Generation of dawn-to-dusk electric field in the Jovian magnetosphere via Region 2-like FAC

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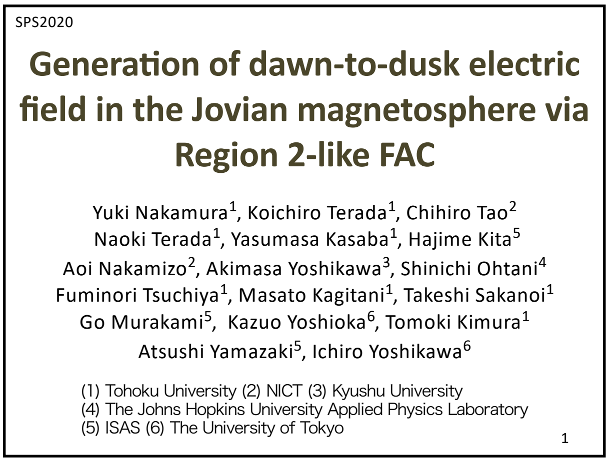
Abstract

Due to Jupiter's strong magnetic field and rapid rotation, it is believed that the plasma dynamics of Jupiter's magnetosphere is dominated by corotation and the effects of the solar wind hardly penetrate deep into the magnetosphere [e.g. *Brice and Ionnidis,* 1970]. However, the evidence that the solar wind influenced the plasma dynamics in the inner magnetosphere was reported by *Murakami et al.* [2016]. Their results indicated that the strength of dawn-to-dusk electric field in the vicinity of Io's orbit changed in time and its variation coincided with the changes in solar wind dynamic pressure. Previous studies [*Goertz and Ip*, 1984; *Murakami et al.*, 2016] suggested that the dawn-to-dusk electric field is generated by the M-I coupling process via Region 2-like field-aligned current (R2-like FAC), which is still not evaluated quantitatively. This study aims to evaluate the strength of dawn-to-dusk electric field in this process using numerical simulations.

We newly developed a Jupiter's ionosphere model composed of a meteoroid ablation model, a photochemical model and an ionospheric potential solver. We found that meteoric ions can play a significant role in the ionospheric conductance in the middle- and low-latitude because of Jupiter's strong magnetic field and strong gravity force. The ionospheric Hall and Pedersen conductances becomes 1-2 orders of magnitudes larger in the case that considers meteoric ions (Case 2) than in the case that doesn't consider meteoric ions (Case 1), and their distributions become axisymmetric. We applied the conductance distribution to the ionospheric potential solver to investigate the dawn-to-dusk electric field in the inner magnetosphere. In Case 1, 275 [mV/m] and 85 [mV/m] at 06:00 LT and at 18:00 LT of Io's orbit, respectively, In Case 2, the strength is ~25 [mV/m] at 06:00 LT and 18:00 LT, which is 10 times and 3.4 times smaller than in Case 1, and is closer to the observation (4-9 mV/m [*Murakami et al.*, 2016]). We also tested the dependence on R2-like FAC strength, which could be affected by the solar wind conditions. The results show that the dawn-to-dusk electric field proportionally increases with the total amount of R2-like FAC. This result suggests that the dawn-to-dusk electric field enhances when the solar dynamic pressure increases, which agrees with the Hisaki observation [*Murakami et al.*, 2016].



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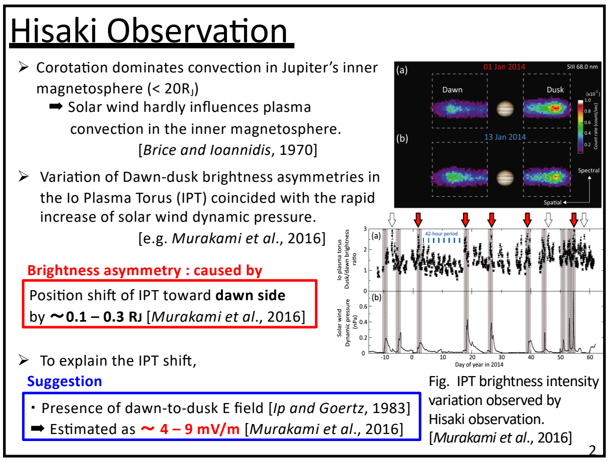


Hisaki Observation

- ➢ Corotation dominates convection in Jupiter's inner magnetosphere (< 20R$_J$)
  ➡ Solar wind hardly influences plasma convection in the inner magnetosphere.
  [*Brice and Ioannidis*, 1970]
- ➢ Variation of Dawn-dusk brightness asymmetries in the Io Plasma Torus (IPT) coincided with the rapid increase of solar wind dynamic pressure.
  [e.g. *Murakami et al.*, 2016]

Brightness asymmetry : caused by

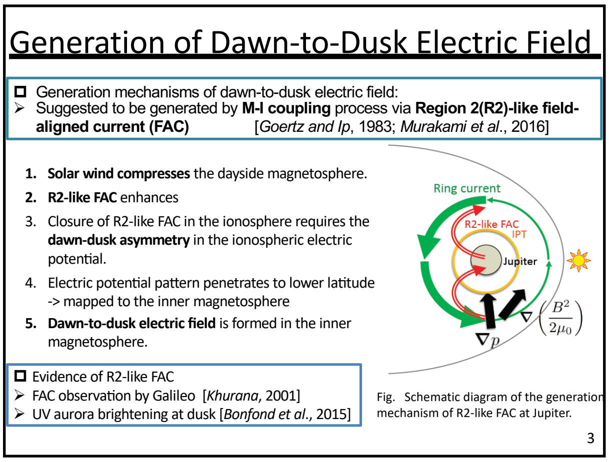
Position shift of IPT toward **dawn side** by **∼0.1 – 0.3 RJ** [*Murakami et al.*, 2016]

- ➢ To explain the IPT shift,

Suggestion

・Presence of dawn-to-dusk E field [*Ip and Goertz*, 1983]
➡ Estimated as **∼ 4 – 9 mV/m** [*Murakami et al.*, 2016]

Fig. IPT brightness intensity variation observed by Hisaki observation. [*Murakami et al.*, 2016]



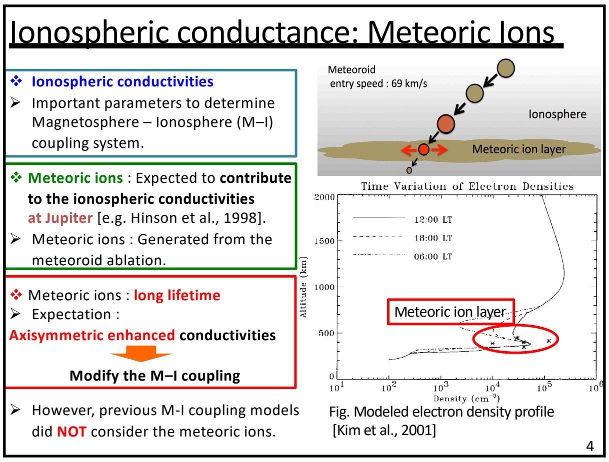
Generation of Dawn-to-Dusk Electric Field

☐ Generation mechanisms of dawn-to-dusk electric field:
- ➢ Suggested to be generated by **M-I coupling** process via **Region 2(R2)-like field-aligned current (FAC)** [*Goertz and Ip*, 1983; *Murakami et al.*, 2016]

1. **Solar wind compresses** the dayside magnetosphere.
2. **R2-like FAC** enhances
3. Closure of R2-like FAC in the ionosphere requires the **dawn-dusk asymmetry** in the ionospheric electric potential.
4. Electric potential pattern penetrates to lower latitude -> mapped to the inner magnetosphere
5. **Dawn-to-dusk electric field** is formed in the inner magnetosphere.

☐ Evidence of R2-like FAC
- ➢ FAC observation by Galileo [*Khurana*, 2001]
- ➢ UV aurora brightening at dusk [*Bonfond et al.*, 2015]

Fig. Schematic diagram of the generation mechanism of R2-like FAC at Jupiter.



Ionospheric conductance: Meteoric Ions

❖ **Ionospheric conductivities**
- ➢ Important parameters to determine Magnetosphere – Ionosphere (M–I) coupling system.

❖ **Meteoric ions** : Expected to **contribute to the ionospheric conductivities at Jupiter** [e.g. Hinson et al., 1998].
- ➢ Meteoric ions : Generated from the meteoroid ablation.

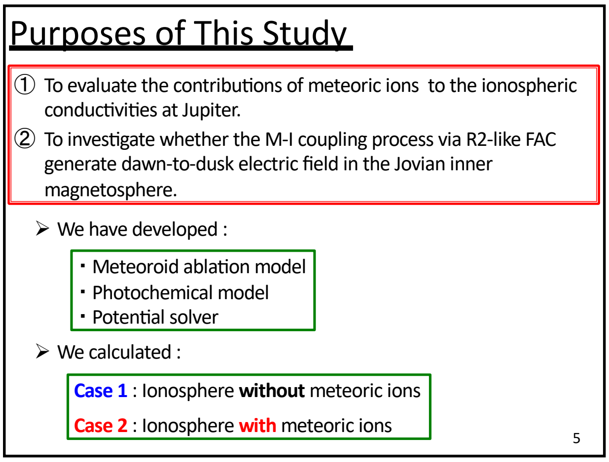
❖ Meteoric ions : **long lifetime**
- ➢ Expectation :

Axisymmetric enhanced conductivities

Modify the M–I coupling

- ➢ However, previous M-I coupling models did **NOT** consider the meteoric ions.

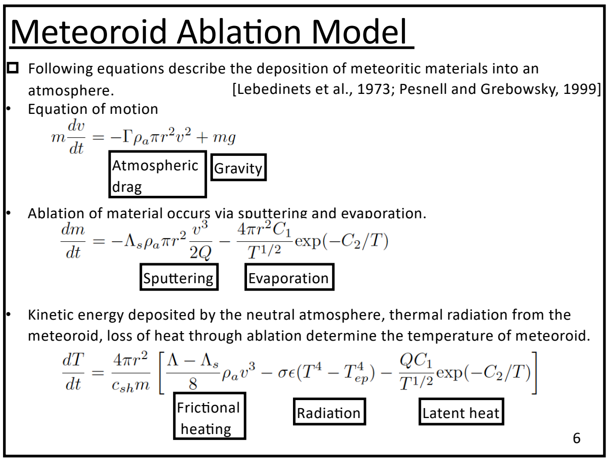
Fig. Modeled electron density profile [Kim et al., 2001]



Purposes of This Study

① To evaluate the contributions of meteoric ions to the ionospheric conductivities at Jupiter.
② To investigate whether the M-I coupling process via R2-like FAC generate dawn-to-dusk electric field in the Jovian inner magnetosphere.

- ➢ We have developed :
  ・Meteoroid ablation model
  ・Photochemical model
  ・Potential solver
- ➢ We calculated :
  Case 1 : Ionosphere **without** meteoric ions
  Case 2 : Ionosphere **with** meteoric ions



Meteoroid Ablation Model

☐ Following equations describe the deposition of meteoritic materials into an atmosphere. [Lebedinets et al., 1973; Pesnell and Grebowsky, 1999]

- Equation of motion

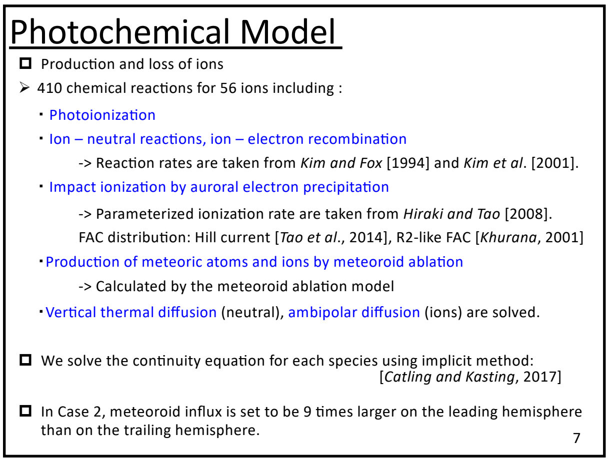
$$m\frac{dv}{dt} = \underbrace{-\Gamma\rho_a\pi r^2 v^2}_{\boxed{\text{Atmospheric drag}}} + \underbrace{mg}_{\boxed{\text{Gravity}}}$$

- Ablation of material occurs via sputtering and evaporation.

$$\frac{dm}{dt} = \underbrace{-\Lambda_s\rho_a\pi r^2\frac{v^3}{2Q}}_{\boxed{\text{Sputtering}}} - \underbrace{\frac{4\pi r^2 C_1}{T^{1/2}}\exp(-C_2/T)}_{\boxed{\text{Evaporation}}}$$

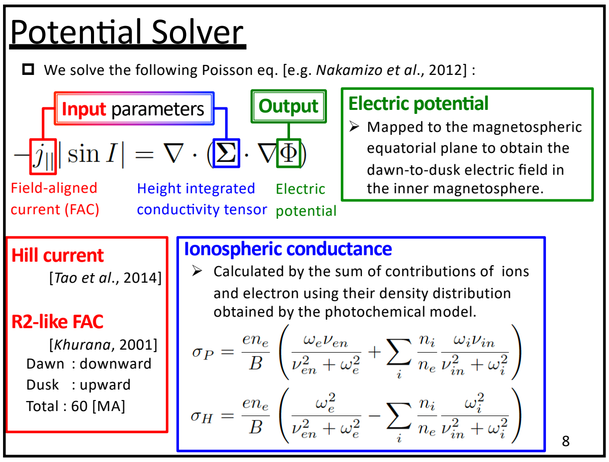
- Kinetic energy deposited by the neutral atmosphere, thermal radiation from the meteoroid, loss of heat through ablation determine the temperature of meteoroid.

$$\frac{dT}{dt} = \frac{4\pi r^2}{c_{sh}m}\left[\underbrace{\frac{\Lambda-\Lambda_s}{8}\rho_a v^3}_{\boxed{\text{Frictional heating}}} - \underbrace{\sigma\epsilon(T^4 - T_{ep}^4)}_{\boxed{\text{Radiation}}} - \underbrace{\frac{QC_1}{T^{1/2}}\exp(-C_2/T)}_{\boxed{\text{Latent heat}}}\right]$$



Photochemical Model

- ☐ Production and loss of ions
  - 410 chemical reactions for 56 ions including :
    - Photoionization
    - Ion – neutral reactions, ion – electron recombination
      - -> Reaction rates are taken from *Kim and Fox* [1994] and *Kim et al*. [2001].
    - Impact ionization by auroral electron precipitation
      - -> Parameterized ionization rate are taken from *Hiraki and Tao* [2008].
      - FAC distribution: Hill current [*Tao et al*., 2014], R2-like FAC [*Khurana*, 2001]
    - Production of meteoric atoms and ions by meteoroid ablation
      - -> Calculated by the meteoroid ablation model
    - Vertical thermal diffusion (neutral), ambipolar diffusion (ions) are solved.
- ☐ We solve the continuity equation for each species using implicit method: [*Catling and Kasting*, 2017]
- ☐ In Case 2, meteoroid influx is set to be 9 times larger on the leading hemisphere than on the trailing hemisphere.



Potential Solver

☐ We solve the following Poisson eq. [e.g. *Nakamizo et al*., 2012] :

Input parameters **Output**

$$-\boxed{j_{\parallel}}|\sin I| = \nabla\cdot(\boxed{\Sigma}\cdot\nabla\boxed{\Phi})$$

Field-aligned current (FAC) Height integrated conductivity tensor Electric potential

Electric potential

- Mapped to the magnetospheric equatorial plane to obtain the dawn-to-dusk electric field in the inner magnetosphere.

Hill current
[*Tao et al*., 2014]

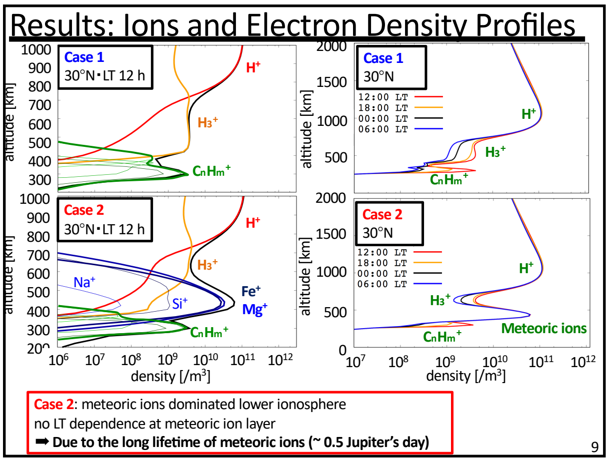
R2-like FAC
[*Khurana*, 2001]
Dawn : downward
Dusk : upward
Total : 60 [MA]

Ionospheric conductance

- Calculated by the sum of contributions of ions and electron using their density distribution obtained by the photochemical model.

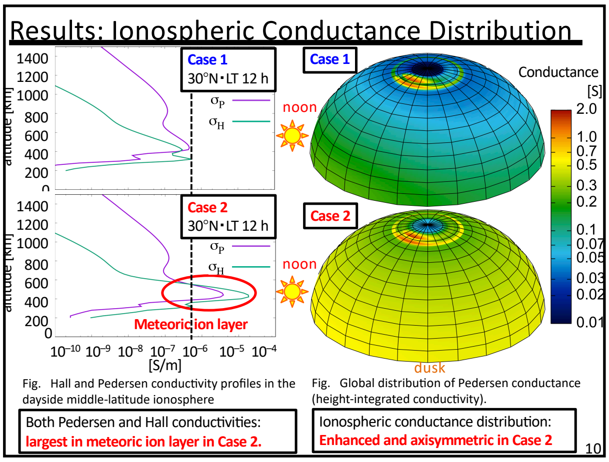
$$\sigma_P = \frac{en_e}{B}\left(\frac{\omega_e\nu_{en}}{\nu_{en}^2+\omega_e^2} + \sum_i \frac{n_i}{n_e}\frac{\omega_i\nu_{in}}{\nu_{in}^2+\omega_i^2}\right)$$

$$\sigma_H = \frac{en_e}{B}\left(\frac{\omega_e^2}{\nu_{en}^2+\omega_e^2} - \sum_i \frac{n_i}{n_e}\frac{\omega_i^2}{\nu_{in}^2+\omega_i^2}\right)$$



Results: Ions and Electron Density Profiles

Case 2: meteoric ions dominated lower ionosphere
no LT dependence at meteoric ion layer
➡ **Due to the long lifetime of meteoric ions (~ 0.5 Jupiter's day)**



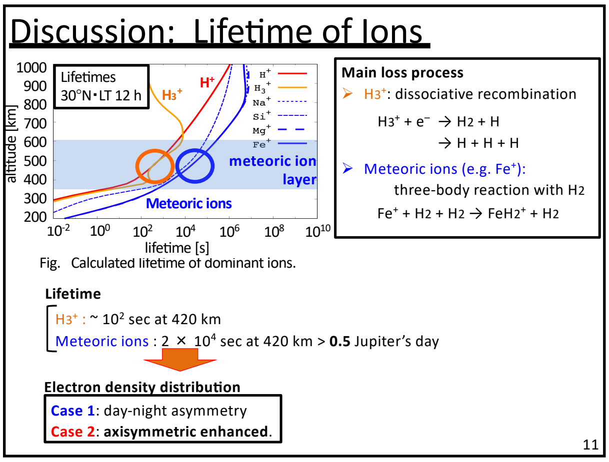
Results: Ionospheric Conductance Distribution

Fig. Hall and Pedersen conductivity profiles in the dayside middle-latitude ionosphere

Fig. Global distribution of Pedersen conductance (height-integrated conductivity).

Both Pedersen and Hall conductivities:
largest in meteoric ion layer in Case 2.

Ionospheric conductance distribution:
Enhanced and axisymmetric in Case 2



Discussion: Lifetime of Ions

Fig. Calculated lifetime of dominant ions.

Main loss process

- H_3^+: dissociative recombination

$$H_3^+ + e^- \rightarrow H_2 + H$$
$$\rightarrow H + H + H$$

- Meteoric ions (e.g. Fe^+):
  three-body reaction with H_2

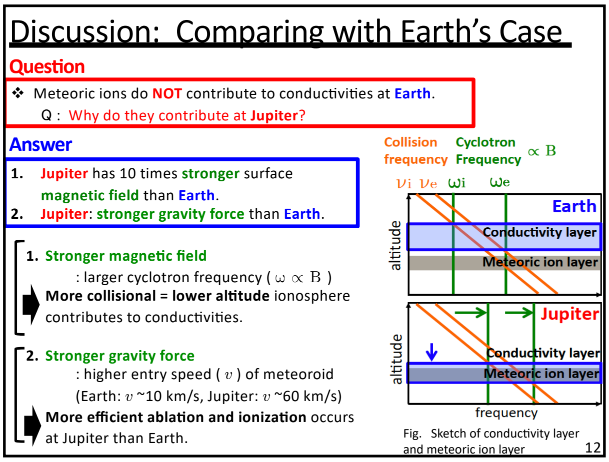
$$Fe^+ + H_2 + H_2 \rightarrow FeH_2^+ + H_2$$

Lifetime

H_3^+ : ~ 10^2 sec at 420 km
Meteoric ions : 2 × 10^4 sec at 420 km > **0.5** Jupiter's day

Electron density distribution

Case 1: day-night asymmetry
Case 2: **axisymmetric enhanced**.



Discussion: Comparing with Earth's Case

Question

- ❖ Meteoric ions do **NOT** contribute to conductivities at **Earth**.
  Q : Why do they contribute at **Jupiter**?

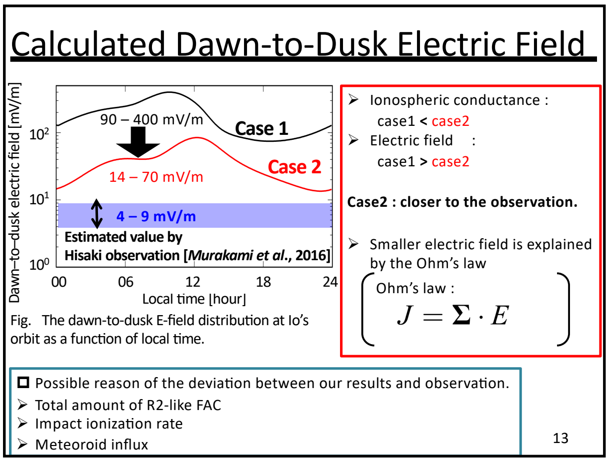
Answer

1. **Jupiter** has 10 times **stronger** surface **magnetic field** than **Earth**.
2. **Jupiter**: **stronger gravity force** than **Earth**.

1. **Stronger magnetic field**
   : larger cyclotron frequency ($\omega \propto \mathrm{B}$)
   ➡ **More collisional = lower altitude** ionosphere contributes to conductivities.

2. **Stronger gravity force**
   : higher entry speed (v) of meteoroid
   (Earth: v ~10 km/s, Jupiter: v ~60 km/s)
   ➡ **More efficient ablation and ionization** occurs at Jupiter than Earth.

Fig. Sketch of conductivity layer and meteoric ion layer



Calculated Dawn-to-Dusk Electric Field

Fig. The dawn-to-dusk E-field distribution at Io's orbit as a function of local time.

- ➢ Ionospheric conductance :
  case1 < case2
- ➢ Electric field :
  case1 > case2

Case2 : closer to the observation.

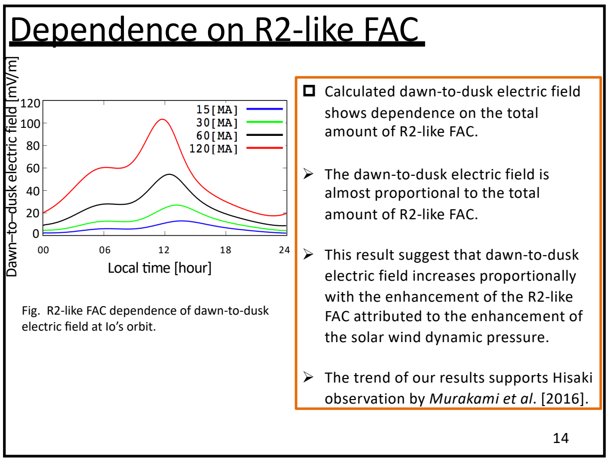
- ➢ Smaller electric field is explained by the Ohm's law

Ohm's law :

$$J = \mathbf{\Sigma} \cdot E$$

☐ Possible reason of the deviation between our results and observation.

- ➢ Total amount of R2-like FAC
- ➢ Impact ionization rate
- ➢ Meteoroid influx



Dependence on R2-like FAC

Fig. R2-like FAC dependence of dawn-to-dusk electric field at Io's orbit.

☐ Calculated dawn-to-dusk electric field shows dependence on the total amount of R2-like FAC.

- ➢ The dawn-to-dusk electric field is almost proportional to the total amount of R2-like FAC.
- ➢ This result suggest that dawn-to-dusk electric field increases proportionally with the enhancement of the R2-like FAC attributed to the enhancement of the solar wind dynamic pressure.
- ➢ The trend of our results supports Hisaki observation by *Murakami et al.* [2016].

Summary

☐ We developed
Meteoroid ablation model
Photochemical model
Potential solver

in order to investigate
the effects of meteoric ions on ionospheric conductance
the generation of dawn-to-dusk electric field

☐ Case 2 : Axisymmetric and enhanced (electron density / ionospheric conductance) distribution

Reasons:
long lifetime of meteoric ions.
Jupiter's **strong magnetic field** and **gravity force**
=> of great interest in comparative planetology

☐ Calculated electric field : Case 1 > Case 2 by a factor of - 10.

- ➢ Case 2 : closer to the Hisaki observation.
  However, there still remains deviations from observation.
- ➢ Dawn-to-dusk electric field increases with the total amount of R2-like FAC, which is consistent with *Murakami et al.* [2016].

◆ **M-I coupling via R2-like FAC can be one of the solution for the effects of solar wind in the inner magnetosphere.**