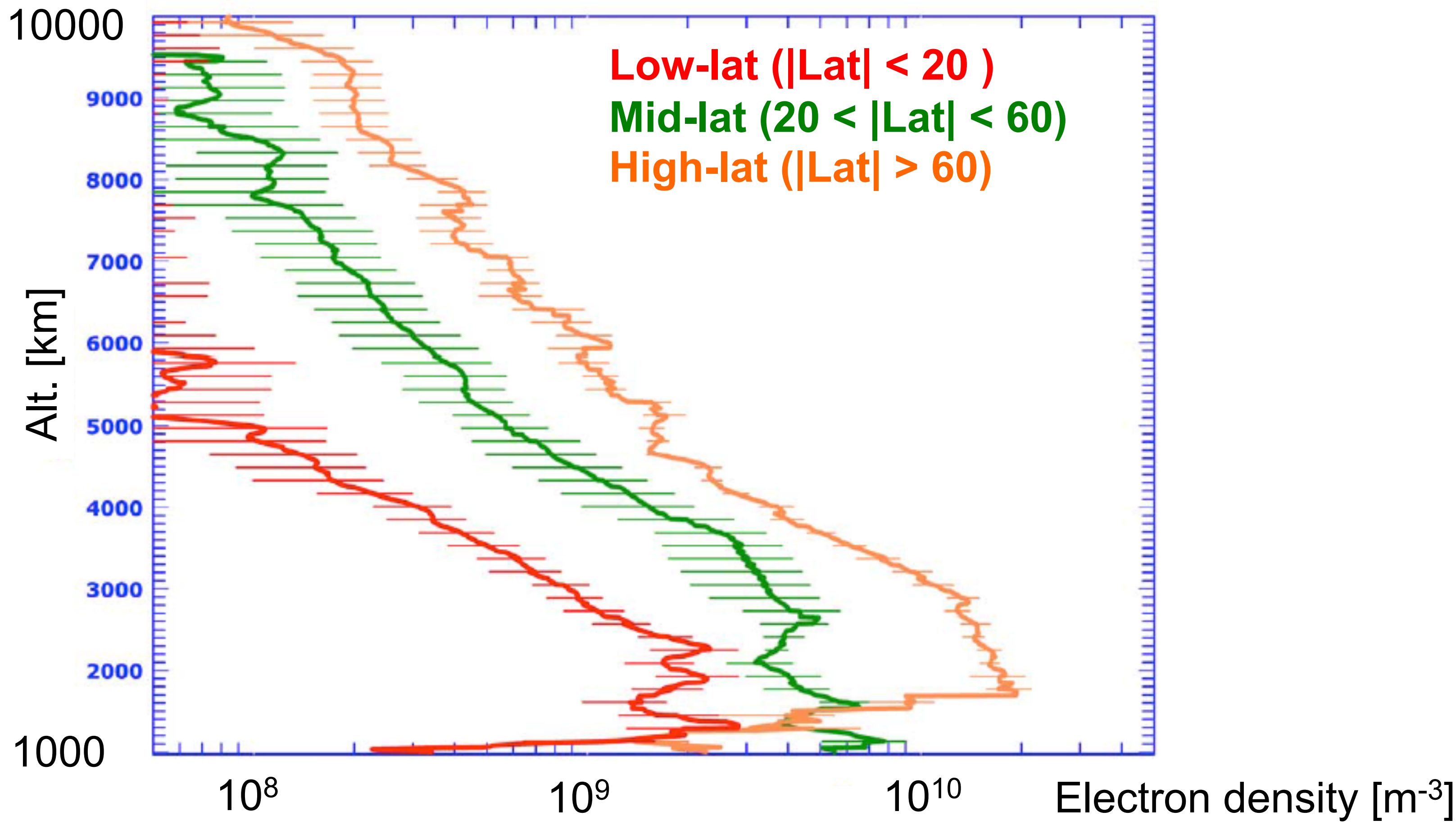
- N_e observation from Cassini occultations
  - N_e (average between dusk and dawn)
    - Peak density: ~10^{10} m^{-3}; Peak alt.: ~1200 km



Electron density by occultations [*Kliore et al.*, 2009]

Saturn's ionosphere

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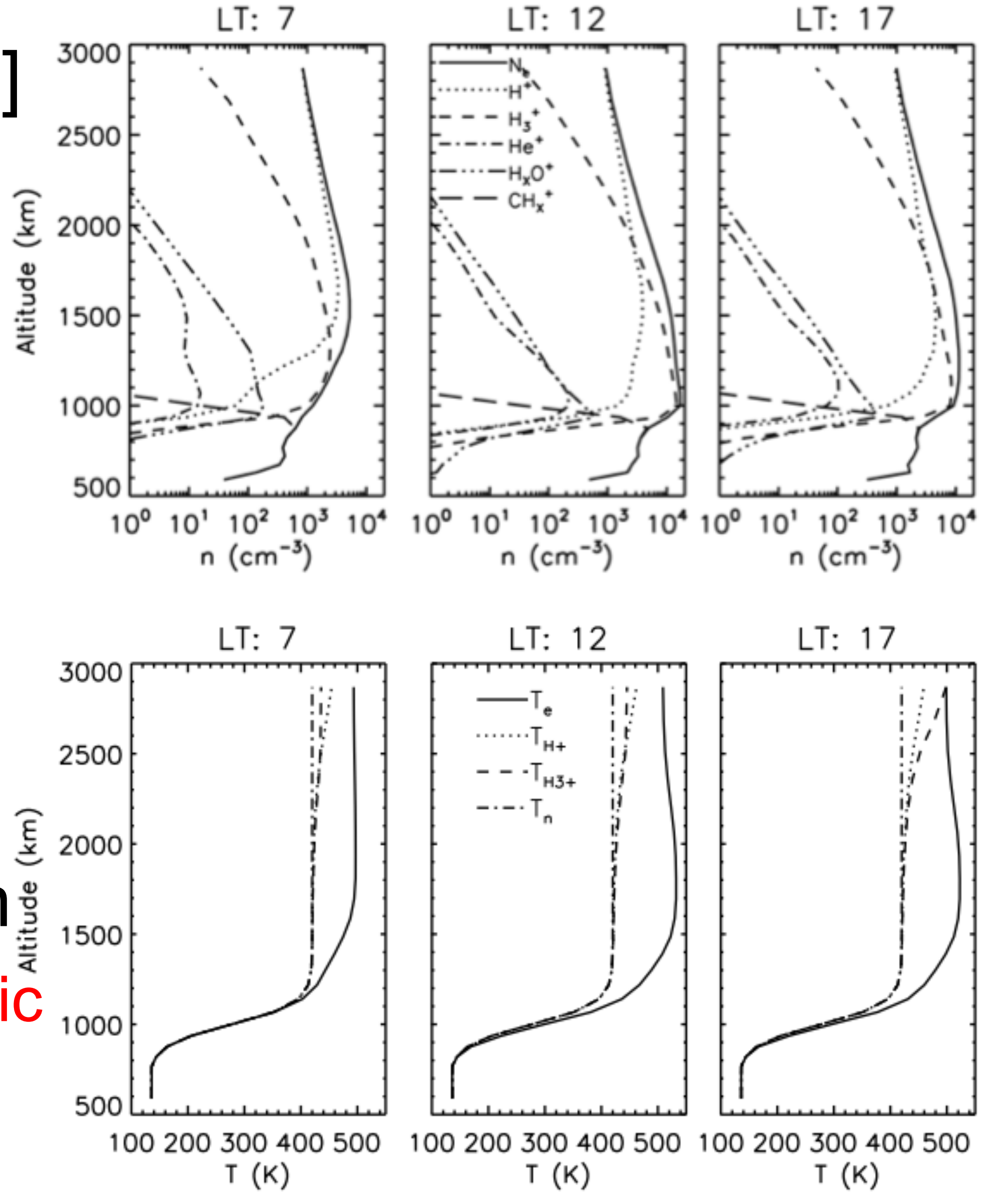
- Model [*Moore et al.* 2008]
  - N_e
    - Average peak density: $\sim 10^{10}$ m^{-3}
    - Peak alt.: ~1200 km
  - T_e
    - Max: 500 K
    - Alt.: > 1500 km
- But only below ~3000 km
  - How is the magnetospheric influence?



Plasma density and temperature by modeling [*Moore et al.*, 2008]

Purpose

- Construction of an ionospheric model including the inner magnetosphere.
- Estimation of the ionospheric Pedersen conductivity from plasma density in the Saturn's ionosphere
- Investigation of the influence of magnetosphere to ionosphere

3 dimensional ionospheric model

$v_{\parallel}$	Field-aligned Velocity
$E_{\parallel}$	Electric field
A	Magnetic flux cross-section
g	Gravity and CF
T	Temperature
Q	Heating rate
κ	Diffusion coefficient

- Primitive equations
  - Ion

Density: $$\frac{\partial \rho_i}{\partial t} + \frac{1}{A}\frac{\partial\left(A\rho_i v_{i,\parallel}\right)}{\partial s} = S_i - L_i$$

Momentum: $$\rho_i \frac{\partial v_{i,\parallel}}{\partial t} + \rho_i v_{i,\parallel}\frac{\partial v_{i,\parallel}}{\partial s} = n_i e E_{\parallel} - \frac{\partial p_i}{\partial s} - \rho_i g - \sum_k \rho_i \nu_{ik}\left(v_{i,\parallel} - v_{k,\parallel}\right)$$

Temperature: $T_i = T_e$

N_i (H^+, H_2^+, H_3^+, He^+, H_2O^+ and H_3O^+),

V_i (H^+, H_2^+, H_3^+, He^+, H_2O^+ and H_3O^+),

T_e, T_i

  - Electron

Density: $$n_e = \sum_i n_i$$

Momentum: $$E_{\parallel} = -\frac{1}{e n_e}\frac{\partial p_e}{\partial s}$$

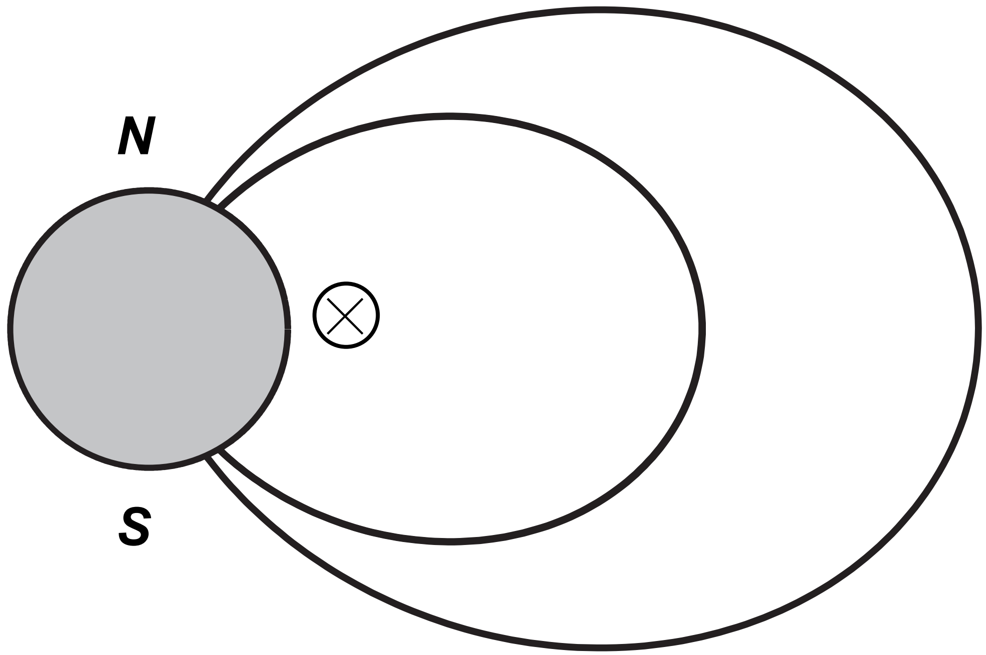
Temperature: $$\frac{\partial T_e}{\partial t} - \frac{2}{3}\frac{1}{A}\frac{\partial}{\partial s}\left(A\kappa_e \frac{\partial T_e}{\partial s}\right) = Q_{EUV} + Q_{coll} + Q_{joule} + Q_{ph,ionos} + Q_{ph,mag}$$

Model

- Dipole coordinate system
  - Along the magnetic field line → 1 dimension

  \+ Increasing the number of magnetic field line → 2 dimensions

  \+ Time evolution → 3 dimensions



3 dimensional ionospheric model

$v_{\parallel}$	Field-aligned Velocity
$E_{\parallel}$	Electric field
A	Magnetic flux cross-section
g	Gravity and CF
T	Temperature
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κ	Diffusion coefficient

- Primitive equations
  - Ion

Source and Loss rate

Density: $$\frac{\partial \rho_i}{\partial t} + \frac{1}{A}\frac{\partial\left(A\rho_i v_{i,\parallel}\right)}{\partial s} = S_i - L_i$$

Momentum: $$\rho_i \frac{\partial v_{i,\parallel}}{\partial t} + \rho_i v_{i,\parallel}\frac{\partial v_{i,\parallel}}{\partial s} = n_i e E_{\parallel} - \frac{\partial p_i}{\partial s} - \rho_i g - \sum_k \rho_i \nu_{ik}\left(v_{i,\parallel} - v_{k,\parallel}\right)$$

Temperature: $T_i = T_e$

N_i (H^+, H_2^+, H_3^+, He^+, H_2O^+ and H_3O^+),

V_i (H^+, H_2^+, H_3^+, He^+, H_2O^+ and H_3O^+),

T_e, T_i

  - Electron

Density: $$n_e = \sum_i n_i$$

Momentum: $$E_{\parallel} = -\frac{1}{e n_e}\frac{\partial p_e}{\partial s}$$

Temperature: $$\frac{\partial T_e}{\partial t} - \frac{2}{3}\frac{1}{A}\frac{\partial}{\partial s}\left(A\kappa_e \frac{\partial T_e}{\partial s}\right) = Q_{EUV} + Q_{coll} + Q_{joule} + Q_{ph,ionos} + Q_{ph,mag}$$

Source & Loss

- Chemical reactions of 6 ion components
  - H^+, H_2^+, H_3^+, He^+, H_2O^+ and H_3O^+
  - 29 reactions

Chemical reaction	Rate coefficiants	References
$H + h\nu \rightarrow H^+ + e^-$		*Moses and Bass* [2000]
$H_2 + h\nu \rightarrow H^+ + H + e^-$		*Moses and Bass* [2000]
$H_2 + h\nu \rightarrow H_2^+ + e^-$		*Moses and Bass* [2000]
$He + h\nu \rightarrow He^+ + e^-$		*Moses and Bass* [2000]
$H_2O + h\nu \rightarrow H^+ + OH + e^-$		*Moses and Bass* [2000]
$H_2O + h\nu \rightarrow H_2O^+ + e^-$		*Moses and Bass* [2000]
$H^+ + e^- \rightarrow H$	$1.9 \times 10^{-16} T_e^{-0.7}$	*Moses and Bass* [2000]; *Kim and Fox* [1994]
$H_2^+ + e^- \rightarrow H + H$	$2.3 \times 10^{-12} T_e^{-0.4}$	*Moses and Bass* [2000]; *Kim and Fox* [1994]
$H_3^+ + e^- \rightarrow H_2 + H$	$7.6 \times 10^{-13} T_e^{-0.5}$	*Moses and Bass* [2000]; *Kim and Fox* [1994]
$H_3^+ + e^- \rightarrow 3H$	$9.7 \times 10^{-13} T_e^{-0.5}$	*Moses and Bass* [2000]; *Kim and Fox* [1994]
$He^+ + e^- \rightarrow He$	$1.9 \times 10^{-16} T_e^{-0.7}$	*Moses and Bass* [2000]; *Kim and Fox* [1994]
$H_2O^+ + e^- \rightarrow O + H_2$	$3.5 \times 10^{-12} T_e^{-0.5}$	*Moses and Bass* [2000]; *Miller et al.* [1997]
$H_2O^+ + e^- \rightarrow OH + H$	$2.8 \times 10^{-12} T_e^{-0.5}$	*Moses and Bass* [2000]; *Miller et al.* [1997]
$H_3O^+ + e^- \rightarrow H_2O + H$	$6.1 \times 10^{-12} T_e^{-0.5}$	*Moses and Bass* [2000]; *Miller et al.* [1997]
$H_3O^+ + e^- \rightarrow OH + 2H$	$1.1 \times 10^{-11} T_e^{-0.5}$	*Moses and Bass* [2000]; *Miller et al.* [1997]
$H^+ + H_2 \rightarrow H_2^+ + H$	see text	*Moses and Bass* [2000]
$H^+ + H_2 + M \rightarrow H_3^+ + M$	3.2×10^{-41}	*Moses and Bass* [2000]; *Kim and Fox* [1994]
$H^+ + H_2O \rightarrow H_2O^+ + H$	8.2×10^{-15}	*Moses and Bass* [2000]; *Anicich* [1993]
$H_2^+ + H \rightarrow H^+ + H_2$	6.4×10^{-16}	*Moses and Bass* [2000]; *Anicich* [1993]
$H_2^+ + H_2 \rightarrow H_3^+ + H$	2.0×10^{-15}	*Moses and Bass* [2000]; *Kim and Fox* [1994]
$H_2^+ + H_2O \rightarrow H_2O^+ + H_2$	3.9×10^{-15}	*Moses and Bass* [2000]; *Anicich* [1993]
$H_2^+ + H_2O \rightarrow H_3O^+ + H$	3.4×10^{-15}	*Moses and Bass* [2000]; *Anicich* [1993]
$H_3^+ + H_2O \rightarrow H_3O^+ + H_2$	5.3×10^{-15}	*Moses and Bass* [2000]; *Anicich* [1993]
$He^+ + H_2 \rightarrow H^+ + H + He$	8.8×10^{-20}	*Matcheva et al.* [2001]; *Perry* [1999]
$He^+ + H_2 \rightarrow H_2^+ + He$	9.4×10^{-21}	*Moses and Bass* [2000]; *Kim and Fox* [1994]
$He^+ + H_2O \rightarrow H^+ + OH + He$	1.9×10^{-16}	*Moses and Bass* [2000]; *Anicich* [1993]
$He^+ + H_2O \rightarrow H_2O^+ + He$	5.5×10^{-17}	*Moses and Bass* [2000]; *Anicich* [1993]
$H_2O^+ + H_2 \rightarrow H_3O^+ + H$	7.6×10^{-16}	*Moses and Bass* [2000]; *Anicich* [1993]
$H_2O^+ + H_2O \rightarrow H_3O^+ + OH$	1.9×10^{-15}	*Moses and Bass* [2000]; *Anicich* [1993]

3 dimensional ionospheric model

- Primitive equations
  - Ion

Density: $$\frac{\partial \rho_i}{\partial t} + \frac{1}{A}\frac{\partial\left(A\rho_i v_{i,\parallel}\right)}{\partial s} = S_i - L_i$$

Source and Loss rate

Momentum: $$\rho_i \frac{\partial v_{i,\parallel}}{\partial t} + \rho_i v_{i,\parallel}\frac{\partial v_{i,\parallel}}{\partial s} = n_i e E_\parallel - \frac{\partial p_i}{\partial s} - \rho_i g - \sum_k \rho_i \nu_{ik}\left(v_{i,\parallel} - v_{k,\parallel}\right)$$

Temperature: $T_i = T_e$

- Electron

Density: $$n_e = \sum_i n_i$$

Momentum: $$E_\parallel = -\frac{1}{en_e}\frac{\partial p_e}{\partial s}$$

Temperature: $$\frac{\partial T_e}{\partial t} - \frac{2}{3}\frac{1}{A}\frac{\partial}{\partial s}\left(A\kappa_e \frac{\partial T_e}{\partial s}\right) = Q_{EUV} + Q_{coll} + Q_{joule} + Q_{ph,ionos} + Q_{ph,mag}$$

Heat flow, Q_{HF}

EUV, collision, Joule heating, photoelectron

Heating rate

$v_\parallel$	Field-aligned Velocity
$E_\parallel$	Electric field
A	Magnetic flux cross-section
g	Gravity and CF
T	Temperature
Q	Heating rate
κ	Diffusion coefficient

N_i (H^+, H_2^+, H_3^+, He^+, H_2O^+ and H_3O^+),

V_i (H^+, H_2^+, H_3^+, He^+, H_2O^+ and H_3O^+),

T_e, T_i

Background neutral atmosphere

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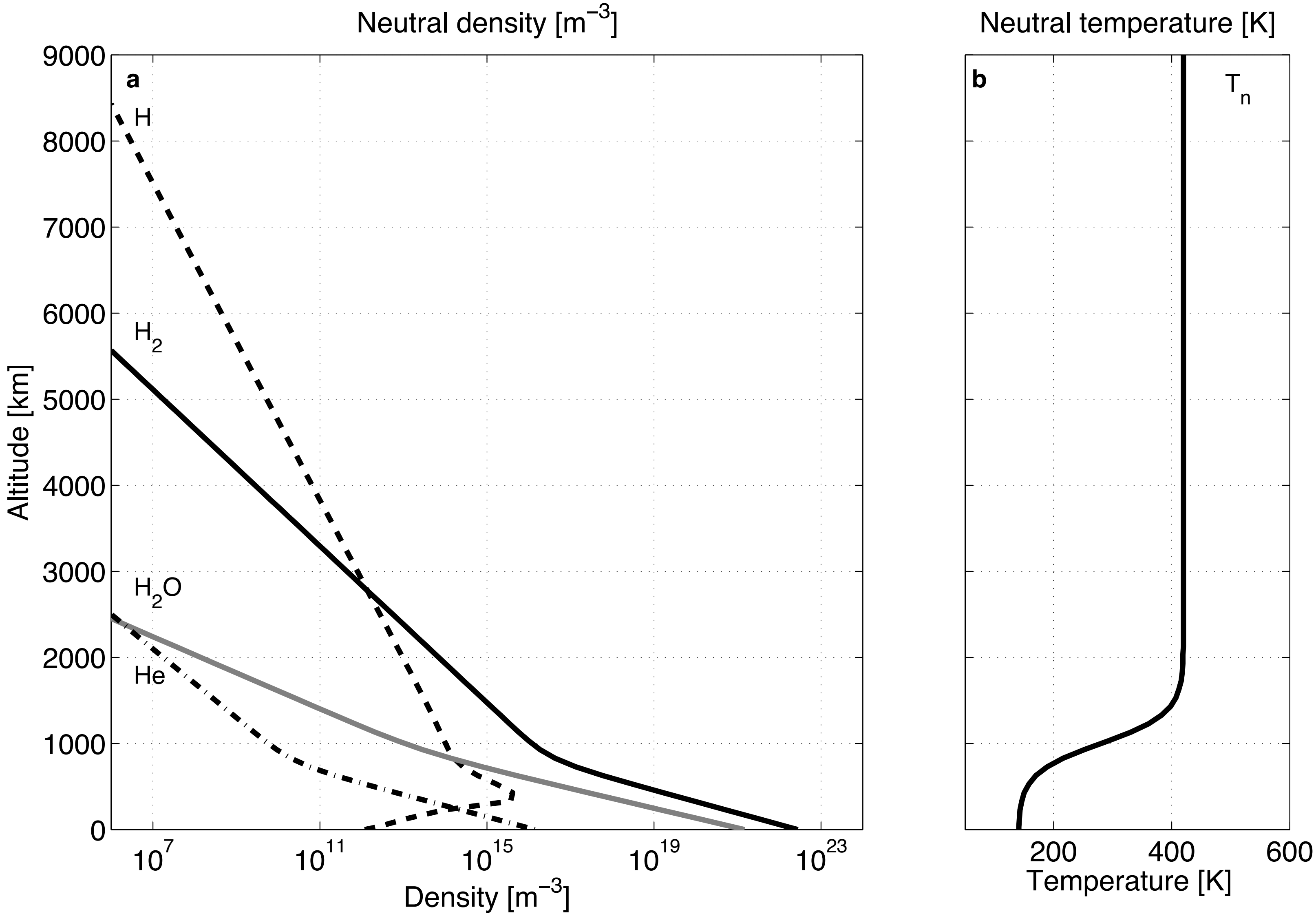

N_i, V_i, σ_p (L=5, LT=12)

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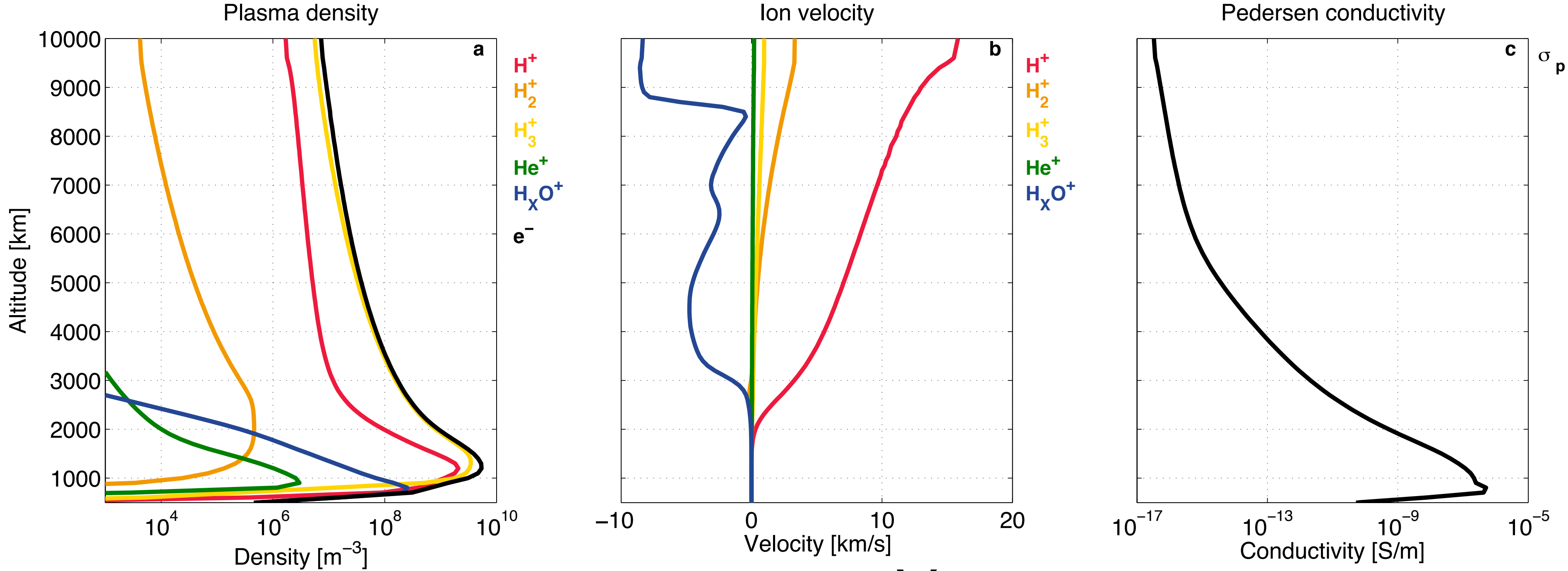
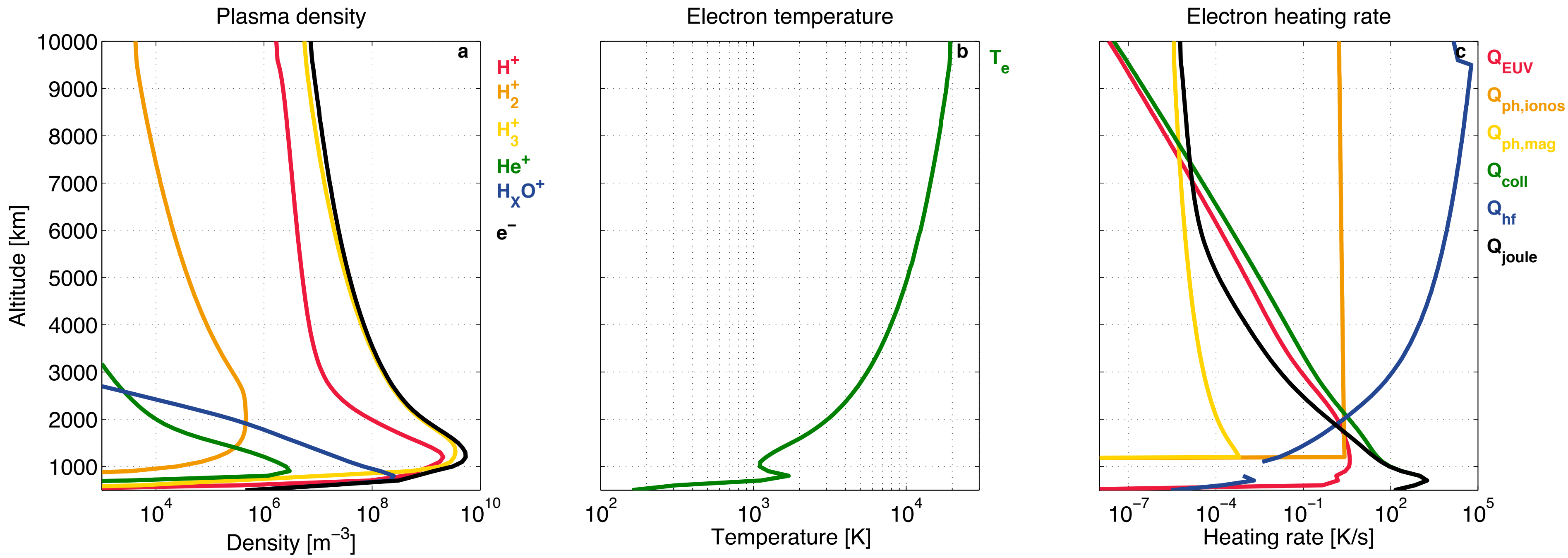


- N_i
  - H_3^+ is dominant.
    Max: ~10^{10} m^{-3}
- σ_i
  - Maximum around 1000 km
- V_i
  - Upward velocity
    - Light component
  - Downward velocity
    - Heavy component

N_i, T_e, Q_e (L=5, LT=12)



- T_e
  - 2000 K at ~1200 km
  - T_e drastically increases.
- Heating rate
  - Q_{Joule} and Q_{coll} are important at low altitude.
  - Q_{HF} is contributing to heat process above topside.

Joule heating & Heat flow

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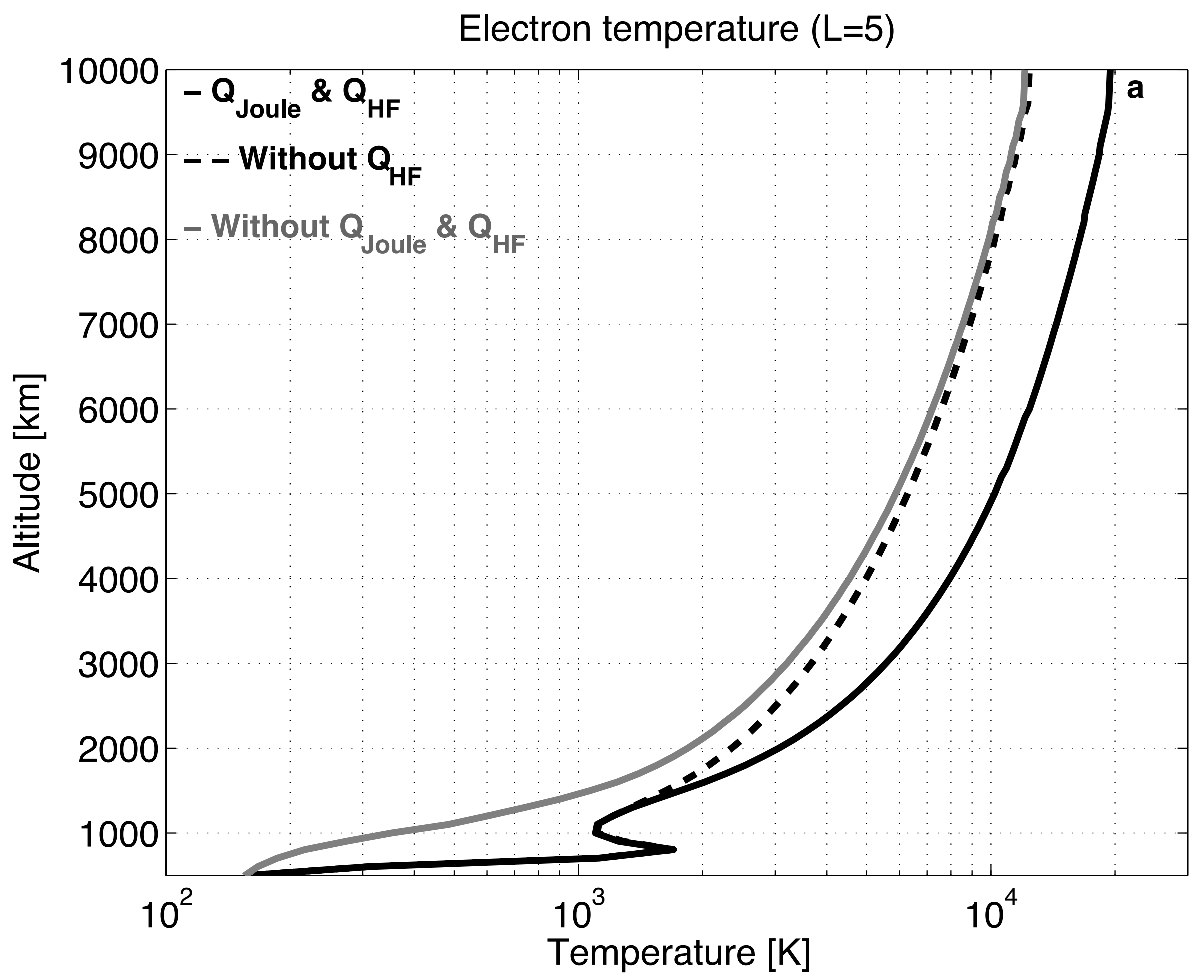

- T_e doesn't have a peak without Q_{Joule}.
- T_e decreases at topside without Q_{HF}.

Diurnal variations of N_e,T_e and σ_p (L=5)

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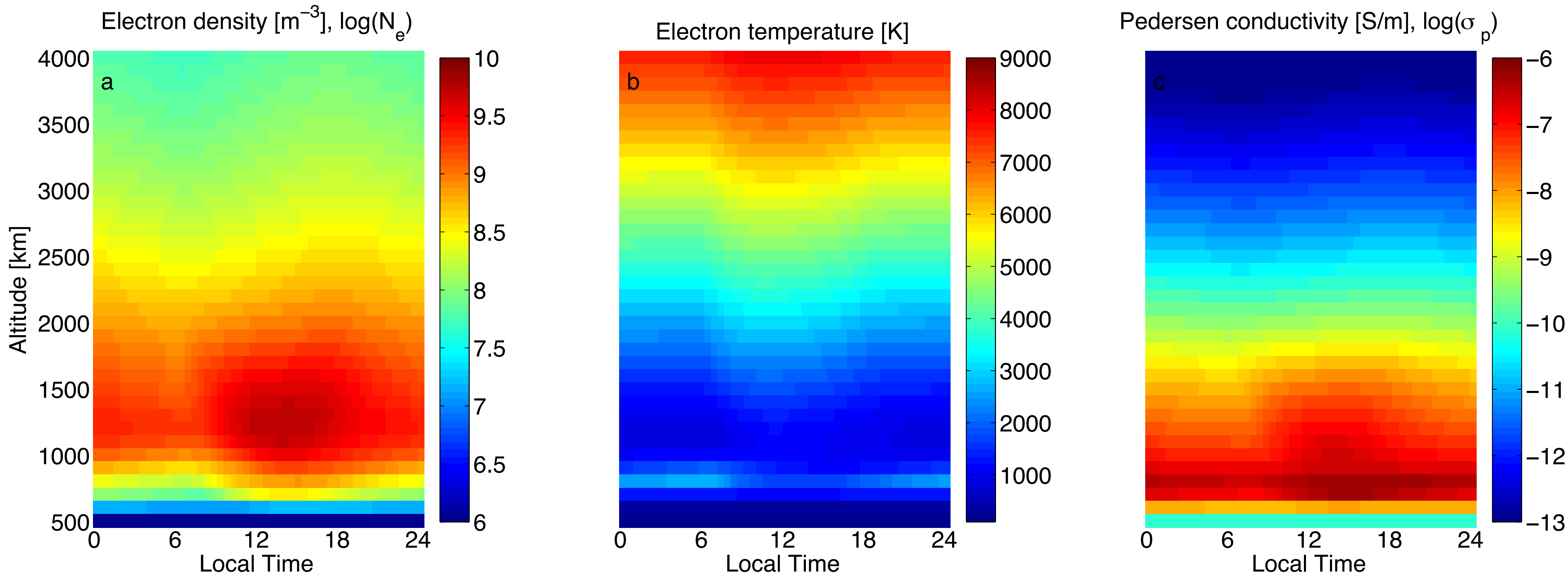

- N_e, σ_p
  - Start to increase after 6 LT
  - Max: ~14 LT
  - N_e and σ_p decreases at high altitudes.
- T_e
  - Max: ~12 LT
  - T_e is kept to high temperature in all LT by Q_{HF}.

Pedersen conductivity

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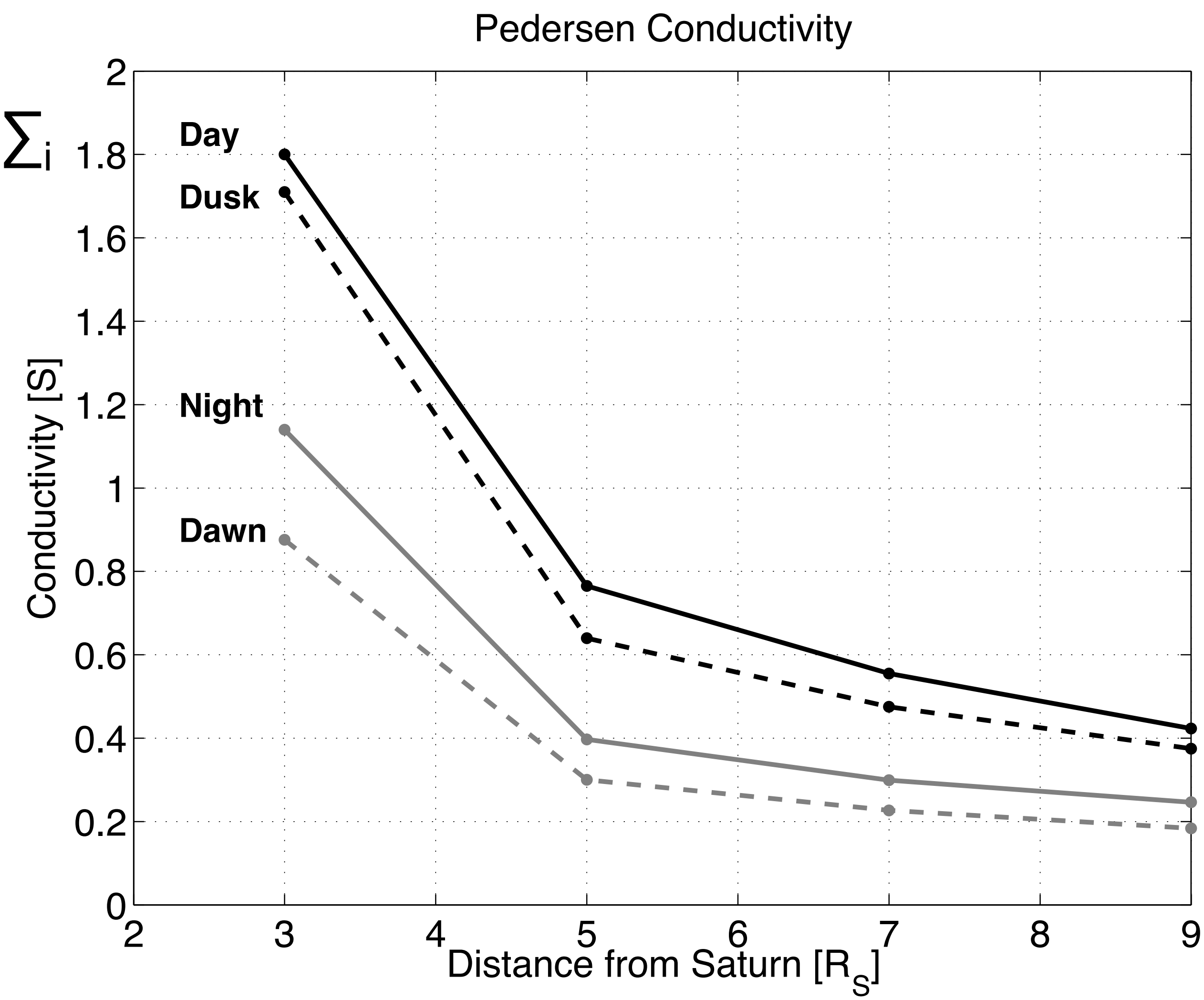
$$\sigma_p = \sum_i \frac{\nu_i}{\nu_{in}^2 + \omega_{ci}^2} \frac{n_i e^2}{m_i} + \frac{\nu_e}{\nu_{en}^2 + \omega_{ce}^2} \frac{n_e e^2}{m_e}$$

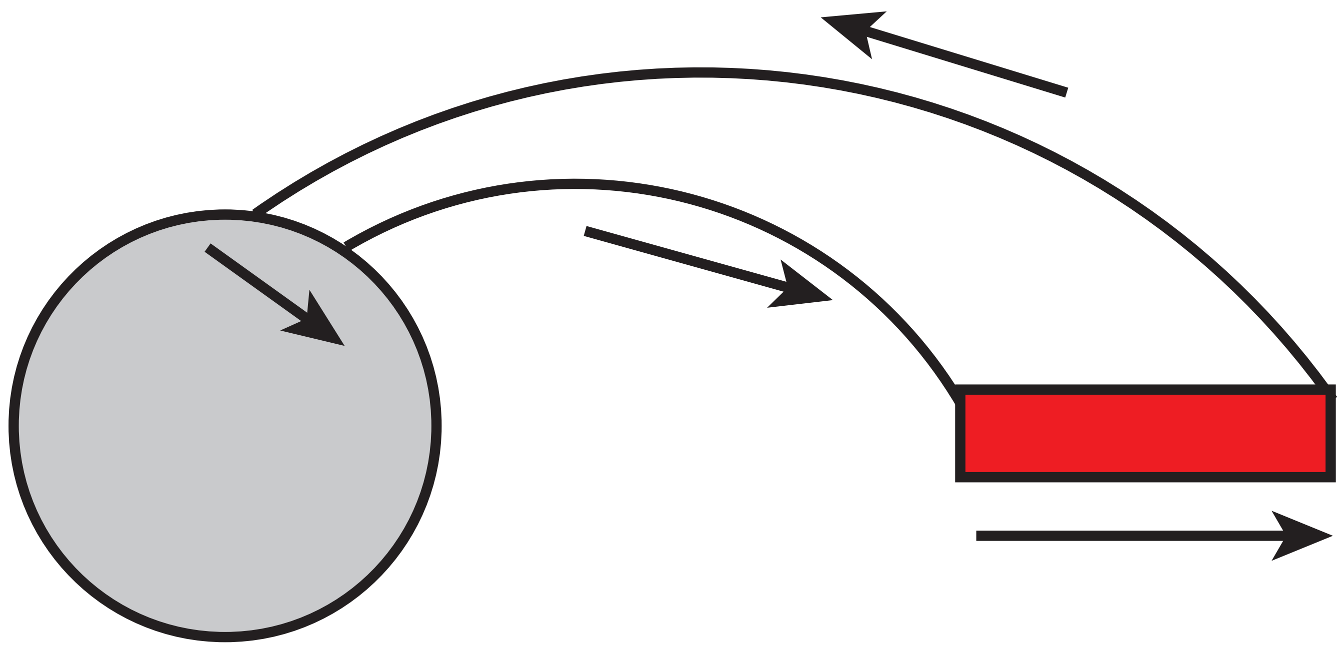
$$\Sigma_i = \int_{z_1}^{z_2} \sigma_p ds$$

- LT dependence of $\sum_i$
- $\sum_i$ decreases with increase of Rs



Magnetospheric ion velocity

1. Modeling of inner magnetosphere with dust-plasma interaction
2. Modeling of ionosphere
3. Magnetosphere-ionosphere coupling



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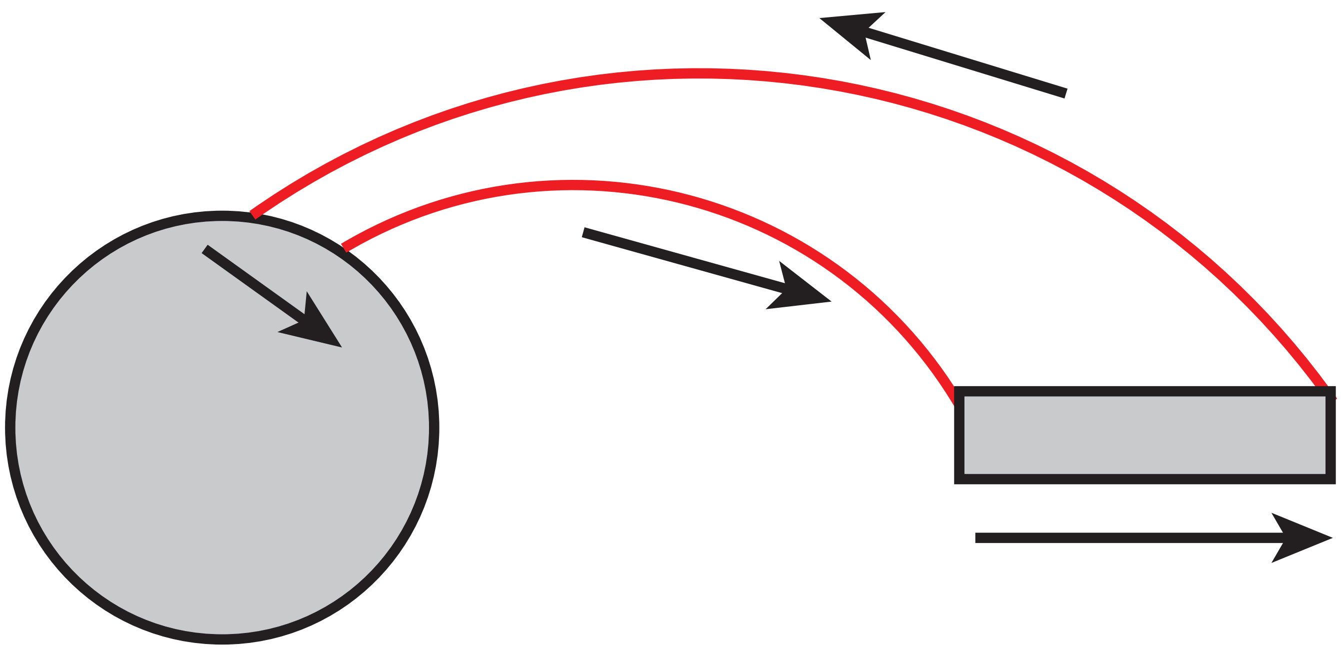

Magnetospheric ion velocity

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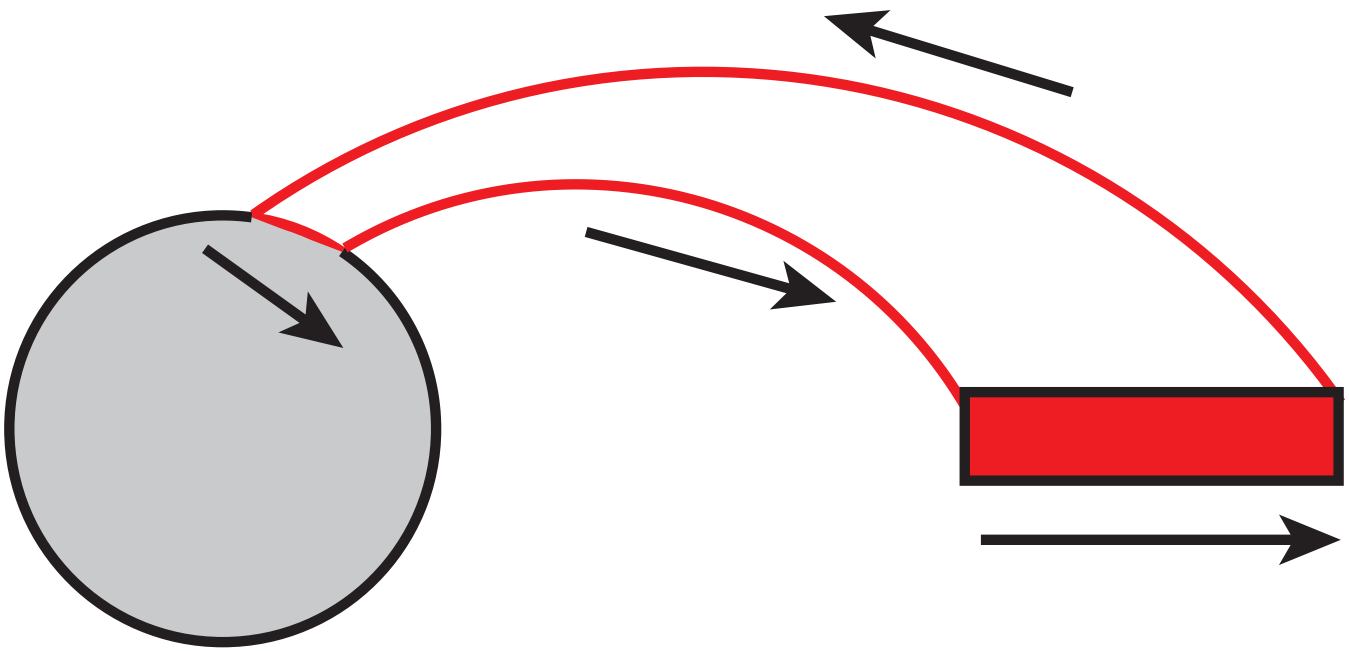

Magnetospheric ion velocity

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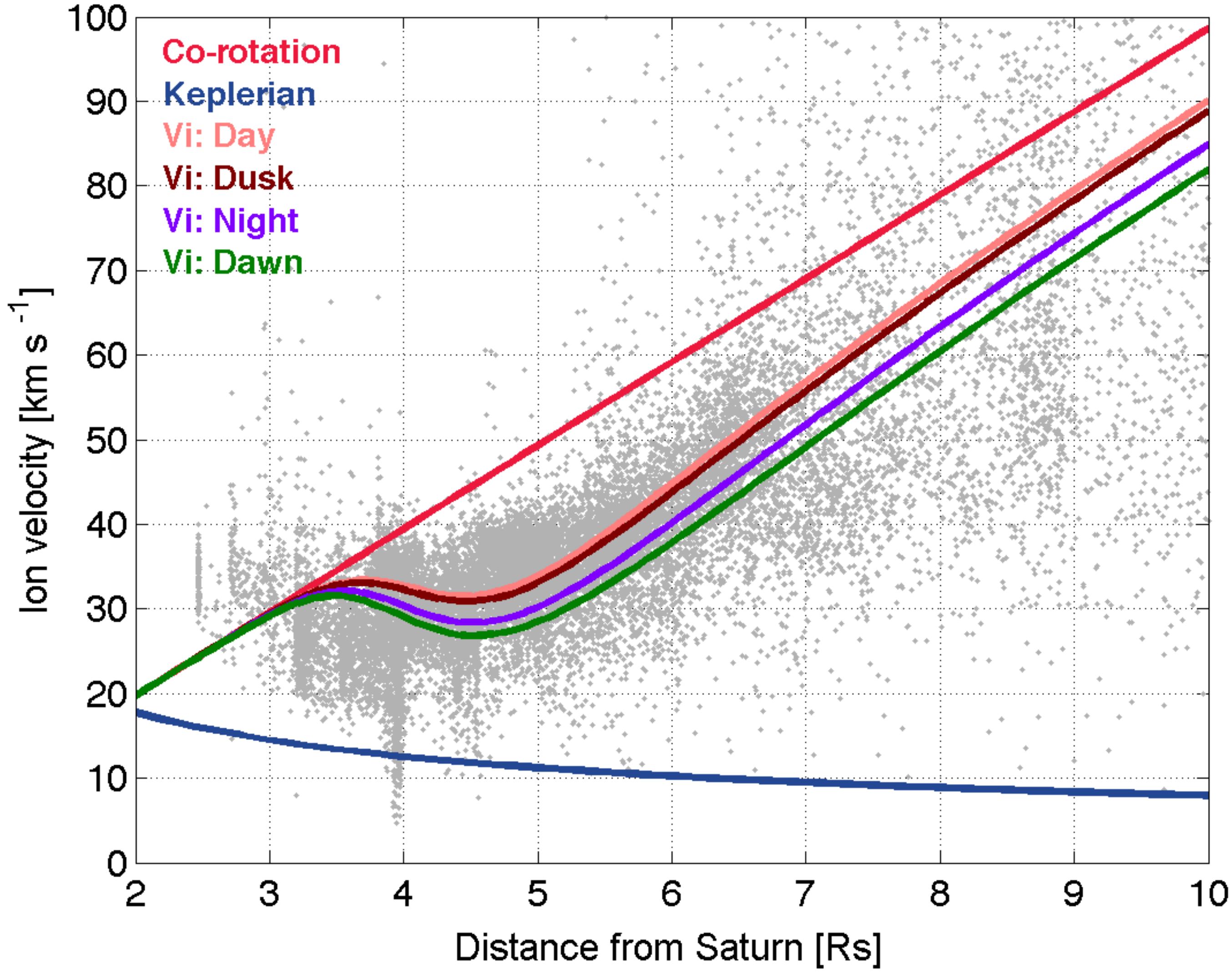
$$\Sigma_i(\mathbf{E}_{cor} - \mathbf{E}) = \mathbf{j}D$$



Large dust density, D=1 R_S

- V_i depends on LT.

Summary

- Ionospheric plasma distribution
  - H_3^+ is dominant at L=5.
    - Peak: 10^9-10^{10} m^{-3}
  - T_e is much higher than that of previous studies at high altitude.
    - 2000 K at ~1200 km; 10000 K at ~5000 km
  - Joule heating and collision heating are important at low altitude, and heat flow at high altitude.
- Ionospheric conductivity
  - Pedersen conductivity depends on LT.
    - Day -> Dusk -> Night -> Dawn
  - The magnetospheric ion speed shows the same tendency as the diurnal variation of conductivity.

Conclusion of this thesis

From Observations

- Inner magnetoshpheric ion speed is slow down from the co-rotation speed.
- Ion speed is Keplerian in the Enceladus plume.

From Modelings

- Ion speed is slow down from the co-rotation speed due to **dust-plasma interaction** and **magnetosphere-ionosphere coupling**.

Reference Works

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- **Sakai, S.**, S. Watanabe, M. W. Morooka, M. K. G. Holmberg, J. –E. Wahlund, D. A. Gurnett, and W. S. Kurth (2013), Dust-plasma interaction through magnetosphere-ionosphere coupling in Saturn's plasma disk, *Planet. Space Sci.*, *75*, 11-16, doi:10.1016/j.pss.2012.11.003.
- **Sakai, S.**, and S. Watanabe (2014), High-speed flow and high temperature plasma in Saturn's mid-latitude ionosphere, in preparation.
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