Title: Numerical radar simulation for the explorations of the ionosphere and plume at Jupiter's icy moons

Jupiter's icy moons such as Europa and Ganymede may harbor subsurface liquid water oceans and have ionospheres created from the oceanic water materials. While only Earth has the ocean on the surface in the current solar system, multiple icy bodies like the icy moons of giant planets have oceans in their subsurface under the icy crust. The icy bodies' oceans are potentially more universal habitable environment than the Earth-type surface ocean. Structures of the ocean and the ionosphere of the icy moos are essential information for understanding the universality of habitable environments. However, the structures of the oceans are unknown because in-situ or lander explorations on the surface of icy objects, the most effective method for exploring the structures, are still at technically conceptional level at present. The structures of ionospheres are still unclear as well because the ionospheric radio occultation and other effective explorations have difficulties of limited observing opportunities. Here we are going to uncover the structures of the ocean and the ionosphere of Jupiter's icy moons by the radar exploration with the Radio & Plasma Wave Investigation (RPWI) and the Radar for Icy Moon Exploration (RIME) onboard the Jupiter ICy moons Explorer (JUICE). For the investigations of radio wave sounding in and around the icy moons with RPWI and RIME ranging in tens KHz to tens MHz, we are now developing a numerical simulation code that models the propagation of electromagnetic (EM) waves in the ionospheres of the icy moons. As the first step, we emulate occultation of the Jovian radio waves by the icy moon's ionospheric structures during the flybys of the Galileo spacecraft to Jupiter's icy moons. In this presentation, we proposed the vertical ionospheric profiles matching the Galileo in-situ observation result at the altitude below the orbiter where only remote observations can reach. As the next step, we will also simulate the reflection and transmission of the EM waves in the icy crust and underlying ocean. After completing these studies, we will be able to elucidate icy moon's ionospheric and subsurface structures by combining our model with the JUICE radar explorations. The combination of our model and the JUICE radar explorations would also constrain the pressure and temperature of the subsurface, which finally lead to deep understandings of the icy moon's habitability.

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

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For more information …
https://github.com/rikuto-yasuda/icymoon_raytracing/blob/master/doc/PPARC_seminer_220207.pdf

Summary

- Developing the numerical simulation code for the radar explorations using natural radio waves to investigate spatial structures of ionosphere created from the water oceanic materials.
- Hydrostatic equilibrium plasma models can mostly explain the Galileo PWS data during Jovian radio emission occultations.
- Some of our results are close the In-situ observation results.

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. While only Earth has the ocean on the surface in the current solar system, multiple icy bodies like the icy moons of giant planets have oceans in their subsurface under the icy crust. The icy bodies' oceans are potentially more universal habitable environment than the Earth-type surface ocean. Structures of the ionosphere of the icy moos are essential information for understanding the universality of habitable environments.

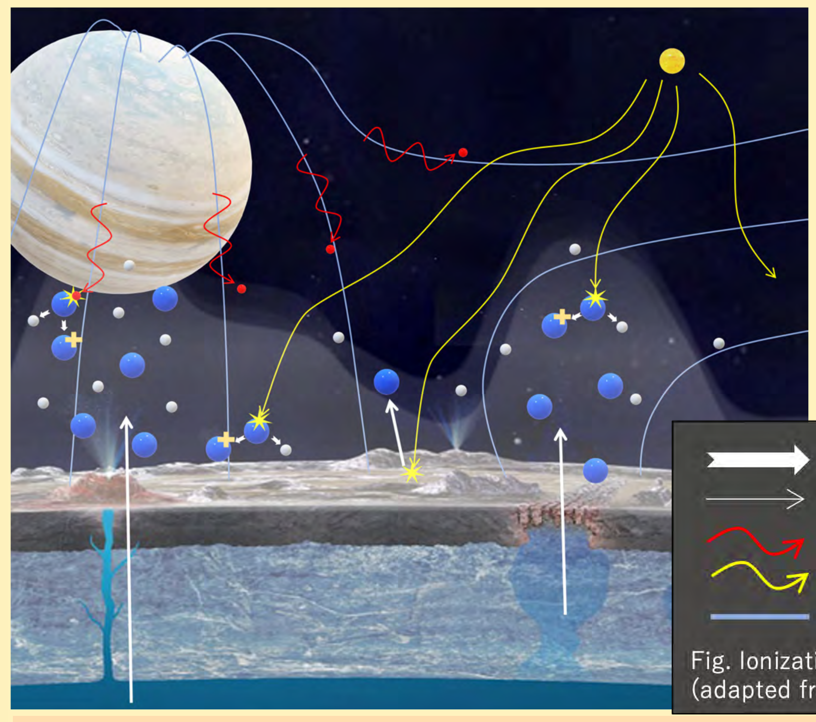
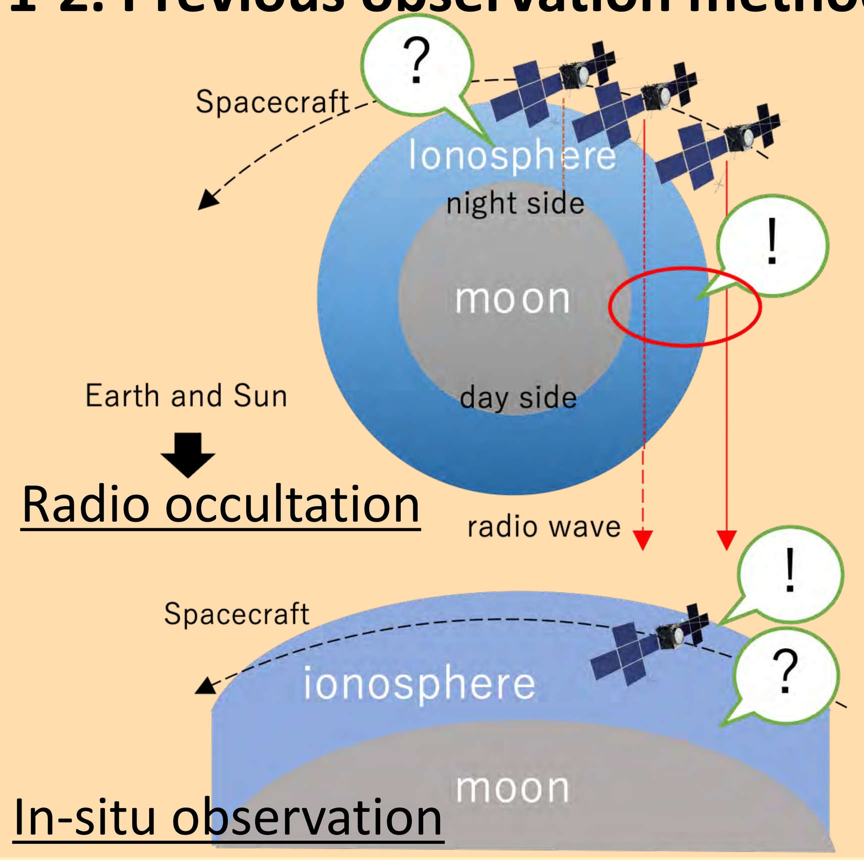


Fig. Ionization process of icy moon (adapted from NASA/JPL, Airbus DS and gcoe-earths.org)

Ionospheric structure of icy moons

- Distribution of atmosphere created from oceanic water materials
- Energy sources into icy moon

1-2. Previous observation methods



Only ionosphere around day–night boundary

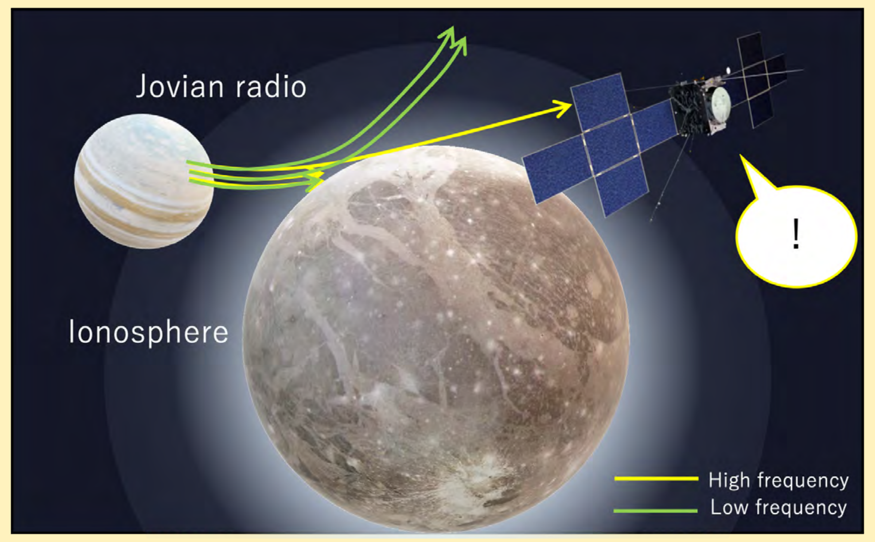
× evaluate the effect of illumination on ionosphere

△ detect the differences between leading and trailing hemisphere

Lack of information at low altitude

△ measure the vertical ionospheric profiles

1-3. Purpose of this study



Jovian radio occultation with JUICE RPWI

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

○ evaluate the effect of illumination on ionosphere

◎ detect the differences between leading and trailing hemisphere

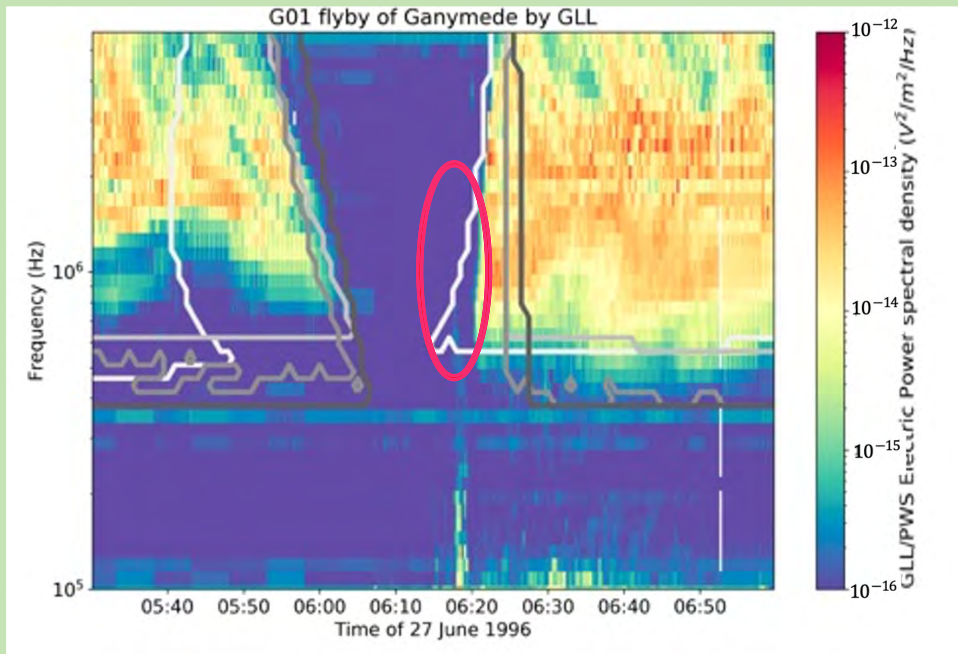
○ measure the vertical ionospheric profiles

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 position of the radio sources
↓
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 prediction mismatch (◯) indicates that propagation effects play an important role in the fine understanding of the radio occultation near Galilean moons.

Fig.10 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 electromagnetic 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 (depending on plasma density)

ω_c : cyclotron frequency (depending on magnetic field)

〜 input parameter 〜

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

↓

〜 output 〜

a full ray path and time $(\vec{r(t)})$

2-3. Ionosphere model and evaluation method

~Ganymede ionosphere model~

Plasma density model (Fig.10)

… Hydrostatic equilibrium plasma

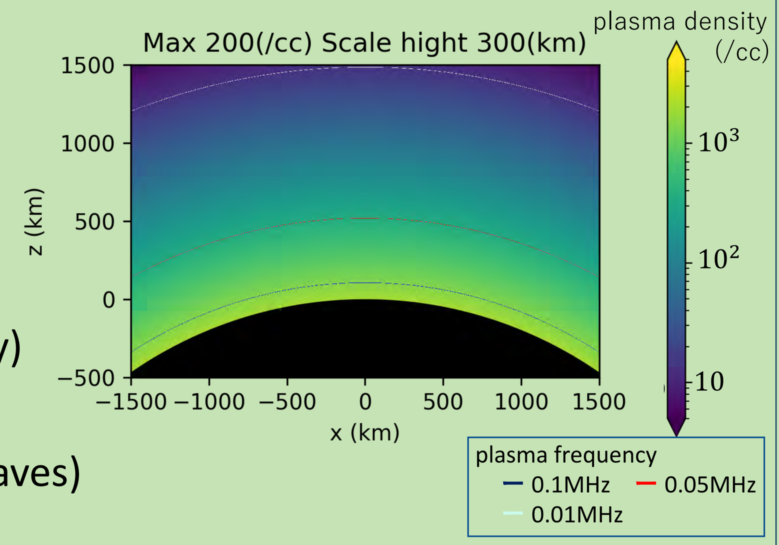
Magnetic field model

… Almost zero magnetic field

(1.0×10^{-11} (T) ・x-axis direction ・uniformly)

※ $f_c < f$ at Ganymede surface

(f_c … Cyclotron frequency, f … Frequency of waves)

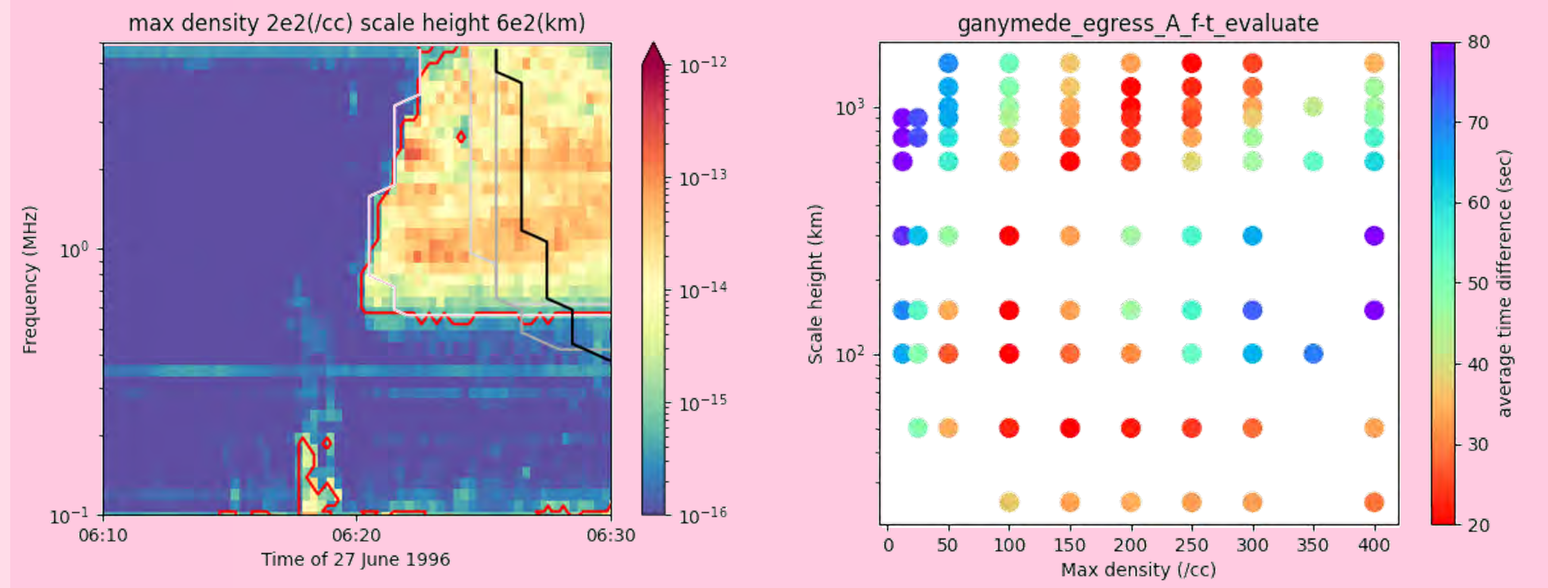


evaluation method

① Emulate the Jovian radio waves using ExPRES results and Raytracing with the hydrostatic equilibrium plasma model
② Judge whether the radio sources are visible or not (Make f-t diagrams)
③ Check the time to finish receiving radio waves (occultation start) and the time to start receiving radio waves (occultation end) for each frequency
④ Examine the time lag between the occultation start/end time and our expected time for each frequency
⑤ Calculate the average time lag for each frequency
⑥ Repeat ①〜⑤ with changing the maximum density and scale height of the hydrostatic equilibrium plasma model

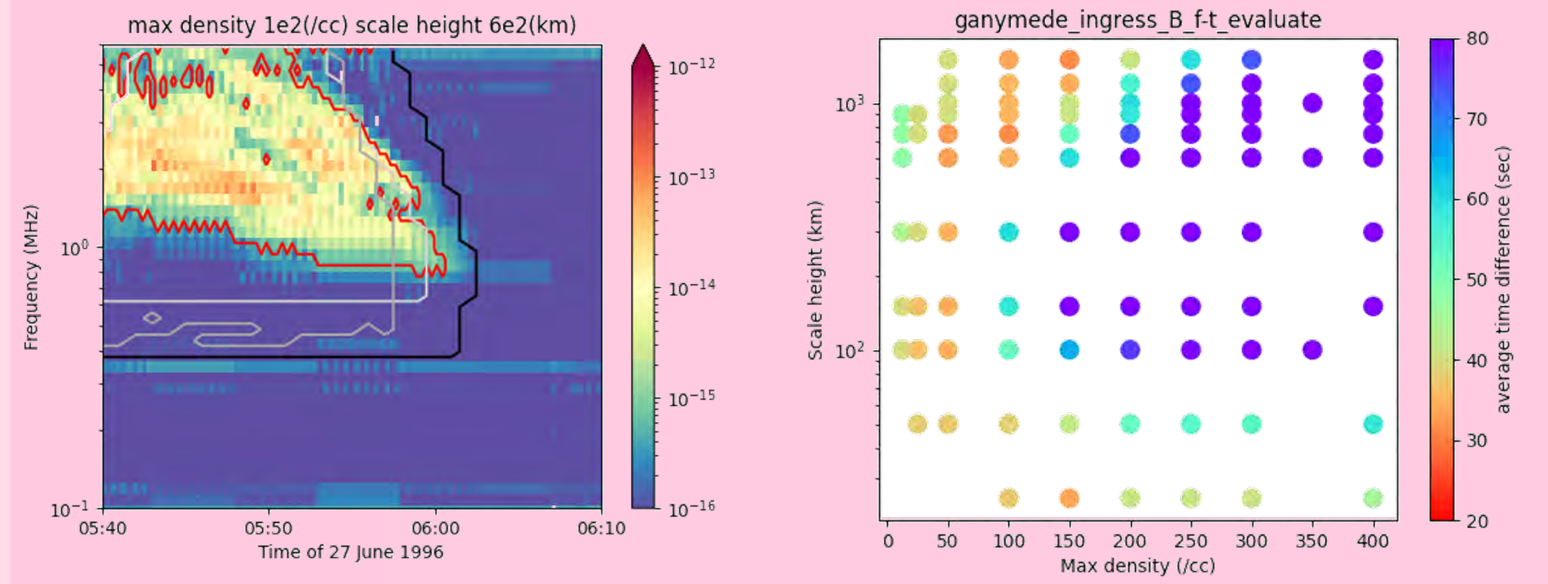
3. Result & Discussion

Galileo Ganymede1 flyby Egress part (leading / dayside)



Scale height	Max density (range | best)	Cf. Previous study
1000 km [Gurnett et al. 1996]	150~300 | 200 (/cc) (20.6 sec)	~ 100 (/cc)
600 km [Eviatar et al. 2001a]	100~200 | 150 (/cc) (20.6 sec)	~ 400 (/cc)
100 km [cf. Eviatar et al. 2001b]	25~200 | 100 (/cc) (19.1 sec)	~ 2500 (/cc)

Galileo Ganymede1 flyby Ingress part (trailing / nightside)



Scale height	Max density (range |best)	Cf. Previous study
1000 km [Gurnett et al. 1996]	- | 50 (/cc) (34.8 sec)	~ 100 (/cc)
600 km [Eviatar et al. 2001a]	- | 100 (/cc) (34.6 sec)	~ 400 (/cc)
100 km [cf. Eviatar et al. 2001b]	- | 100 (/cc) (35.2 sec)	~ 2500 (/cc)

- Hydrostatic equilibrium plasma models can mostly explain the Galileo PWS data during Jovian radio emission occultations.
- Some of our results are close the In-situ observation results.
- There is day-night asymmetry of ionospheric structure in our result.
- We are considering new methods for distinguish these plasma distributions (Using Faraday rotation, radio direction, intensity and phase)

4. Future work

- Applying this method for other Galileo PWS data during Jovian radio emission occultations by Jupiter's icy moons.
- We are going to simulate reflection and transmission of the EM waves in the ice crust and underlying ocean to explore their structures.

Reference

- Kimura et al, 2008a, Occurrence and source characteristics of the high-latitude components of Jovian broadband kilometric radiation
- Cecconi et al, 2021, Auroral Radio Source Occultation Modeling and Application to the JUICE Science Mission Planning
- Gurnett et al. 1996, Evidence for a Magnetosphere at Ganymede from Plasma-wave Observations by the Galileo Spacecraft.
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