A Test Particle Simulation for the Jovian Magnetospheric Electrons Precipitating into Europa's Oxygen Atmosphere

*Shinnosuke Satoh[1], Fuminori Tsuchiya[1], Shotaro Sakai[1], Yasumasa Kasaba[1], Rikuto Yasuda[1], Tomoki Kimura[2]

1. Tohoku University, Japan   2. Tokyo University of Science, Japan

TOHOKU UNIVERSITY

TOHOKU University PARC Planetary Plasma and Atmospheric Research Center

shinnosuke.satoh@pparc.gp.tohoku.ac.jp

1

Key

Europa has a north-south asymmetric 135.6 nm oxygen emissions on its atmosphere. This study is intended to reveal how the asymmetric aurora morphology is created using a test particle simulation for the Jovian magnetospheric electrons.

Europa / Oxygen aurora / Electron precipitation / Test particle simulation

Appendix is here!

2

INTRODUCTION

Europa's Atmosphere

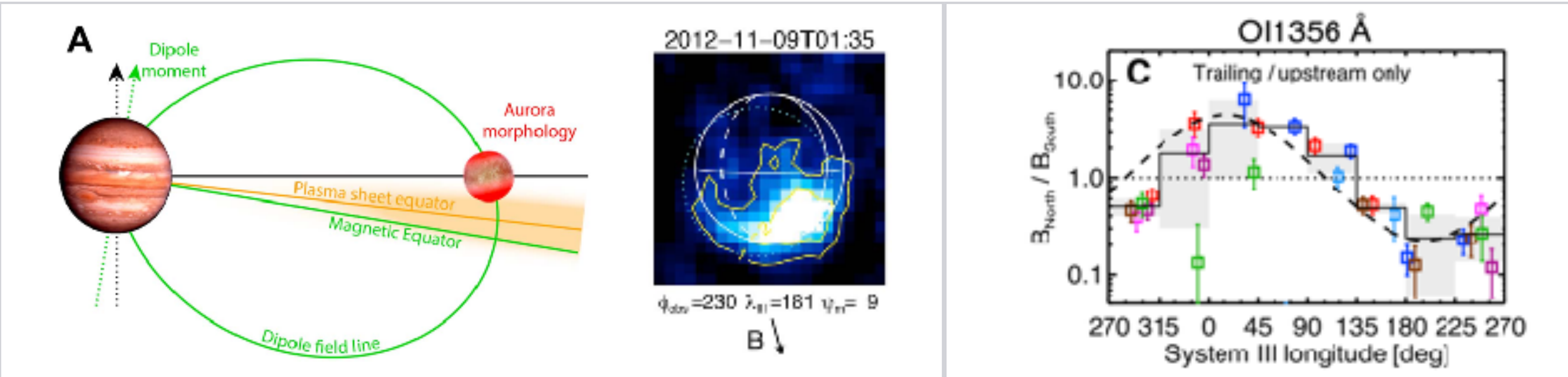
- Europa has a tenuous atmosphere. It consists mostly of O_2 molecules.
- O_2 is generated through radiolysis of H_2O and sputtered from icy surface.

Europa global view of natural (left) and enhanced colors (right). [NASA/JPL/University of Arizona]

135.6 nm Oxygen Emission on Europa Roth+2016[i]

- Roth+2016 analyzed 135.6 nm oxygen emissions observed by HST.
- Brighter when Europa is closer to the plasma sheet center
  → Correlation between brightness and Sys. III longitude
- Brighter on the hemisphere that faces the plasma sheet center
  → When Europa is "above" the plasma sheet center, the southern hemisphere has brighter emission on it.

Up to 5x north-south ratio on the trailing hemisphere



(Left) Geometry when the 135.6 nm emission is brighter on the southern hemisphere. (Right) Plot of north-south brightness ratio to Europa's System III longitude. [Roth+2016]

Cause of Asymmetry

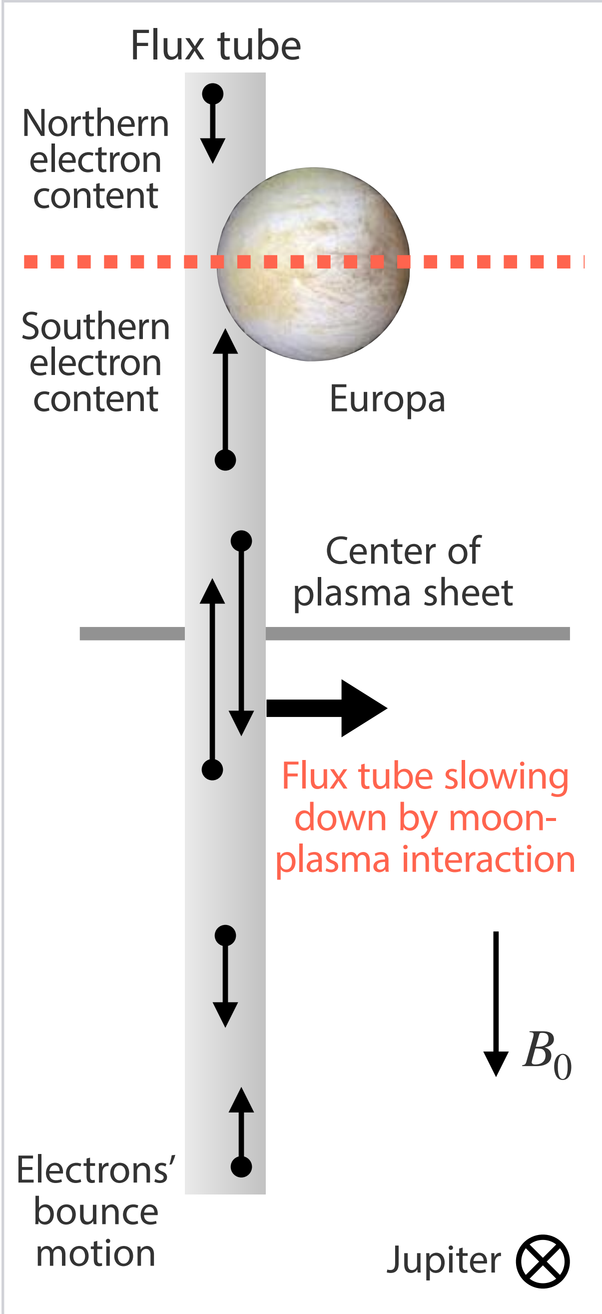
Retherford+2003[ii]

- Retherford+2003 explained the similar north-south asymmetry found on Io.
- If a flux tube slows down from the corotation by moon-plasma interaction, most electrons collide before passing over Io.

Time of passing over Europa's diameter	>	1/2 period of bounce motion along field line

- When Europa is located "above" the plasma sheet, the southern hemisphere has more electron flux.

We evaluate this with a particle simulation and derive the electron flux & 135.6 nm brightness.



Models

- The moon-plasma interaction in a cylinder described by Ip 1996[vi]:

$$V_x = 0 \;\; V_y = \alpha V_0 \text{ for } r < R_c$$

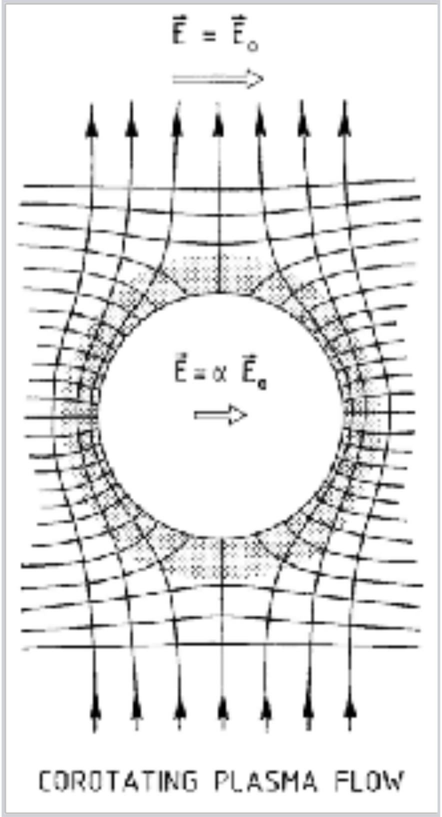
α is the interaction strength

(i.e., no MHD interaction if $\alpha = 1$)

y-axis: orbit / corotation
V_0: background corotation velocity
R_c: radius of the cylinder (= Europa's radius)

- The intersecting flux tube is assumed to be uniformly decelerated throughout the field line.
  → The ExB drift of all the electrons slows down in the flux tube.

This assumption does NOT represent the actual interaction. We only use this to see what happens when all the electron content in the flux tube precipitates into Europa's atmosphere.



Moon-plasma interaction around Europa [Ip 1996]

Back-tracing of Electron Motion

Cassidy+2013[iii]

- Trace electrons' motion in a dipole magnetosphere back in time, from Europa's surface to the magnetic equator
- The reverse motion that intersects the surface again is forbidden.
- Derive the electron flux and estimate the 135.6 nm brightness

Electron flux [cm^{-2} s^{-1}] $\mathrm{d}F_s = \left(\vec{v_s}\cdot\vec{n_s}\right) N_{eq} f_{eq}(v_{eq}, \alpha_{eq})\mathrm{d}v_{eq}\mathrm{d}\alpha_{eq}$

Brightness of 135.6 nm emission [Rayleigh] $\mathrm{d}I = \dfrac{10^{-6}}{4\pi} N_{O_2}\sigma(v) v N_{eq} f_{eq}(v_{eq})\mathrm{d}v_{eq}\mathrm{d}\alpha_{eq}$

→ Integrated

N_{eq} :Electron number density at the magnetic equator, 160 cm^{-3} [iv]

f_{eq} : Electron energy distribution function at the magnetic equator. Maxwellian with kT = 20 eV (95%) & 250 eV (5%)[v]

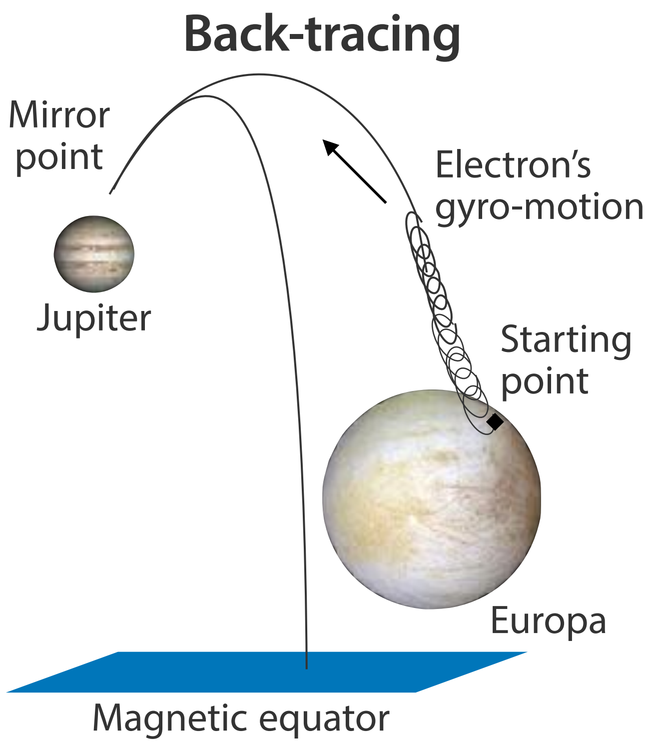
v_{eq} : Electron velocity at magnetic equator

α_{eq} : Electron pitch angle at the magnetic equator

N_{O_2} : Column density of Europa's O_2 atmosphere, 1.4x10^{15} cm^{-2} [i]

$\sigma(v)$: Cross section for 135.6 nm emissions [cm^2] [vii]

v : Electron velocity at Europa's surface



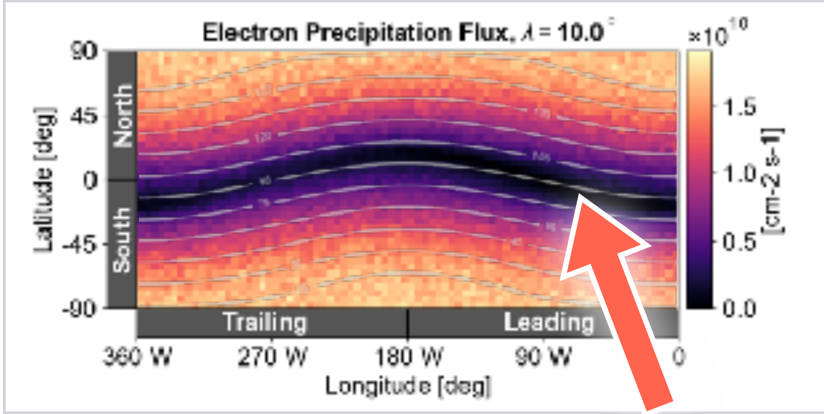
Electron Number Flux to Surface

- Europa's magnetic latitude = 10°
- Reduced flux at lower latitudes, where the magnetic field lines are tangential to the surface.
- A smaller α (stronger interaction) forms the north-south asymmetry

Table 1. Derived electron flux

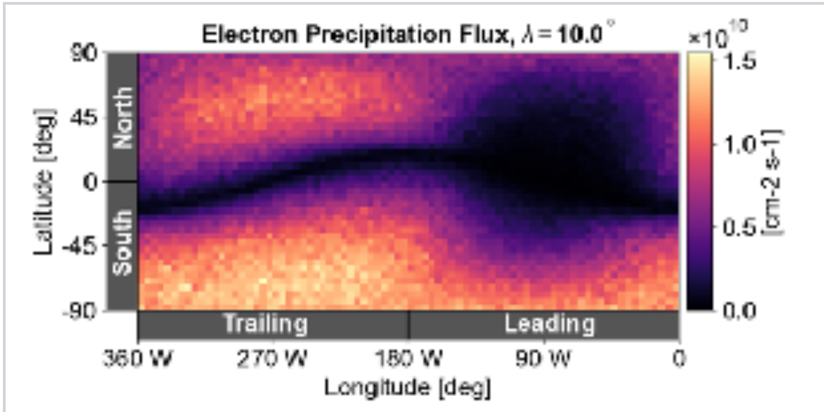
α	Trailing hemisphere: Polar regions [10^{10} cm^{-2} s^{-1}] North	Trailing hemisphere: Polar regions [10^{10} cm^{-2} s^{-1}] South	Trailing hemisphere: N-S ratio	Leading hemisphere: Polar regions [10^{10} cm^{-2} s^{-1}] North	Leading hemisphere: Polar regions [10^{10} cm^{-2} s^{-1}] South	Leading hemisphere: N-S ratio
1	**1.61**	**1.61**	**1.00**	**1.58**	**1.58**	**1.00**
0.5	**1.59**	**1.60**	**1.01**	**1.57**	**1.58**	**1.01**
0.1	**1.29**	**1.49**	**1.16**	**1.13**	**1.41**	**1.24**
0.05	**0.81**	**1.30**	**1.60**	**0.50**	**1.07**	**2.14**

$\alpha = 1$ **- Fully on the corotation**



Magnetic field lines are tangential to the surface in this area. Electrons precipitate where the field lines "stick" into the surface.

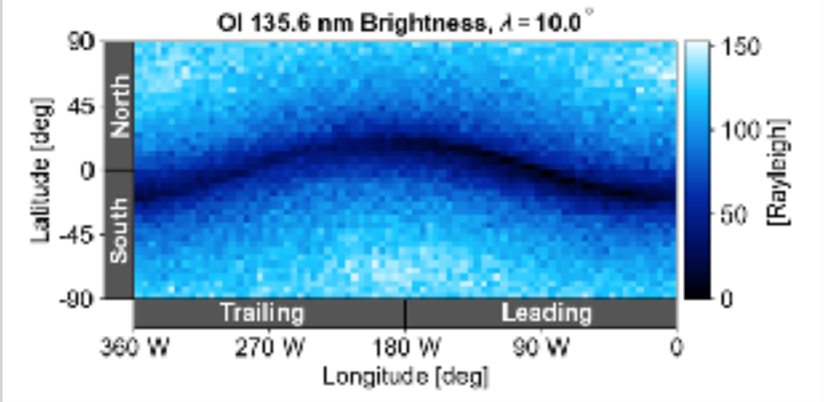
$\alpha = 0.05$ **- 5% of corotation**



135.6 nm Emission Brightness

- Converted from electron flux
- Reduced brightness at lower latitudes, the same as electron flux
- A smaller α (stronger interaction) forms the north-south asymmetry of 135.6 nm brightness

$\alpha = 1$ - Fully on the corotation



$\alpha = 0.05$ - 5% of corotation

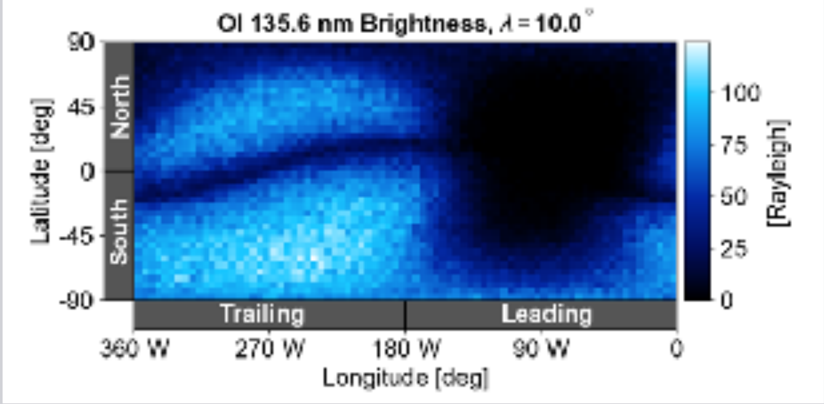


Table 2. Estimated 135.6 nm emission brightness

α	Trailing hemisphere: Polar regions [Rayleigh] North	Trailing hemisphere: Polar regions [Rayleigh] South	Trailing hemisphere: N-S ratio	Leading hemisphere: Polar regions [Rayleigh] North	Leading hemisphere: Polar regions [Rayleigh] South	Leading hemisphere: N-S ratio
1	**124**	**125**	**1.01**	**123**	**124**	**1.01**
0.5	**122**	**125**	**1.02**	**120**	**124**	**1.03**
0.1	**83**	**117**	**1.42**	**62**	**110**	**1.77**
0.05	11	60	5.56	33	92	2.82

Compared to Observation Results

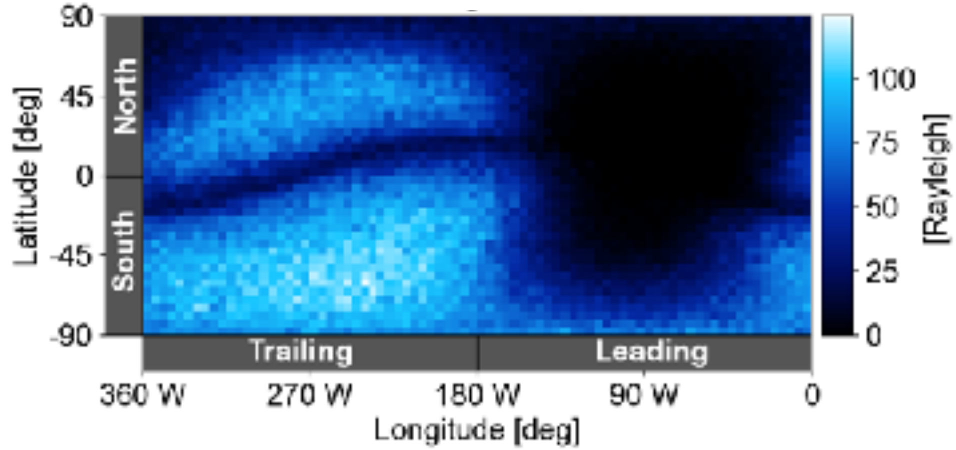
Trailing Hemisphere

- ✓ Fainter at the lower latitudes
- △ North-south brightness ratio estimated at 2.82, less than observed (~ 5).

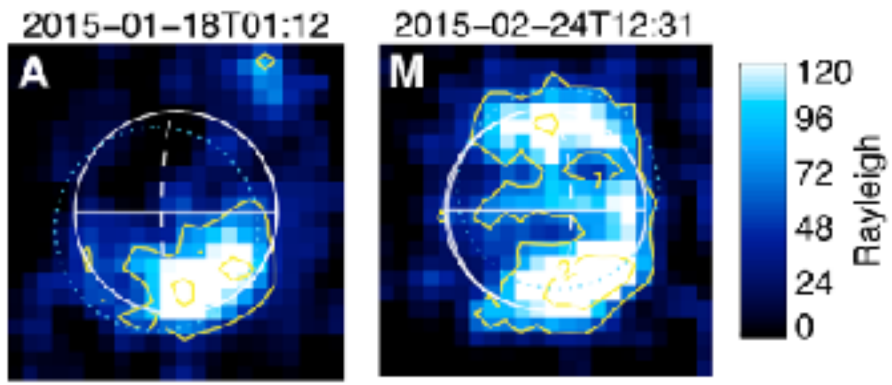
Leading Hemisphere

- ✗ A few Rayleigh of emissions on the north
- ✗ North-south brightness ratio estimated at 5.56, larger than observed (< 2).

Our Result $\alpha = 0.05$



HST Observation [i]

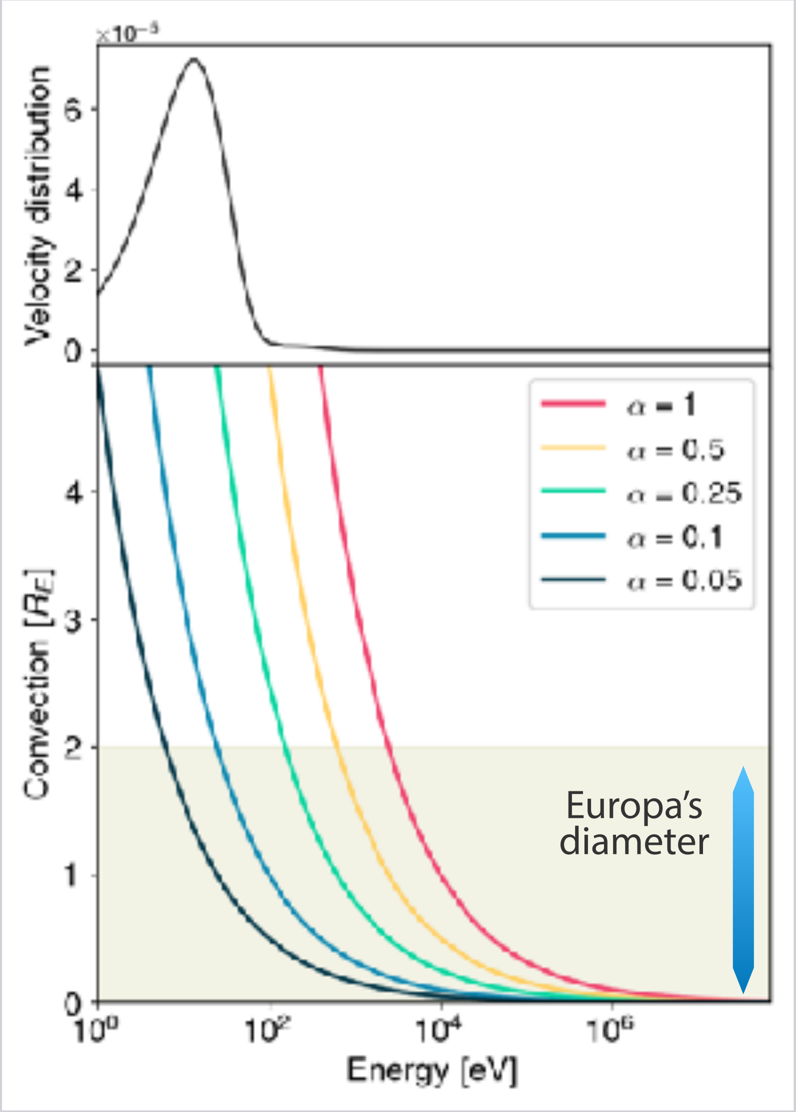


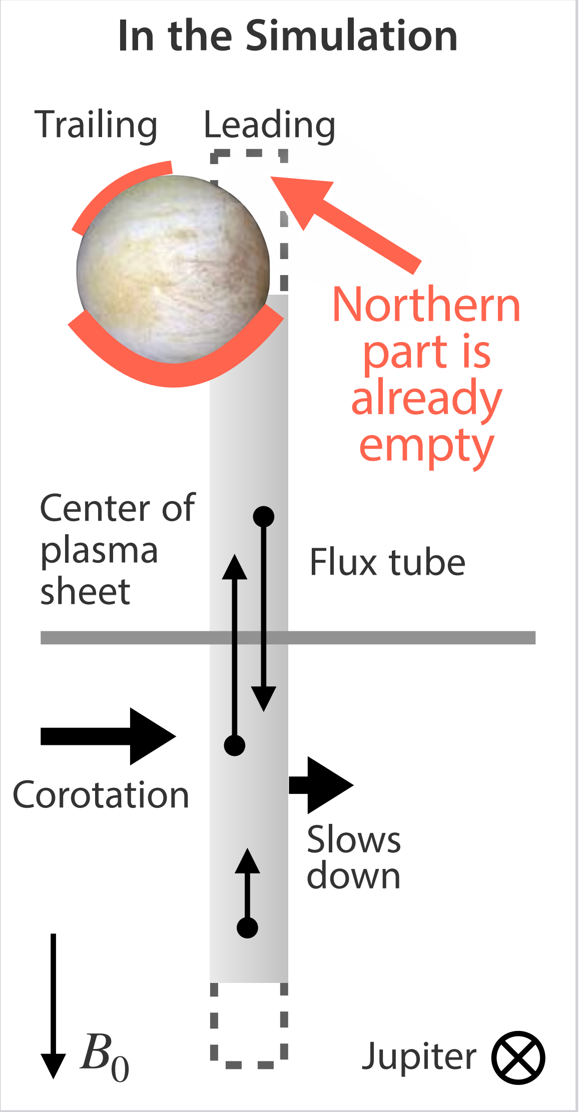
Trailing side Leading side

Morphology on the Leading Hemisphere

With $\alpha = 0.05$, electrons with most populated energy (~20 eV) CANNOT reach the northern leading side due to the collision with the trailing side.

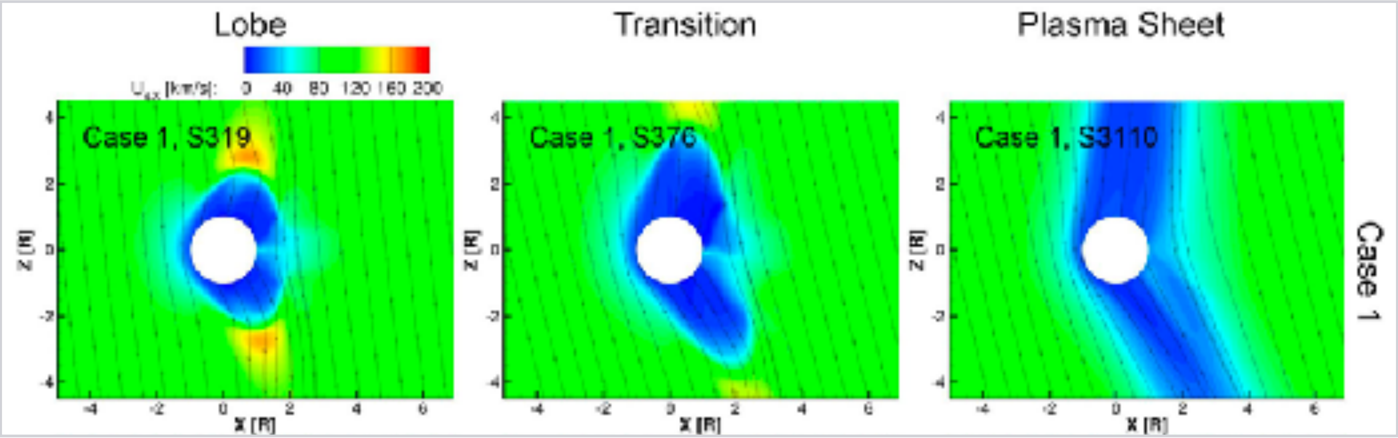
[Above] The Maxwellian energy distribution for Jovian magnetospheric electrons at Europa's orbit (9.4 RJ) with T = 20 eV (95%) and 250 eV (5%).
[Below] Electron's Convection distance during a round trip from the magnetic equator to the mirror point. The shaded area shows Europa's diameter.





Moon-Plasma Interaction

North-south ratio enlarged if z-scale of the Alfvén wing is larger.
→ an extreme condition is a flux tube uniformly decelerated throughout the field line.



The velocity distribution of plasma convection due to the moon-plasma interaction. "Lobe" is when Europa is the farthest from the plasma sheet center, "Plasma Sheet" is when Europa is at the plasma sheet center, and "Transition" is when Europa is in the midst. The z-scale of Alfvén wing does NOT expand throughout the field line. [Harris+2020]

Asymmetry formation may require:

- Smaller α (stronger interaction)
- Larger z-scale of Alfvén wing

But near Europa, actually:

- Larger α (weaker interaction)
- Smaller z-scale of Alfvén wing

Results

With a scenario by Retherford+2003, we found:

- ✓ Decelerated flux tube creates a non-uniform electron flux into Europa's atmosphere.
- △ North-south brightness ratio estimated at 2.82 on the trailing side, not 5 as observed.

Discussions

- Underestimated brightness on the leading side
  → the loss of electron content on the trailing side
- Asymmetry is formed with a stronger moon-plasma interaction and a larger z-height of Alfvén wing.
  → the opposite to Europa's plasma condition

What kind of mechanism do we need additionally to recreate the observed morphology?

Future work!

REFERENCES

i. Roth et al. (2016), https://doi.org/10.1002/2015JA022073
ii. Retherford et al. (2003), https://doi.org/10.1029/2002JA009710
iii. Cassidy et al. (2013), https://doi.org/10.1016/j.pss.2012.07.008
iv. Bagenal et al. (2011), https://doi.org/10.1029/2010JA016294
v. Bagenal et al. (2015), https://doi.org/10.1016/j.icarus.2015.07.036
vi. Ip (1996), https://doi.org/10.1006/icar.1996.0052
vii. Kanik et al. (2013), https://doi.org/10.1029/2000JE001423