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Numerical radar simulation for the explorations of the ionosphere at Jupiter's icy moons

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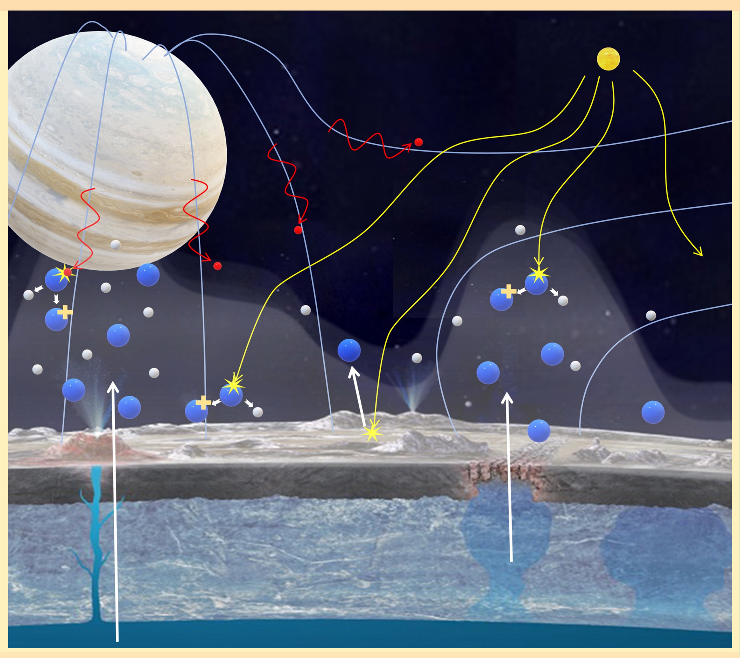
Summary

- Developing the numerical simulation code for the JUICE radar explorations using Jovian radio waves to investigate ionospheric structures of icy moons.
- Estimating the Ganymede and Callisto ionospheric structure.

1-1. Ionosphere of Jupiter's icy moon

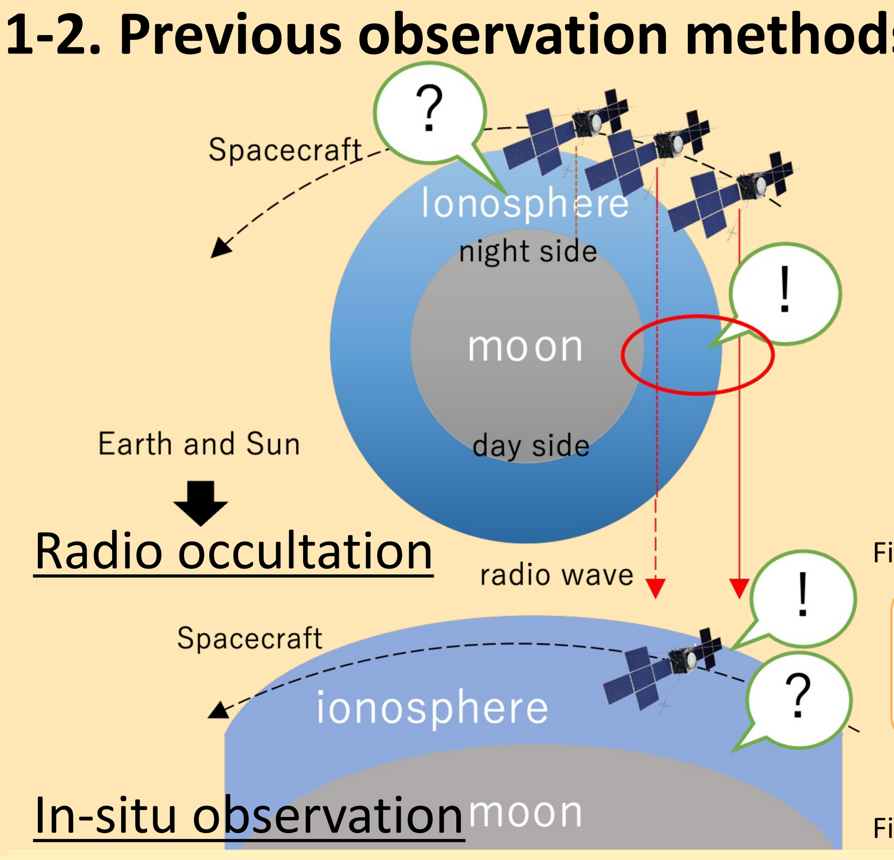
Jupiter's icy moons may harbor subsurface liquid water oceans and have ionospheres created from the oceanic water materials. Structures of the ionosphere of the icy moos are essential information for understanding the universality of habitable environments.



ionization
atmosphere supply
energetic electron supply
solar EUV
magnetic field line
electron of icy moon's ionosphere
energetic electron
atmosphere of icy moon
ionized atmosphere

Fig.1 Ionization process of icy moon (adapted from NASA/JPL, Airbus DS and goes-earth.org)

1-2. Previous observation methods



Ionosphere only around day and night boundary

× evaluate the effect of illumination on ionosphere

△ detect the differences between leading and trailing hemisphere

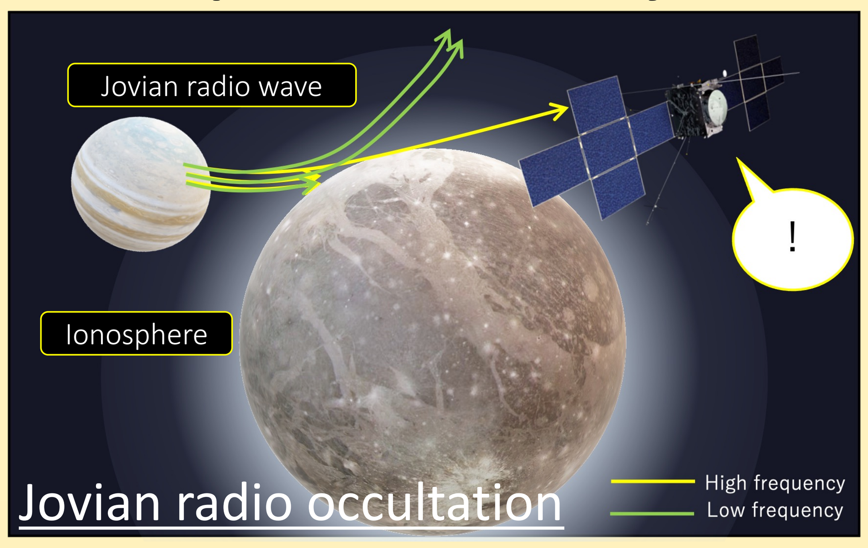
Fig.2 Radio occultation

Lack of information at low altitude

△ measure the vertical ionospheric profiles

Fig.3 In-situ observation

1-3. Purpose of this study



◯ evaluate the effect of illumination on ionosphere

◎ detect the differences between leading and trailing hemisphere

◯ measure the vertical ionospheric profiles

Fig.4 Jovian radio occultation

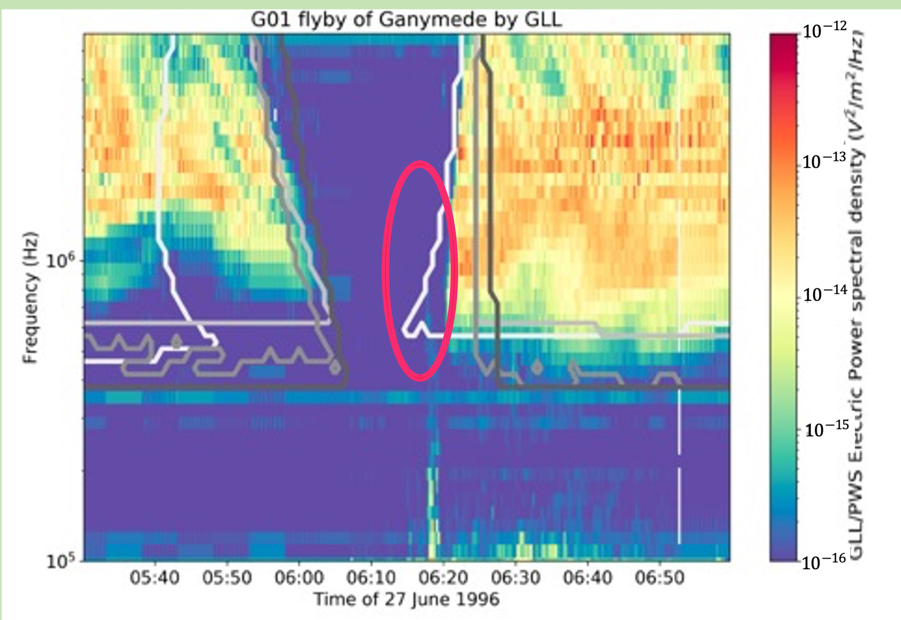
(RPWI … A radio plasma wave instrument to characterize radio emission and plasma environment)

develop the numerical simulation code for the radar explorations using natural radio waves and investigate spatial structures of the ionosphere

2-1. Radio Emission Simulations (ExPRES) [Cecconi et al, 2021]

Ephemeris of the observer, the radio sources and Jupiter's icy moon

Judging whether the radio sources are visible or not



- The emission angle between the magnetic field vector and the emitted wave vector is computed in the frame of the CMI theory
- Assuming a straight-line propagation (no refraction)

- The occultation spectral egress occurs later than predicted. (no refraction assumption.) (Fig. 10)
- Low frequency radio waves are refracted by the ionosphere of the icy moon (?)

Fig.5 Superimposed Galileo PWS data and ExPRES simulations during Jovian radio emission occultations by Ganymede . The four types of emission (A, B, C, D) are separated (from white to darkgrey, resp.) [Cecconi et al, 2021]

2-2. Raytracing [Kimura et al, 2008a etc..]

Tracing propagation paths of radio waves in the magnetized plasma, sequentially solving the Appleton-Hartree equation.

(Cold plasma・Discarding plasma collision)

$\vec{r}, t$: ray path and position of a time

ω_p : plasma frequency

ω_c : cyclotron frequency

～ input parameter ～

- Magnetic field model $\omega_c(\vec{r}, t)$
- Plasma density model $\omega_p(\vec{r}, t)$
- Frequency of wave （ω）
- Initial position （$\vec{r_0}$） and wave vector （$\vec{k_0}$）

～ output ～

a full ray path and time $(r(t))$

2-3. Ionosphere model and evaluation method

① Emulate the Jovian radio waves using ExPRES and Raytracing with the hydrostatic equilibrium plasma model

② Examine the time difference between the actual occultation time and our expectation for each frequency (Fig. 6)

③ Calculate the average time difference for each frequency

④ Repeat ①～③ with changing the maximum density and scale height

Hydrostatic equilibrium plasma

$$n_e = n_{max} \exp\left(-\frac{z}{h_{scale}}\right) \text{ (/cc)}$$

n_e … electron density (/cc)
z … height (km)
n_{max} … maximaum density (/cc)
h_{scale} … scale heigh (km) ⇨ 2 parameters

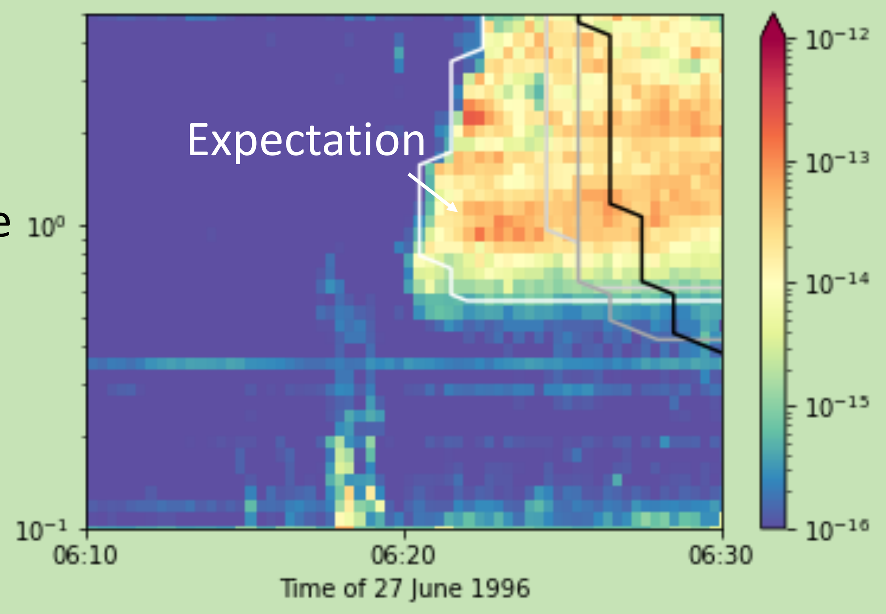


Fig.6 Superimposed Galileo PWS data and our results, assuming hydrostatic equilibrium plasma [Max density : 200 (/cc) Scale height : 600 (km)]

3. Result and Discussion

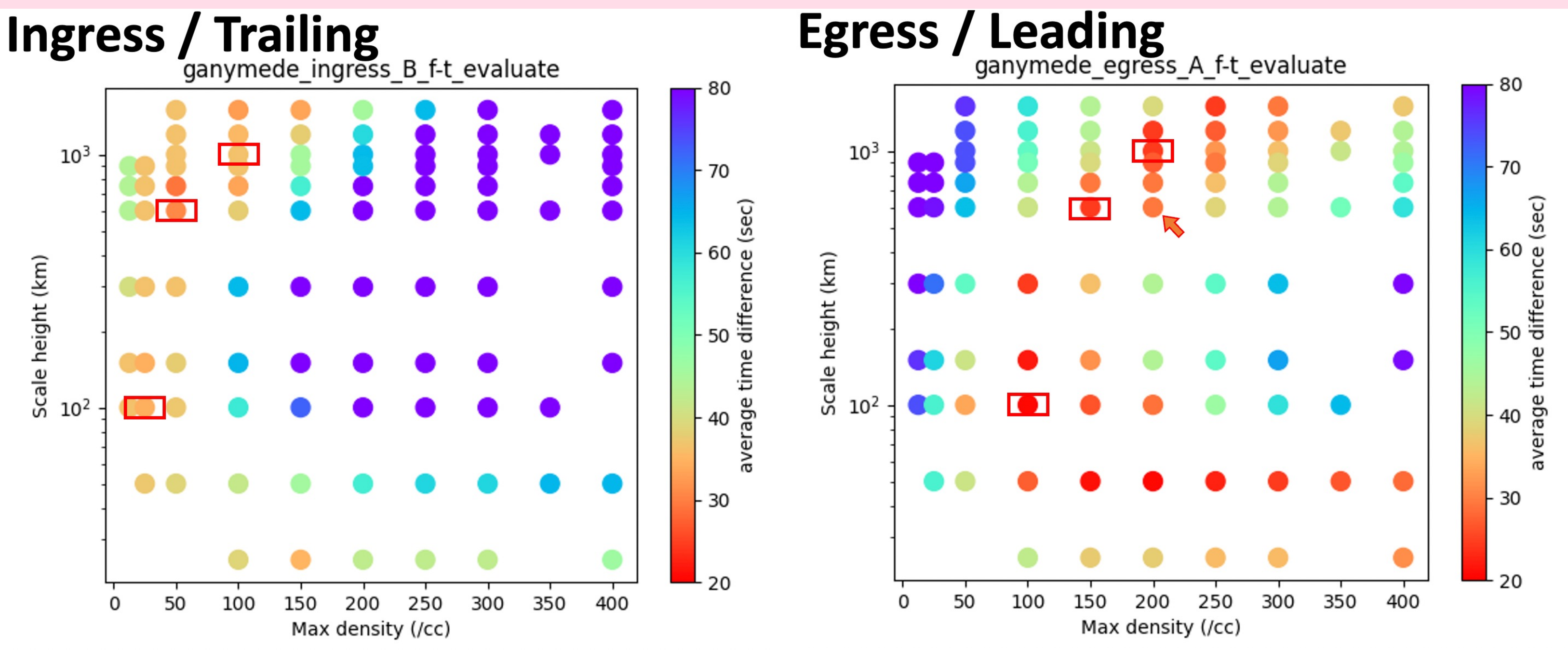


Fig.7 The average time difference between the observation results and our expected time
… Max densities when our results match the observation assuming the scale height is 100/600/1000 (km) [Table. 1]
… Max densities and scale height in Fig. 6 Right

Scale height	Ingress / Trailing Max (time diff)	Egress / Leading max (time diff)
1000 km	100 (36.4 sec)	200 (/cc) (24.6 sec)
600 km	50 (30.8 sec)	150 (/cc) (24.6 sec)
100 km	25 (34.6 sec)	100 (/cc) (20.6 sec)

Asymmetry (about 100 /cc)

Table.1 Our results of Ganymede ionosphere max densities assuming some scale height pattern for Ganymede1 flyby..

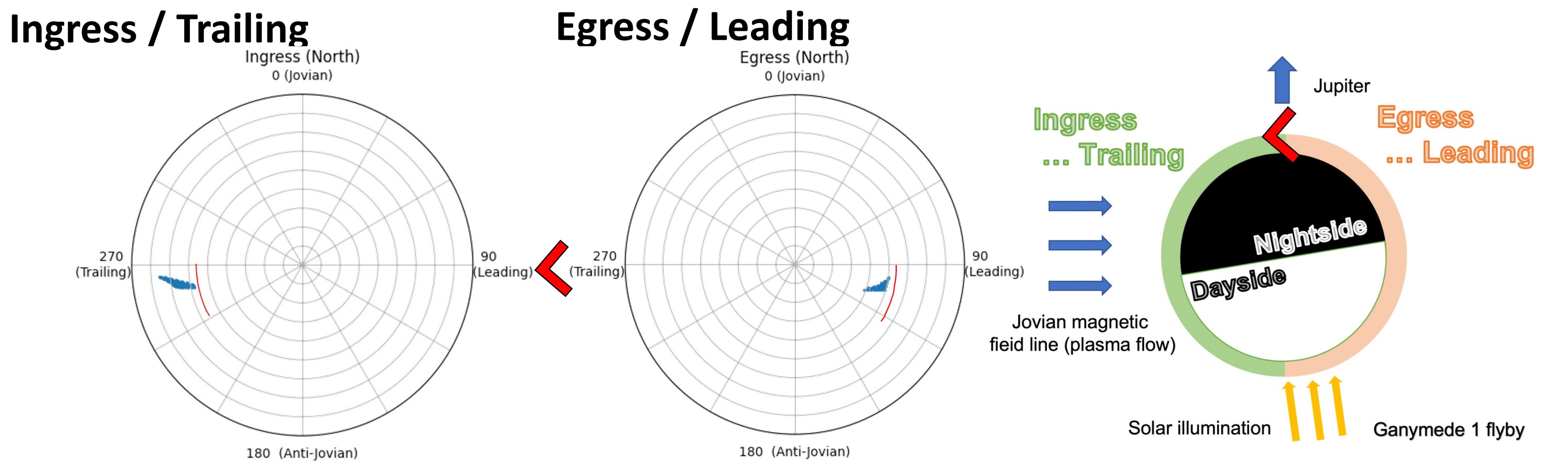
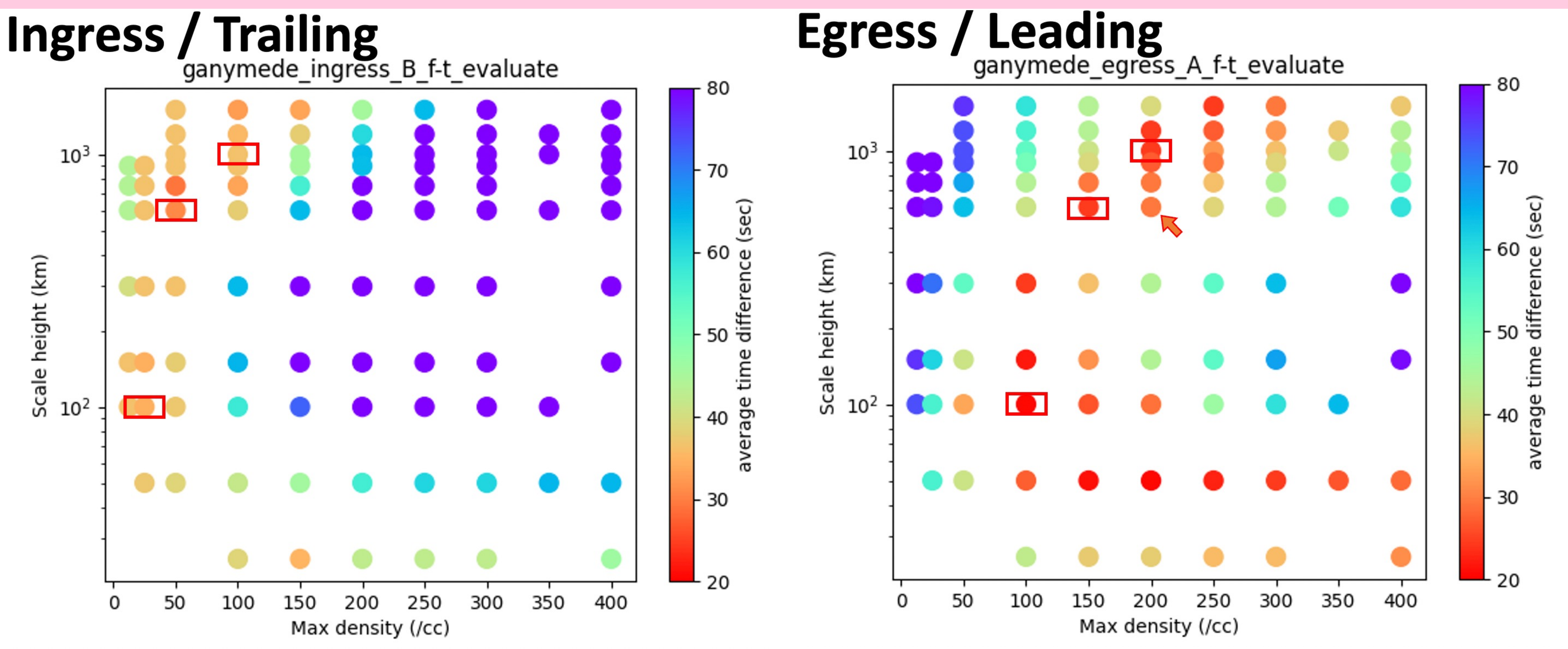


Fig.8 (Left and middle) Observation points of Ganymede (Tangential point of Jovian radio wave) while Ingress (5:51~6:05) and Egress timing (6:14~6:23). [Blue dot: tangential point, Red line: OCFL (open/closed field line) boundary (According to Khurana et al., 2007)] (Right) The geometry of Galileo Ganymede1 flyby.

- Leading-trailing asymmetry of ionospheric structure in our results of Ganymede.
- Asymmetry is formed by the solar illumination effect (Fig. 8 Left and middle)
  The atmosphere is ionized by solar EUV to produce an observable ionosphere [Kriore et al., 2001] (Radio occultation data)
- Asymmetry is formed by the injection of energetic plasma in Jovian magnetosphere？
  The OCFL (open/closed field line) boundary [Khurana et al., 2007] (Fig. 8 Right)
  Ingress part (Ganymede longitude 240 ~270) … about 30 degrees north
  Egress part (Ganymede longitude 90 ~120) … about 35 degrees north

Ingress / Trailing
Egress / Leading



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4. Future work

- Consider new methods using new information obtained by JUICE (ex. Polarization … Detect faraday rotation and measure the total electron density along the Jovian radio path)
- Reveal detail structures of the ionospheres by JUICE radio observation results