Influence of Europa's Time-Varying Electromagnetic Environment on Magnetospheric Ion Precipitation and Surface Weathering

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Lucas Liuzzo[2], Hannes Arnold[1], Sven Simon[1]

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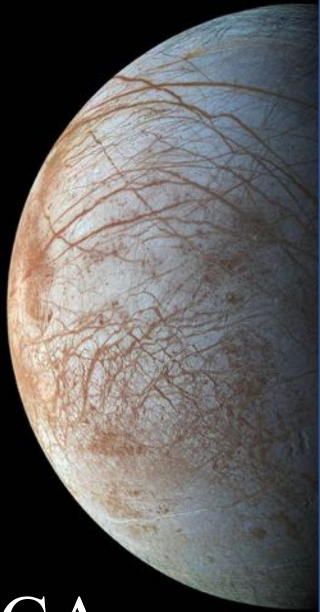


Europa

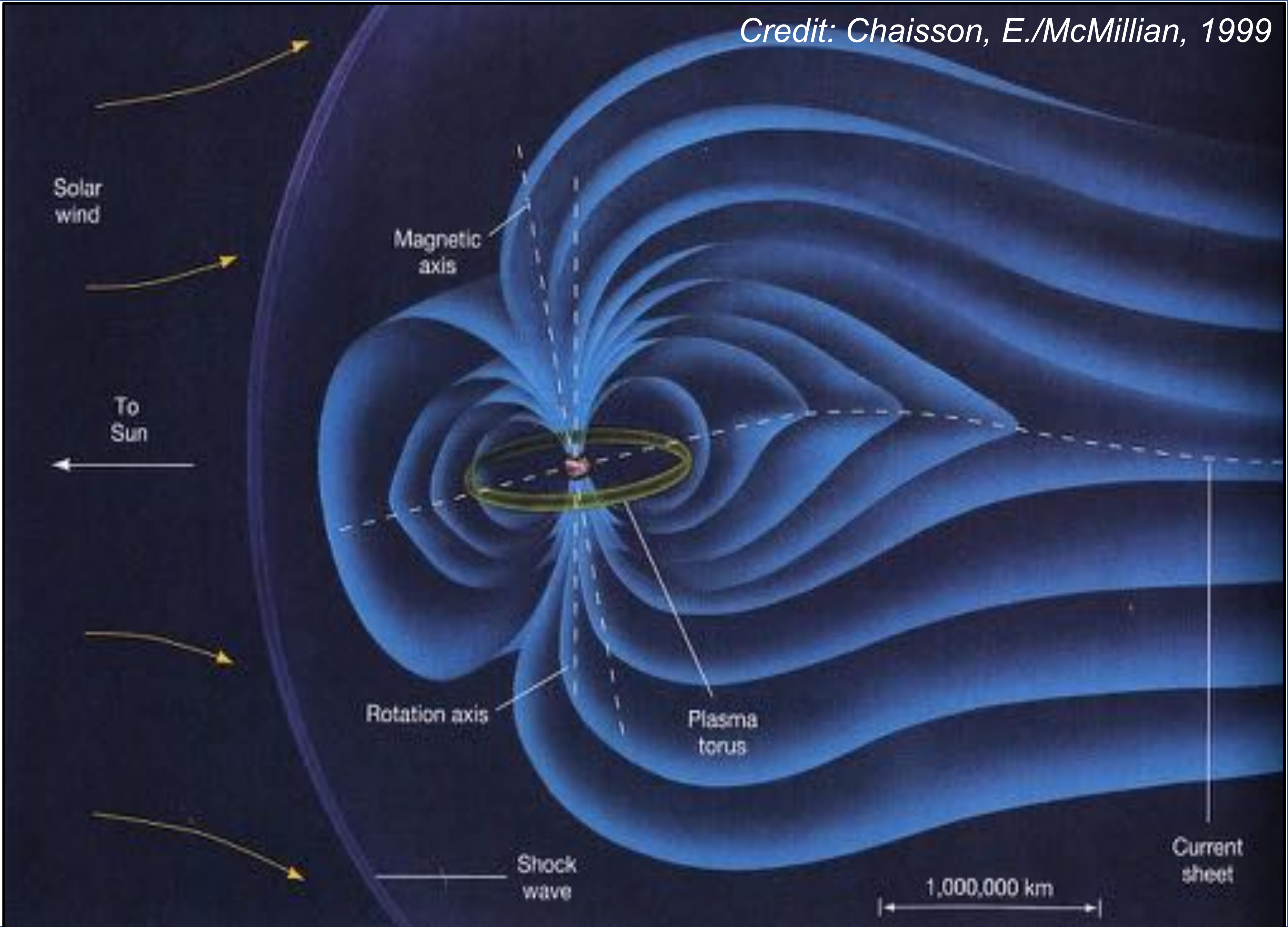
(paddison6@gatech.edu)

- Radius R_E = 1560.8 km.
- Orbital distance = 9.38 Jupiter radii (R_J = 71,492 km).
- Subsurface ocean
  - Discovered in Galileo magnetic field data (induction signal)
- Dilute, molecular oxygen exosphere, observed by HST and Galileo

Jupiter's Magnetosphere I

(paddison6@gatech.edu)

- **Magnetosphere**: extends 50 R_J upstream and hundreds of R_J downstream
- Magnetic axis **inclined** by 9.6º
- Populated by a zoo of **plasma** species
- Thermal **plasma sheet** in magnetic equatorial plane



Credit: Chaisson, E./McMillian, 1999

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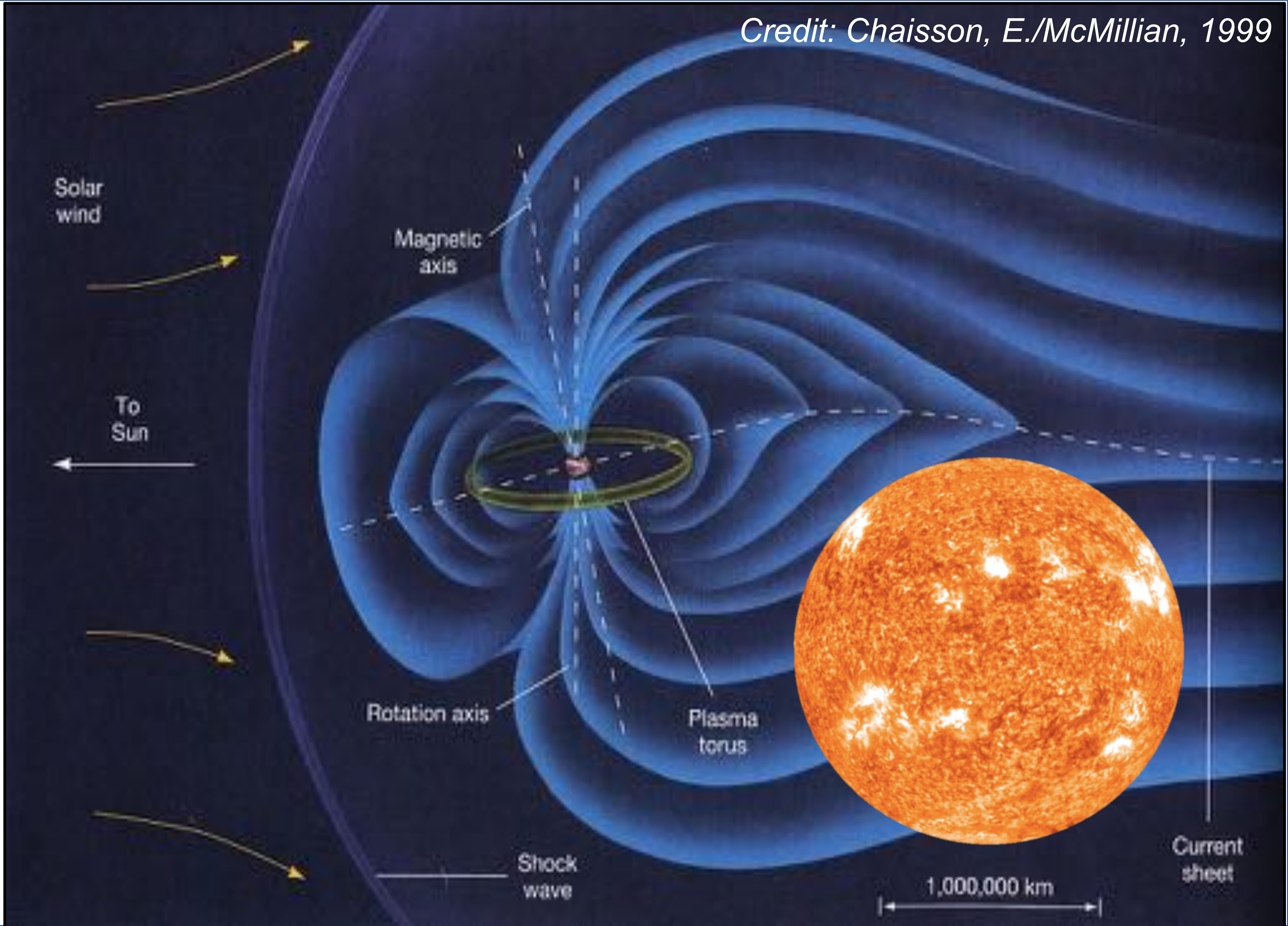

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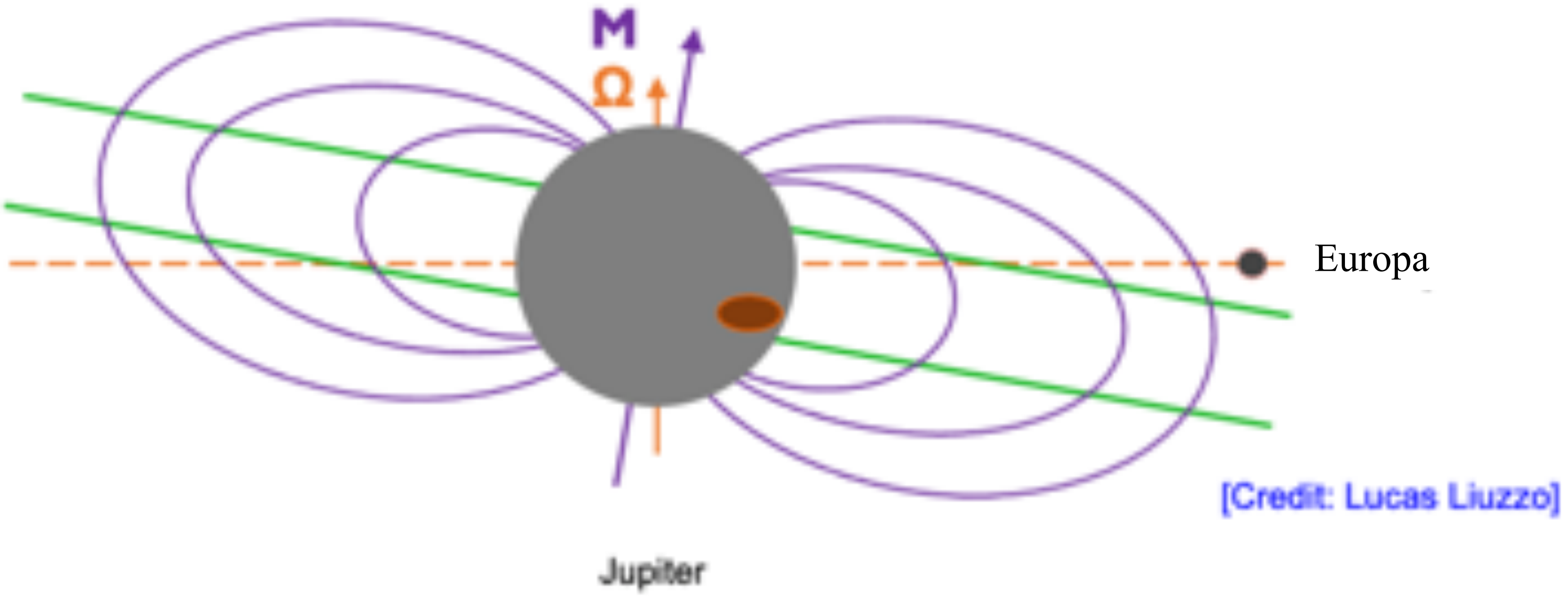
M: Magnetic Axis
Ω: Rotation Axis
Plasma Sheet



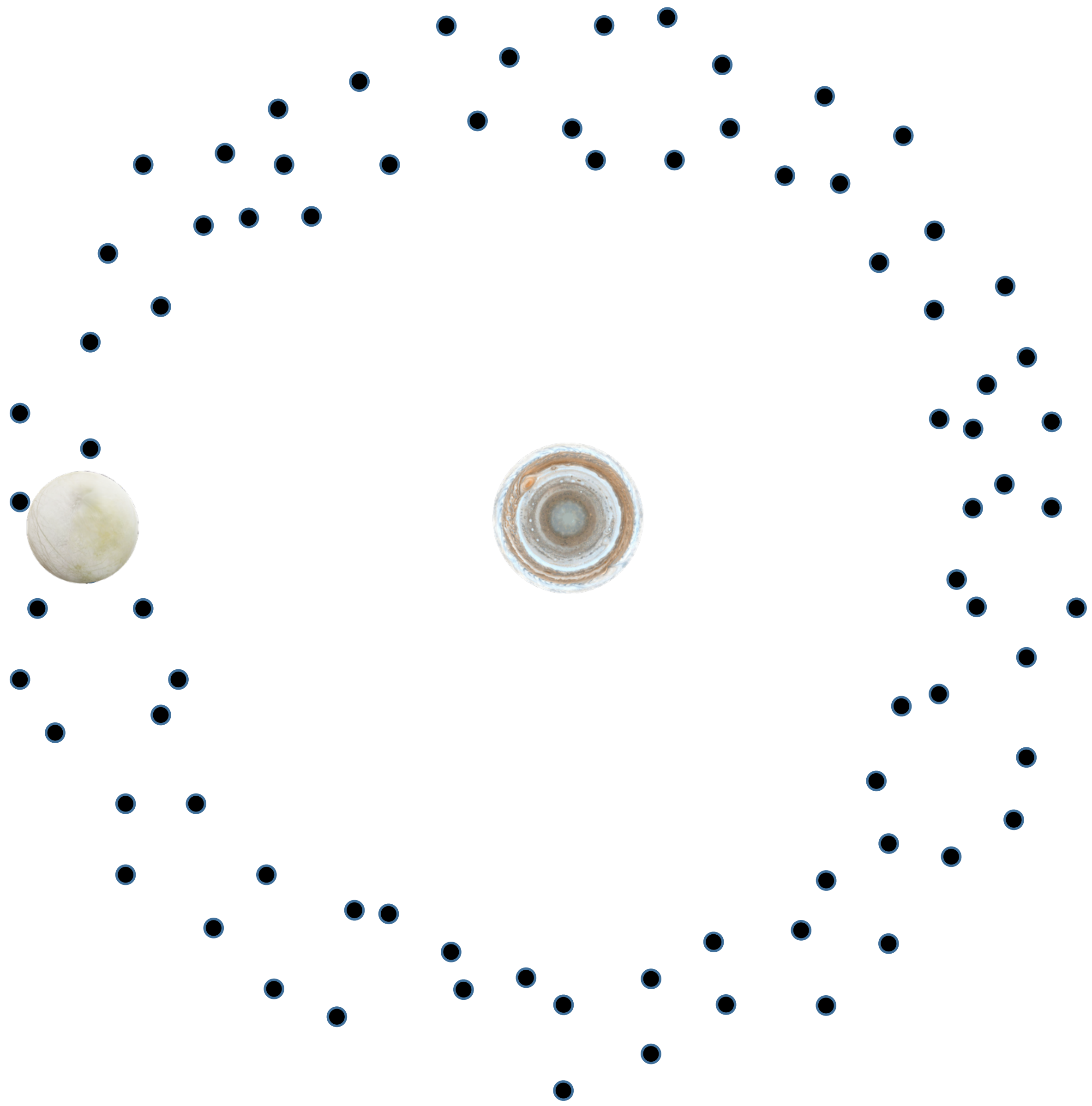
- **Magnetic axis** inclined by 9.6° against **rotation axis**
- **Plasma sheet** confined near **magnetic equator**
- **Magnetic equator** and **plasma sheet** swing over Europa

Magnetospheric conditions at Europa's orbit periodically change!

Europa's Thermal Plasma Interaction

(paddison6@gatech.edu)

- **(Nearly) corotating** plasma overtakes Europa!



Thermal Plasma Sheet

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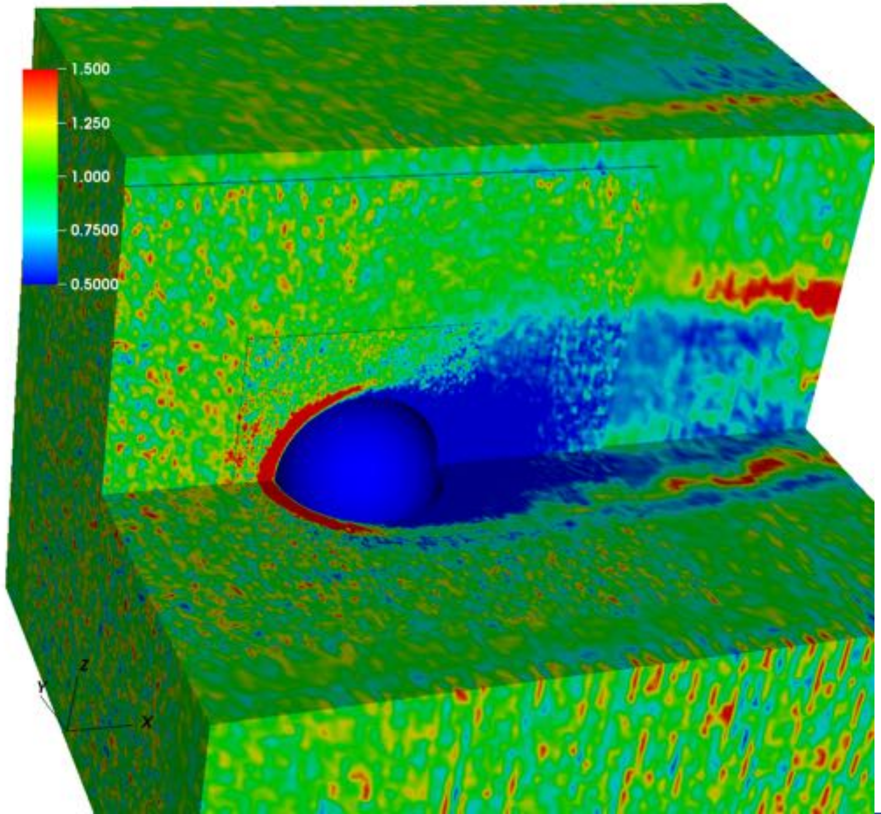

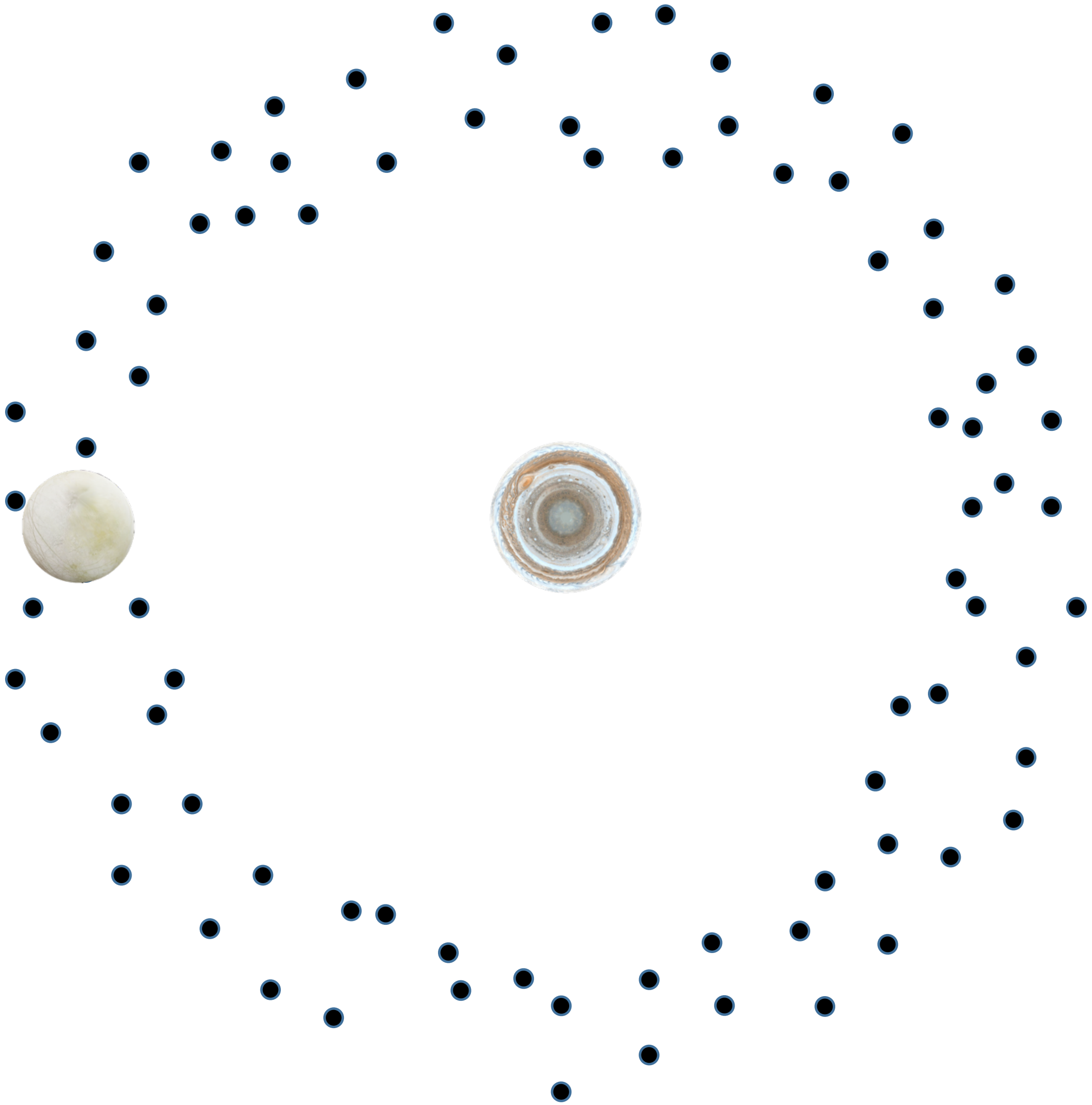

Flow deflection at Europa

Magnetic Field Perturbations Near Europa

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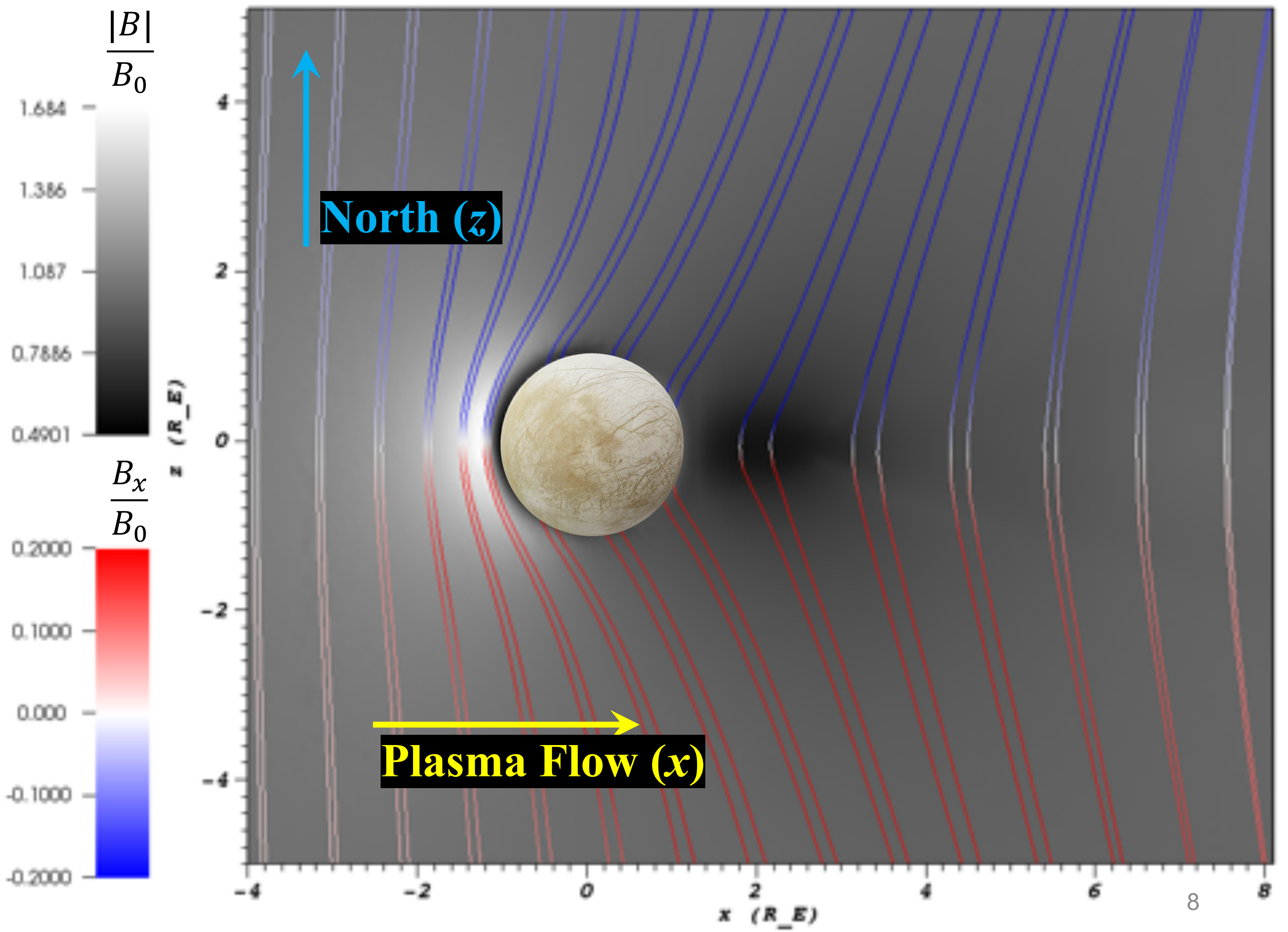
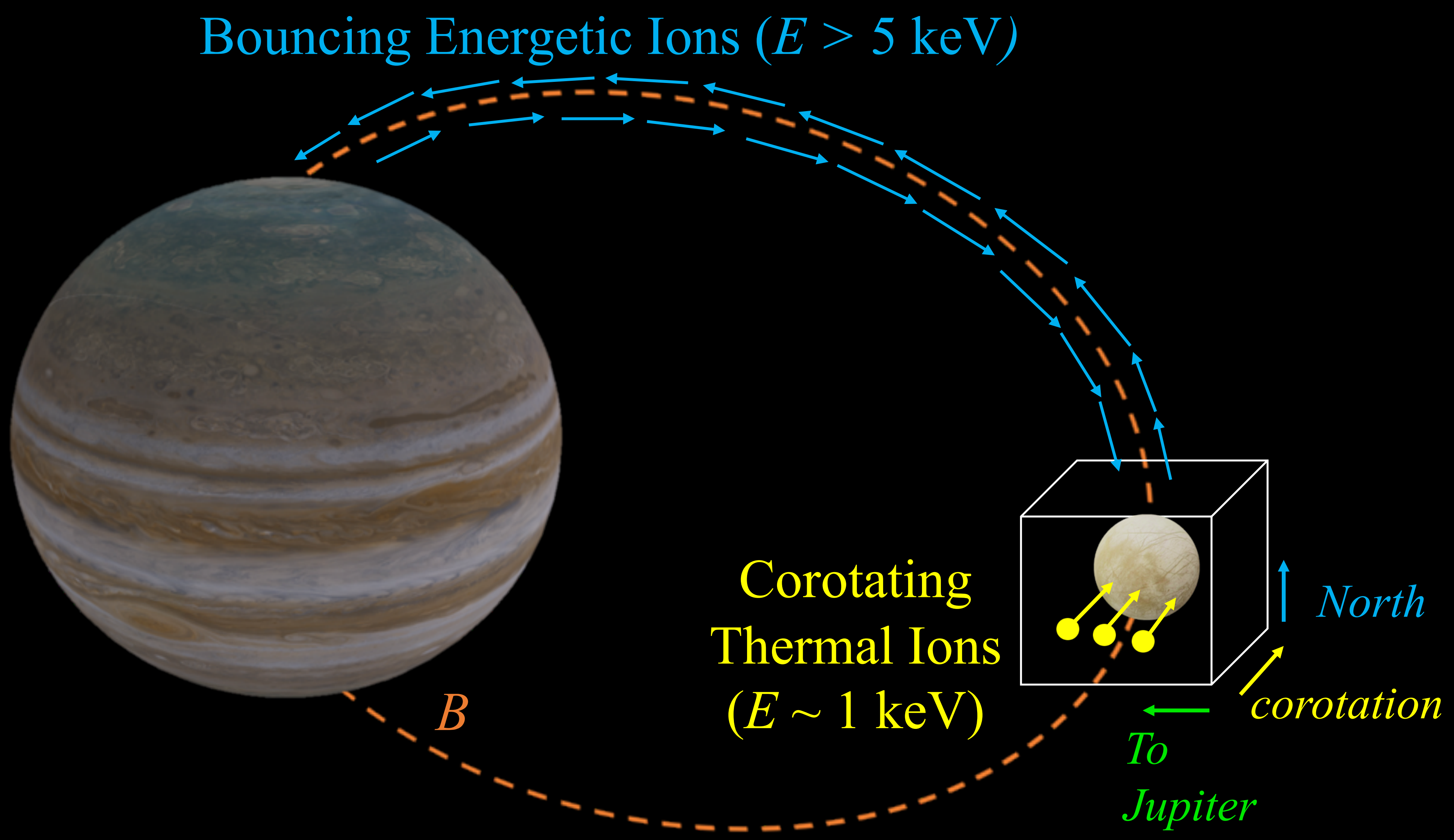
- **Sub-alfvenic** plasma interaction with ionosphere and induced dipole.
- **Ionization of exosphere:** mass-loading, slows the plasma
- Field lines frozen into plasma: pileup, **draping**



Magnetospheric Ion Bombardment of Europa I

(paddison6@gatech.edu)



Magnetospheric Ion Bombardment of Europa II

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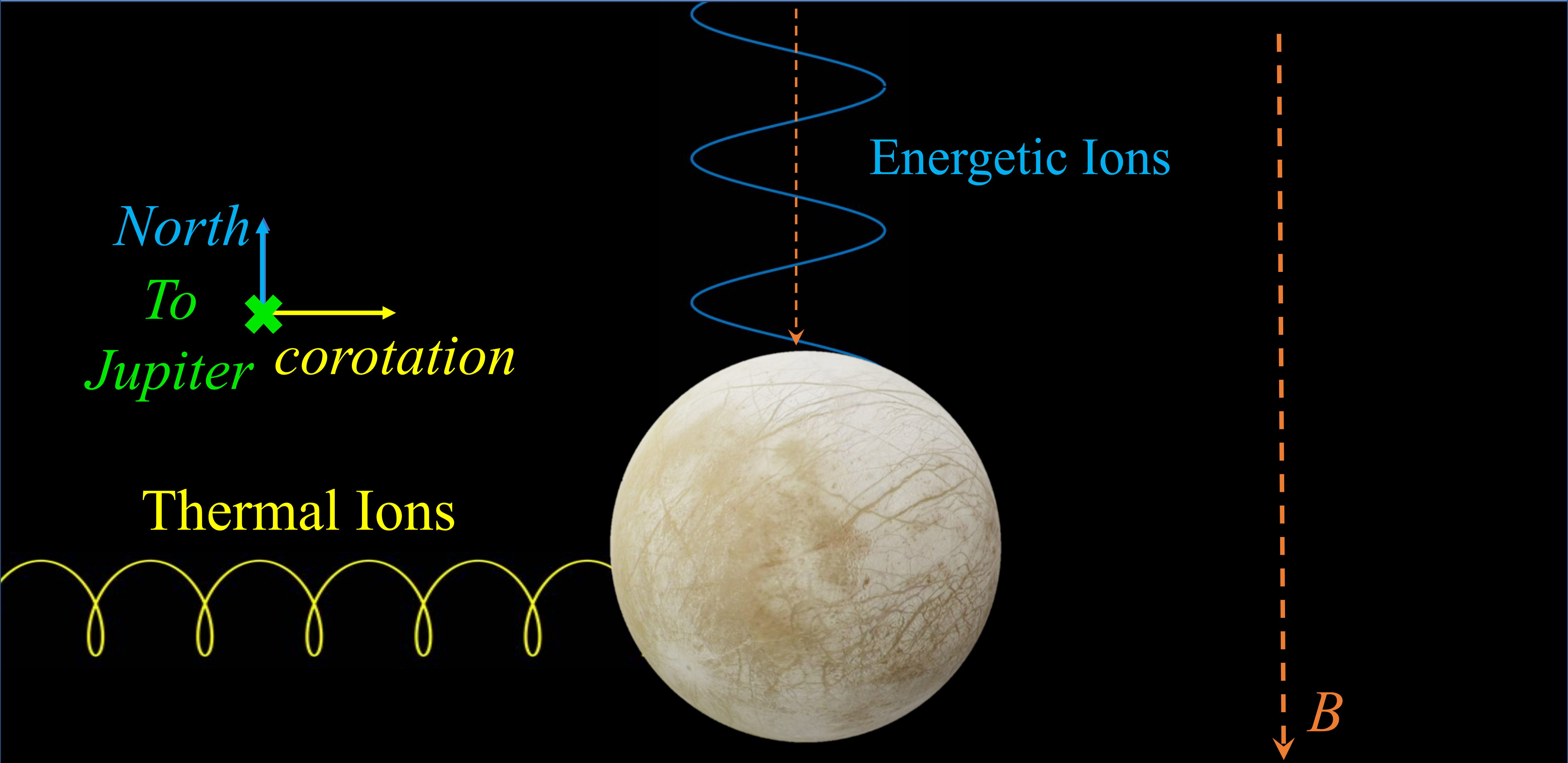

Europa's Diverse Surface Coloration

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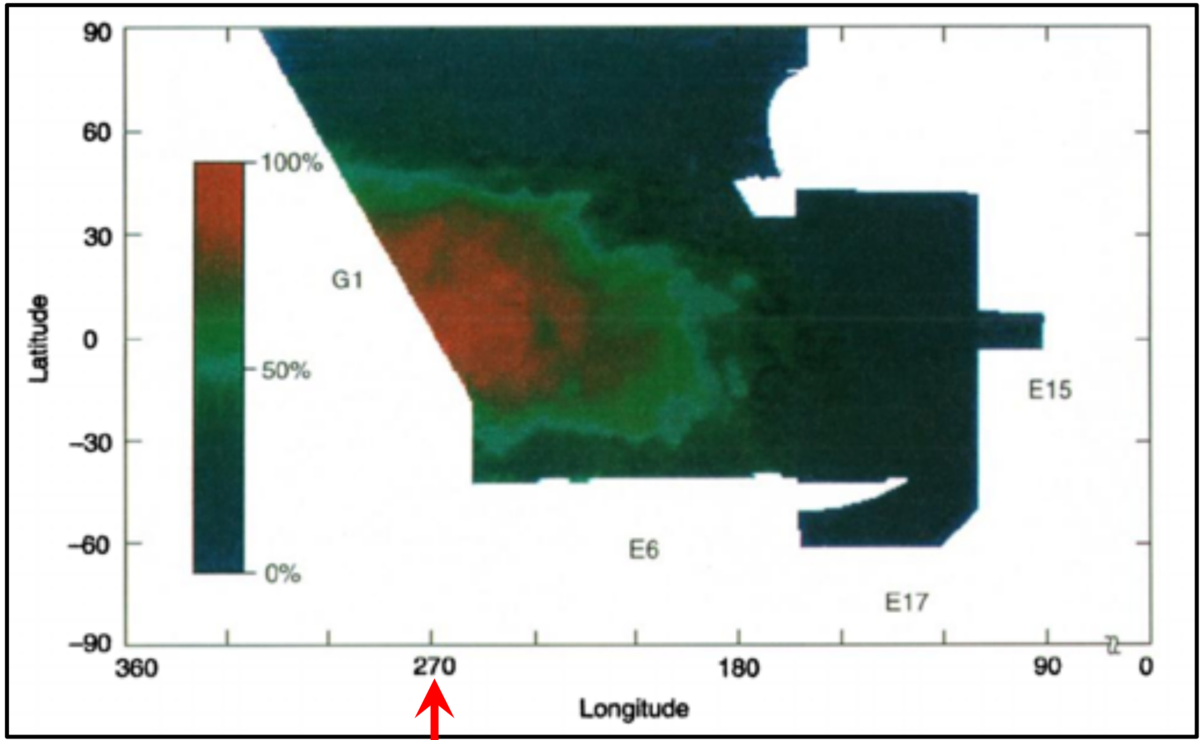
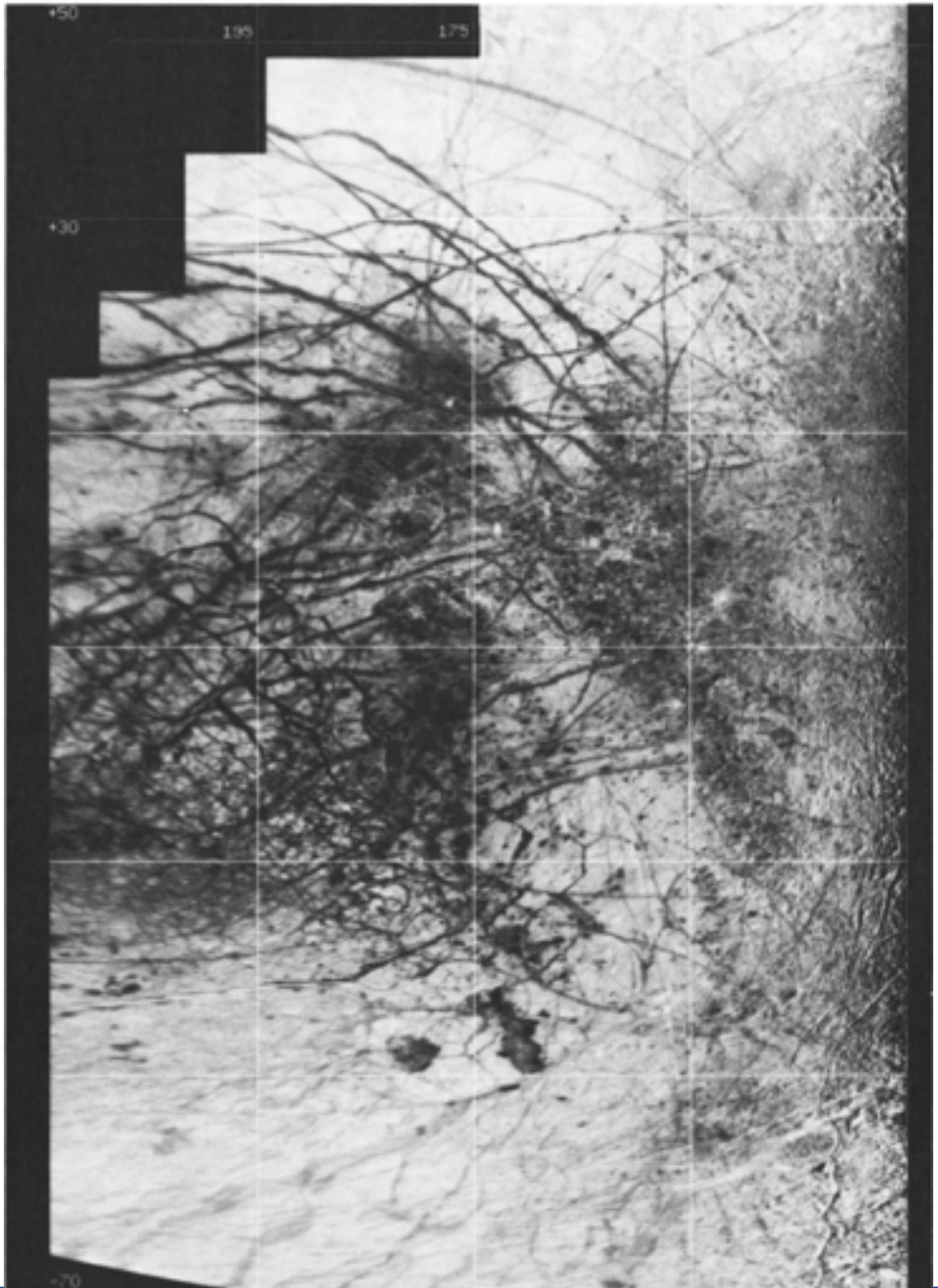
Hydrate concentration on Europa's surface (*Paranicas et al., 2001*)



Upstream Apex

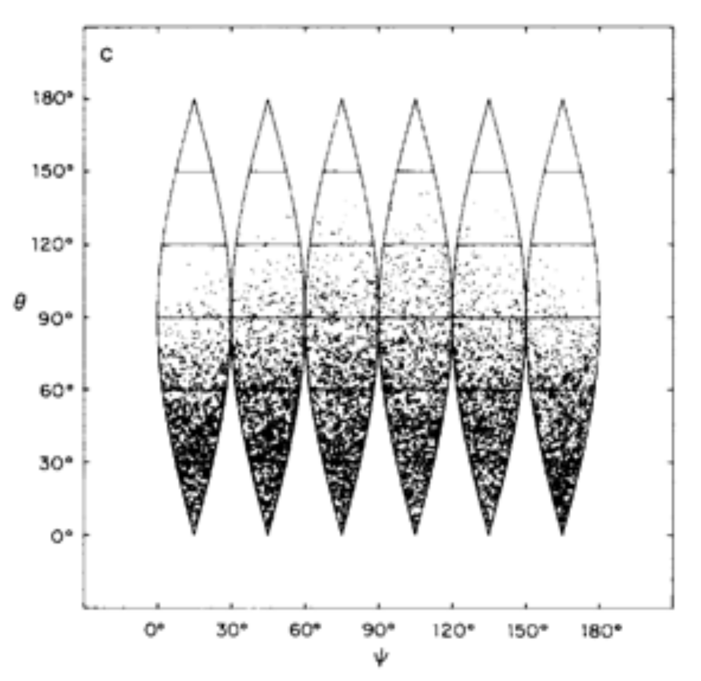


Mosaic of Europa's trailing hemisphere as imaged by Galileo. (*McEwen 1986*).

Preceding Work on Ion Bombardment

(paddison6@gatech.edu)

Pospieszalska & Johnson, 1989



- **"Photo-plate" approach, thermal and energetic sulfur ions**

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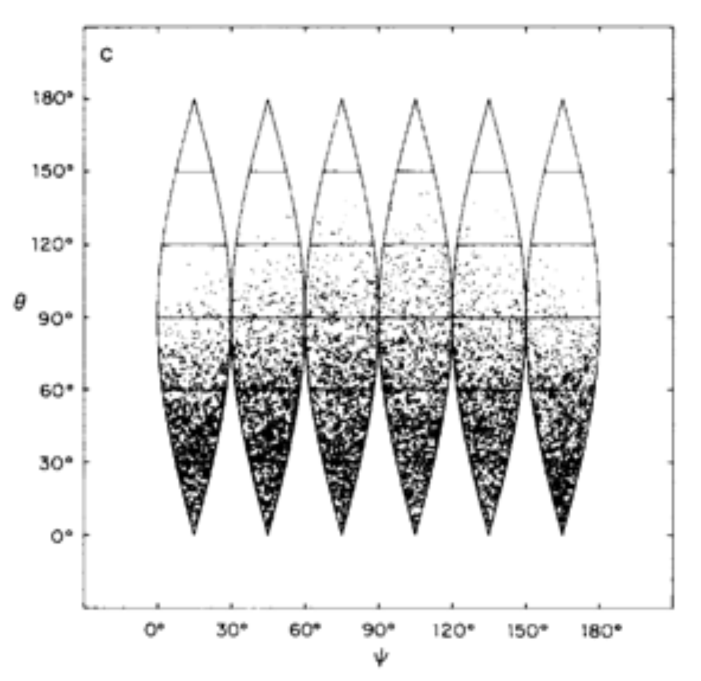

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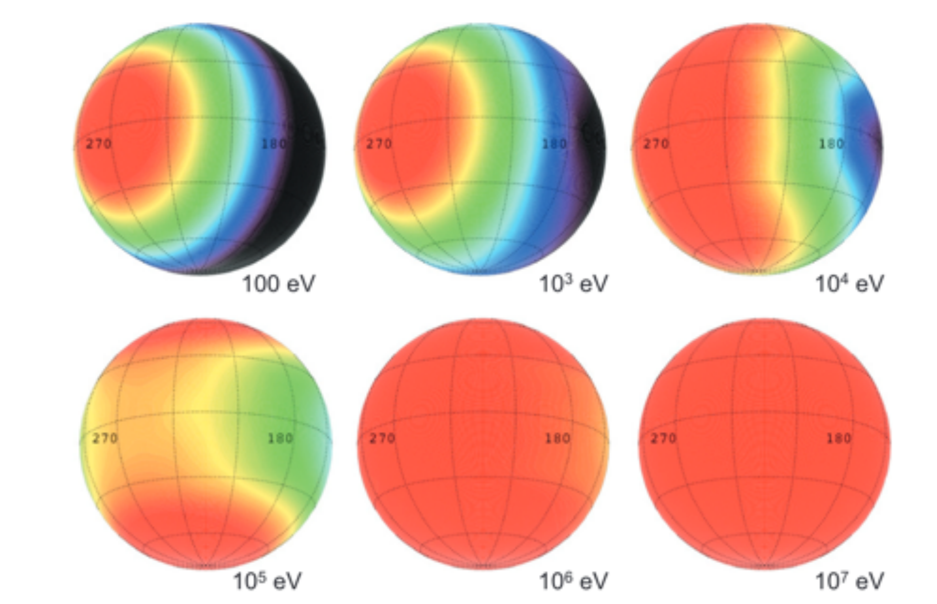
Cassidy et al., 2013



- Modeled surface flux from ~ 1 keV to 10 MeV
- Hydrogen, oxygen, and sulfur ions

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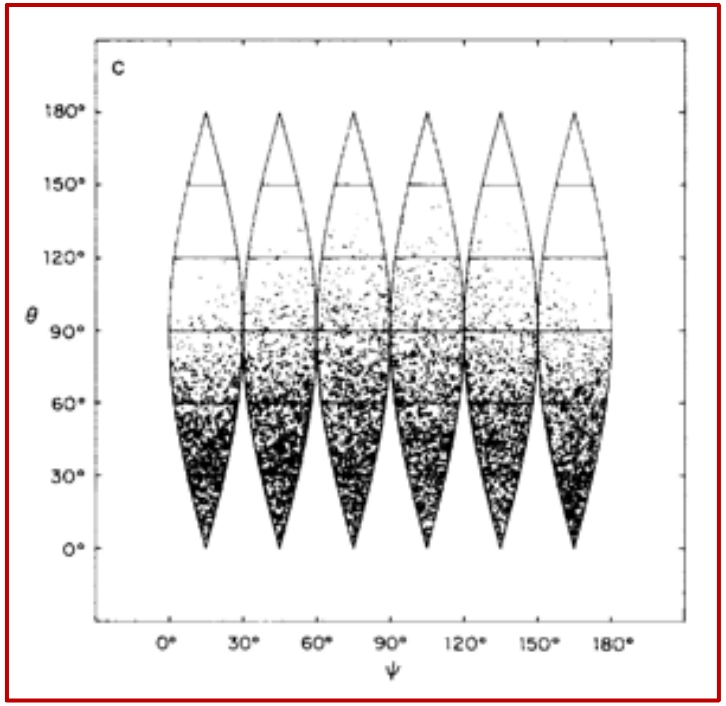

- "Photo-plate" approach, thermal and energetic sulfur ions

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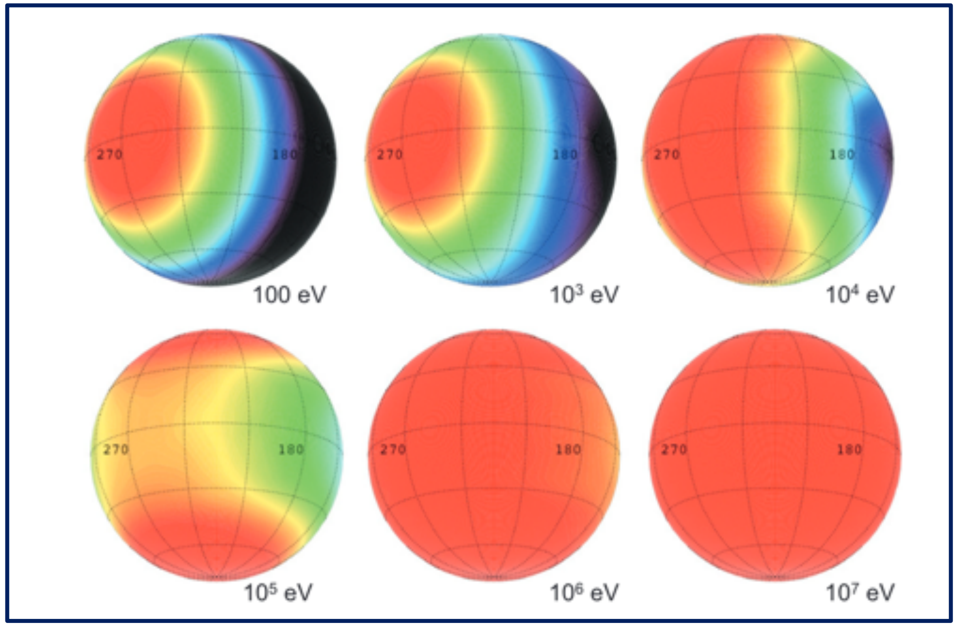

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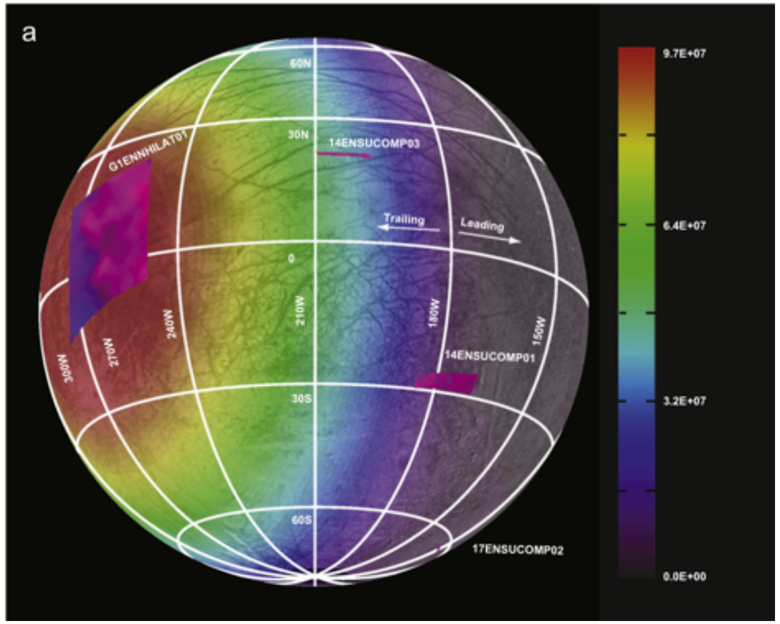
Dalton et al., 2013



- Found correlation between measured H_2SO_4 distribution and modeled sulfur ion flux from *Cassidy et al., 2013*.

All three studies: uniform magnetic field, found trailing hemisphere "bullseye"

Our Approach

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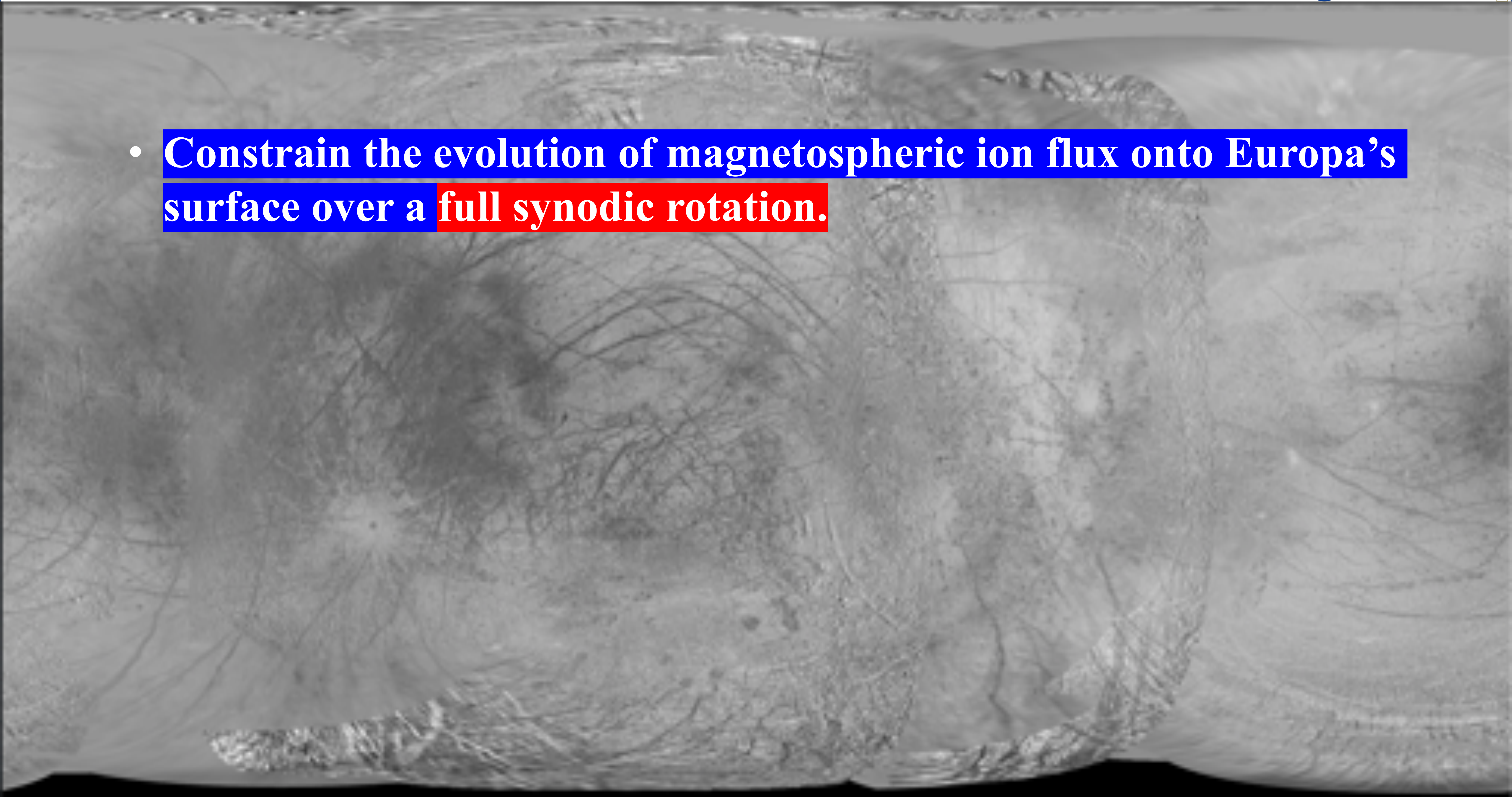
Goals of this Study



- **Constrain the evolution of magnetospheric ion flux onto Europa's surface over a full synodic rotation.**

Goals of this Study

(paddison6@gatech.edu)

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- Determine influence of field perturbations on surface flux pattern.

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- Determine influence of field perturbations on surface flux pattern.
- Correlate modeled ion surface fluxes with measured surface features.
- Constrain exogenic or endogenic origin of surface compounds.

Pilot Study: Breer et al., 2019

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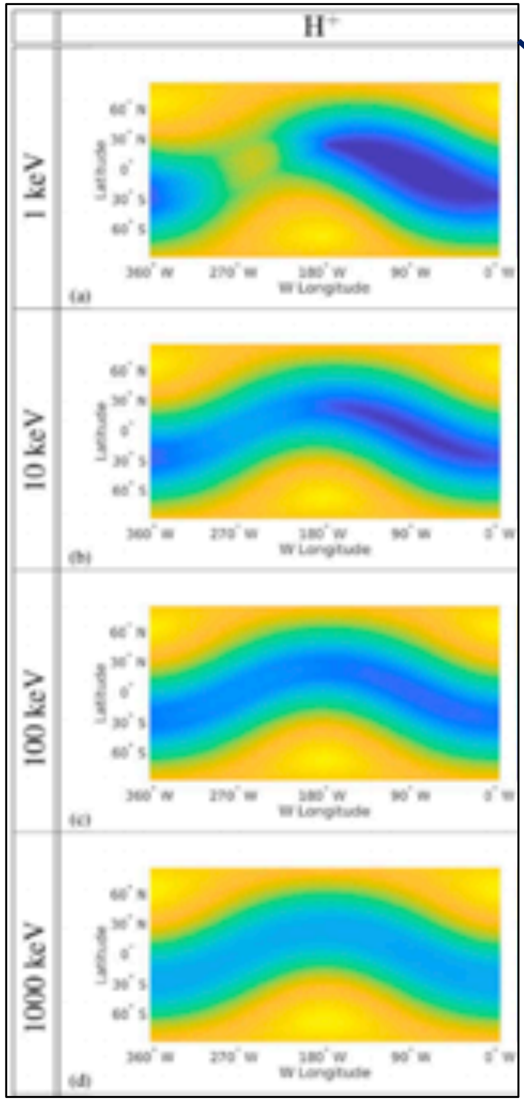
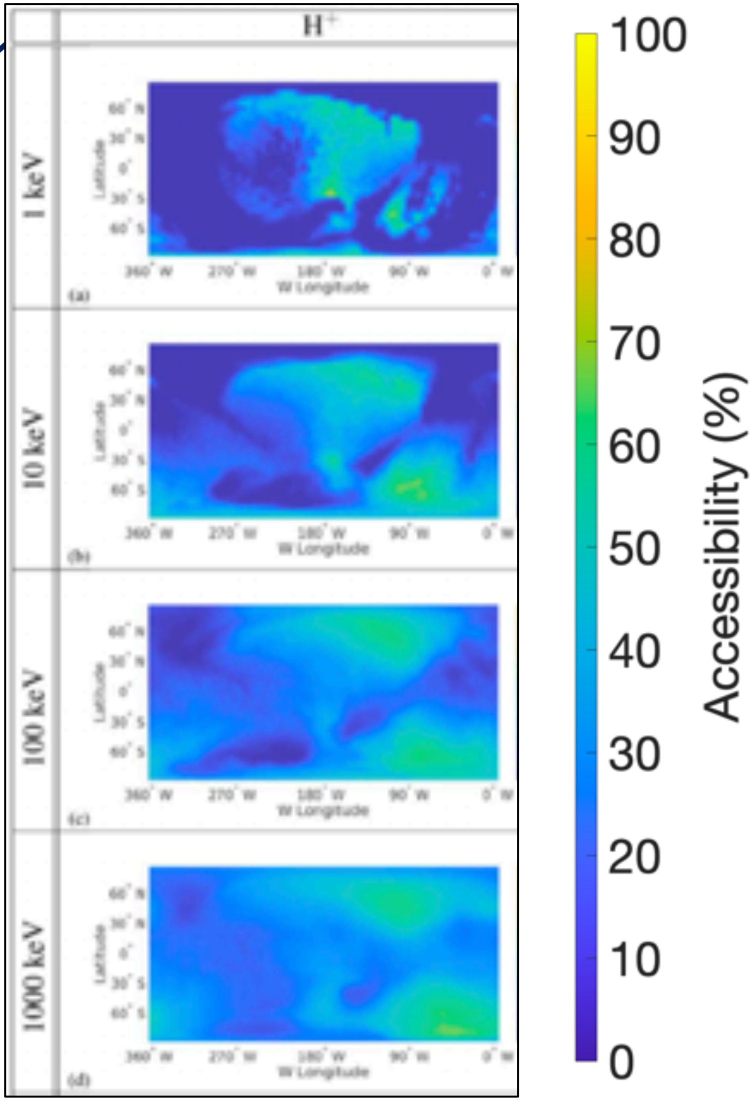
Uniform Fields



Field perturbations significantly alter ion dynamics!

Draped Fields



- **Surface shielded by magnetic field deformation!**
- **Did not calculate flux, nor examine time variability**

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- **A hybrid model for field perturbations (*Arnold et al., 2019, 2020a,b*)**

+

- **A particle tracing tool (*Liuzzo et al., 2019a,b*)**

Modeling Europa's Plasma Interaction

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- **3D hybrid model AIKEF (ion particles, electron fluid)**

- **Lorentz Force Law**

$$\frac{\mathrm{d}\underline{x}_\nu}{\mathrm{d}t} = \underline{v}_\nu \quad \text{and} \quad \frac{\mathrm{d}\underline{v}_\nu}{\mathrm{d}t} = \frac{e}{m_\nu}\left(\underline{E} + \underline{v}_\nu \times \underline{B}\right)$$

- **Navier-Stokes Eqn.**

$$0 = n_e m_e \frac{\mathrm{d}\underline{u}_e}{\mathrm{d}t} = -e n_e \left(\underline{E} + \underline{u}_e \times \underline{B}\right) - \nabla P_e$$

- **Ohm's Law**

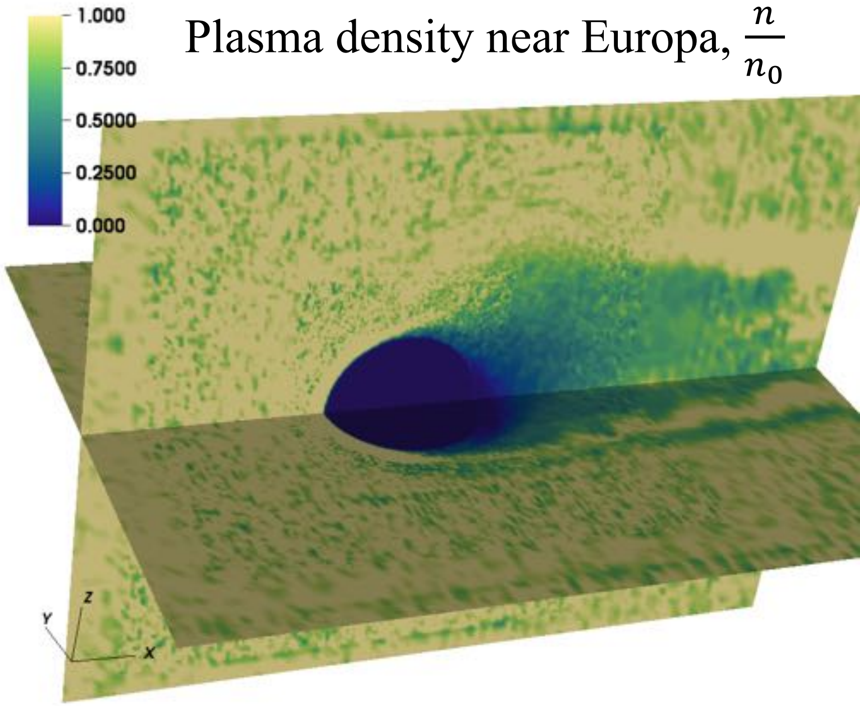
$$\underline{E} = -\underline{u}_i \times \underline{B} + \frac{(\nabla \times \underline{B}) \times \underline{B}}{\mu_0 \rho_c} - \frac{\nabla P_e}{\rho_c}$$

- **Faraday's Law**

$$\frac{\partial \underline{B}}{\partial t} = \nabla \times (\underline{u}_i \times \underline{B}) - \nabla \times \left[\frac{(\nabla \times \underline{B}) \times \underline{B}}{\mu_0 \rho_c}\right]$$

- **Adiabatic Law**

$$P_e = P_{e,0}\left(\frac{\rho_c}{\rho_{c,0}}\right)^{\kappa}$$



Plasma density near Europa, $\frac{n}{n_0}$

GENTOo GEN-2 Magnetospheric Ion Tracer

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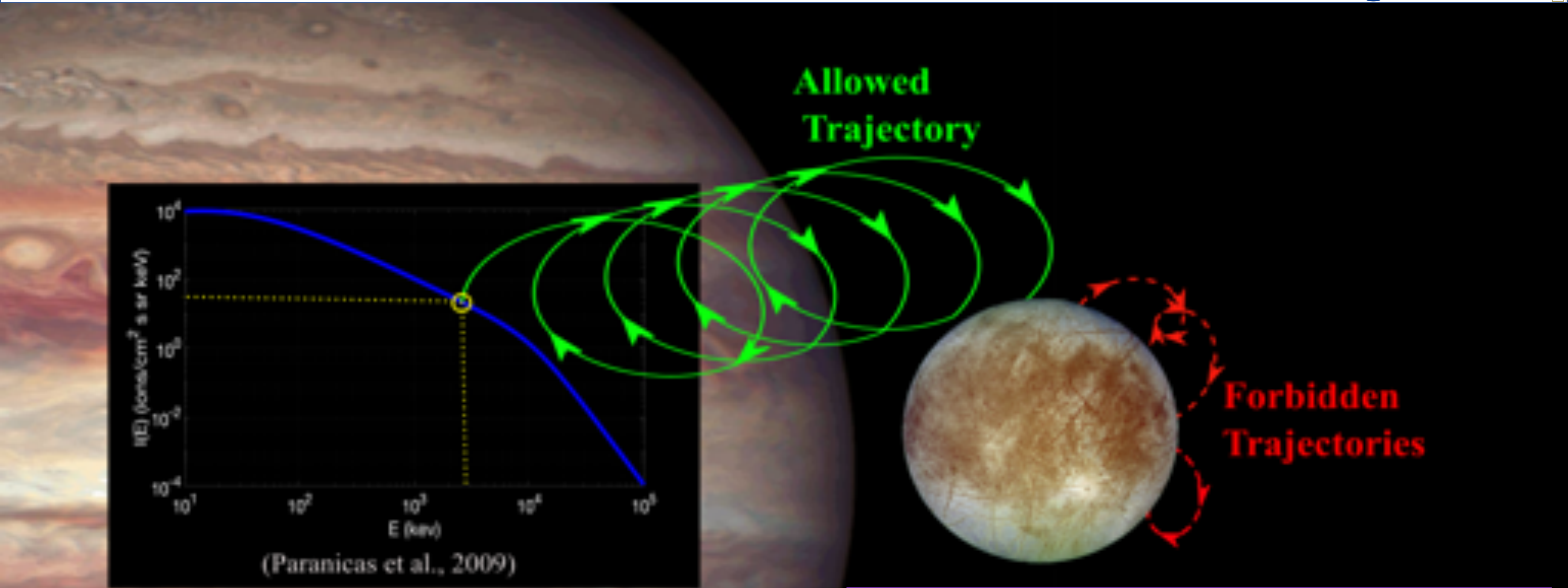

$$\frac{\mathrm{d}\underline{x}_\nu}{\mathrm{d}t} = \underline{v}_\nu \quad \text{and} \quad \frac{\mathrm{d}\underline{v}_\nu}{\mathrm{d}t} = \frac{e}{m_\nu}\left(\underline{E} + \underline{v}_\nu \times \underline{B}\right)$$

- Backtracing: $\mathrm{d}t < 0$
- Combines modeled trajectories with measured upstream distributions

Variability of the Upstream Plasma Density

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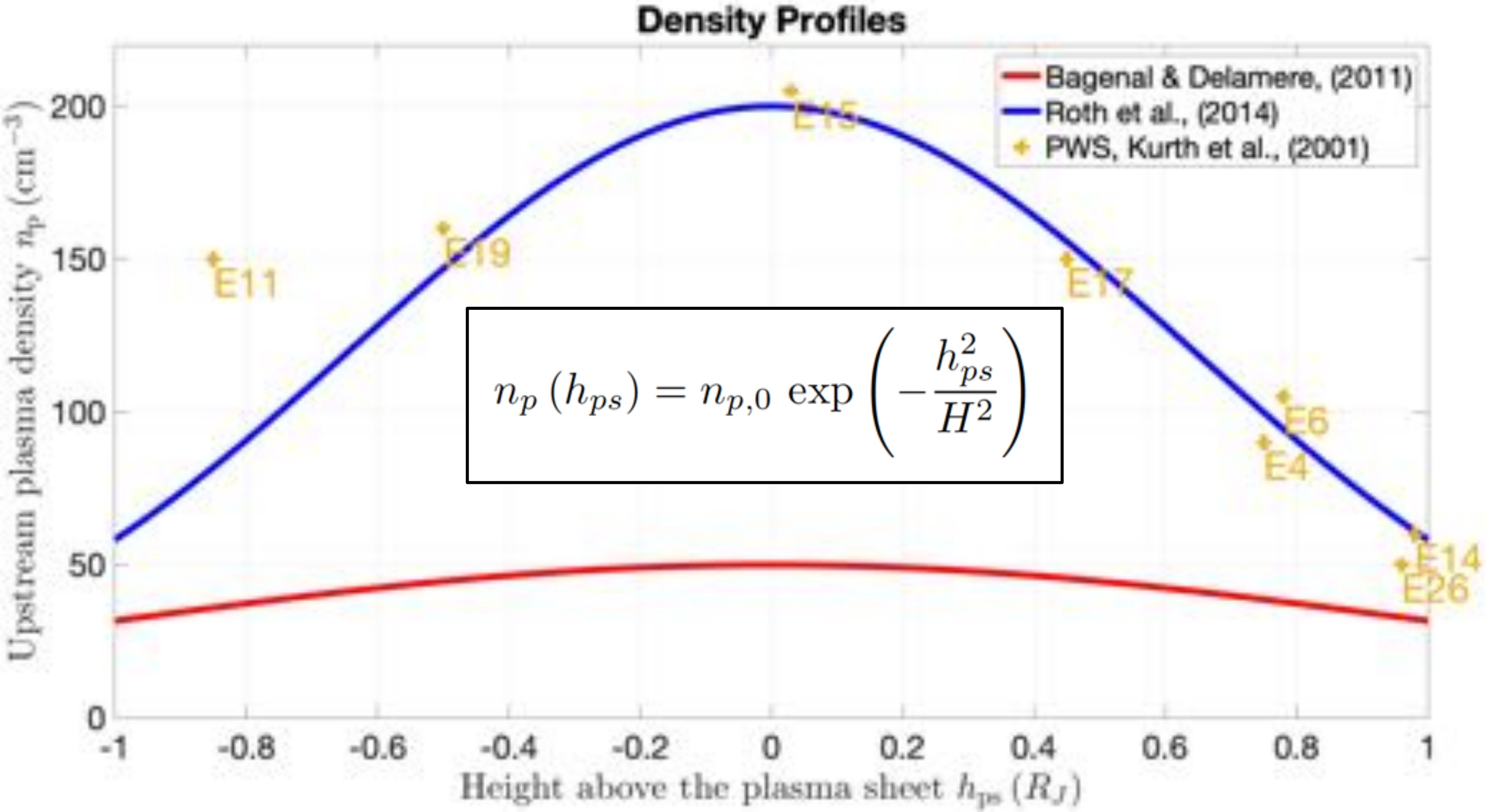

$$n_p\left(h_{ps}\right) = n_{p,0}\exp\left(-\frac{h_{ps}^2}{H^2}\right)$$

- Gaussian density profile *(Hill & Michel, 1976)*
- Values of $n_{p,0}$ and "scale height" H in literature vary, 50-200 cm^{-3}, 0.9-1.9 R_J

Modeling Europa's Exosphere

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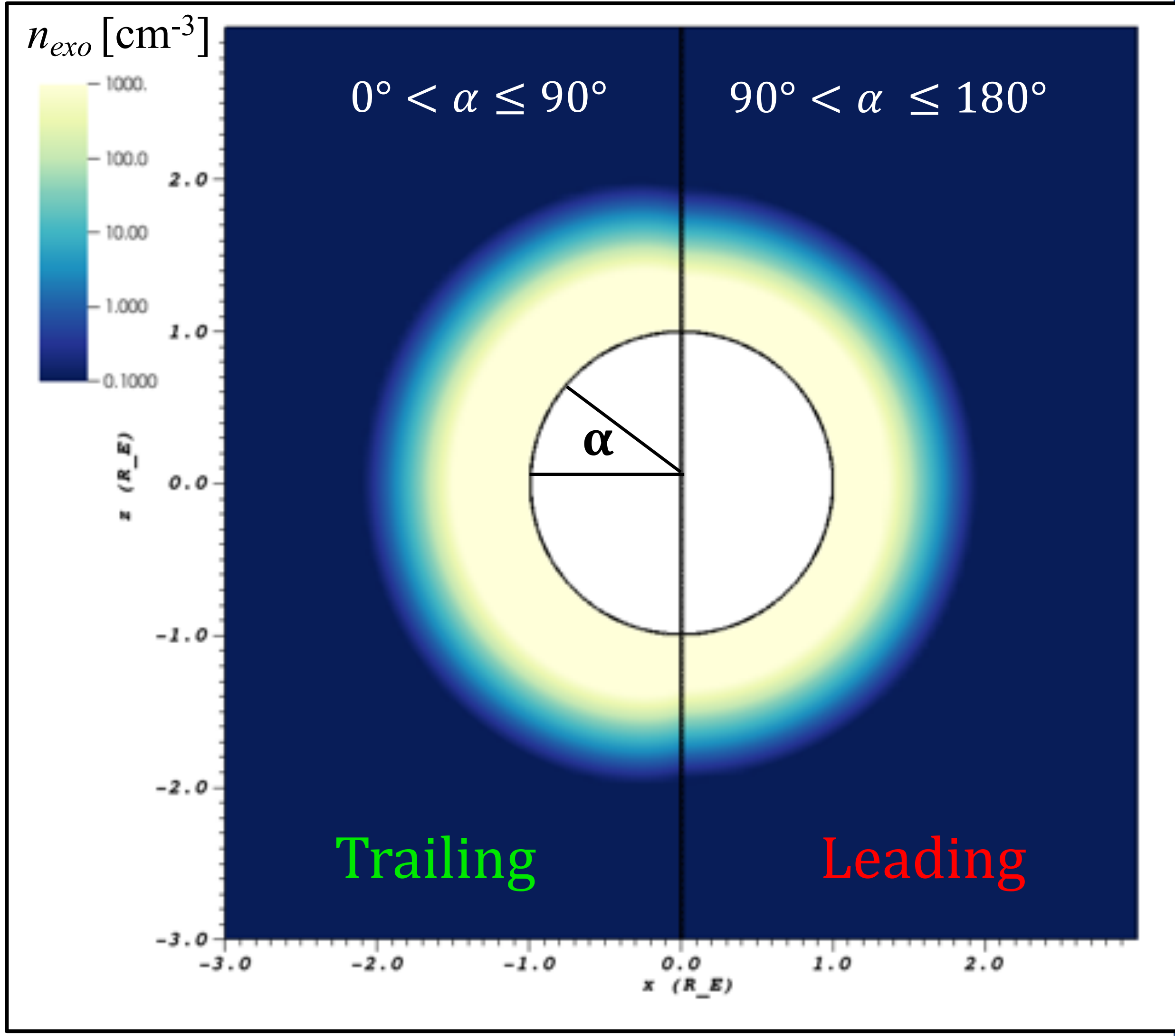
- Molecular oxygen (*Plainaki et al., 2018*).
- **Ram-wake asymmetry** (e.g., *Rubin et al., 2015; Arnold et al., 2020a*)

- **Leading/Wakeside Hemisphere**

$$n_{n,L}(h) = n_{n,0} \cdot \exp\left(-\frac{h}{h_0}\right), \qquad 90° < \alpha \leq 180°$$

- **Trailing/Ramside Hemisphere**

$$n_{n,T}(h,\alpha) = n_{n,L}(h) \cdot (1 + A \cdot \cos(\alpha)), \qquad \alpha \leq 90°$$



Modeling the Time-Variability of Ion Surface Flux

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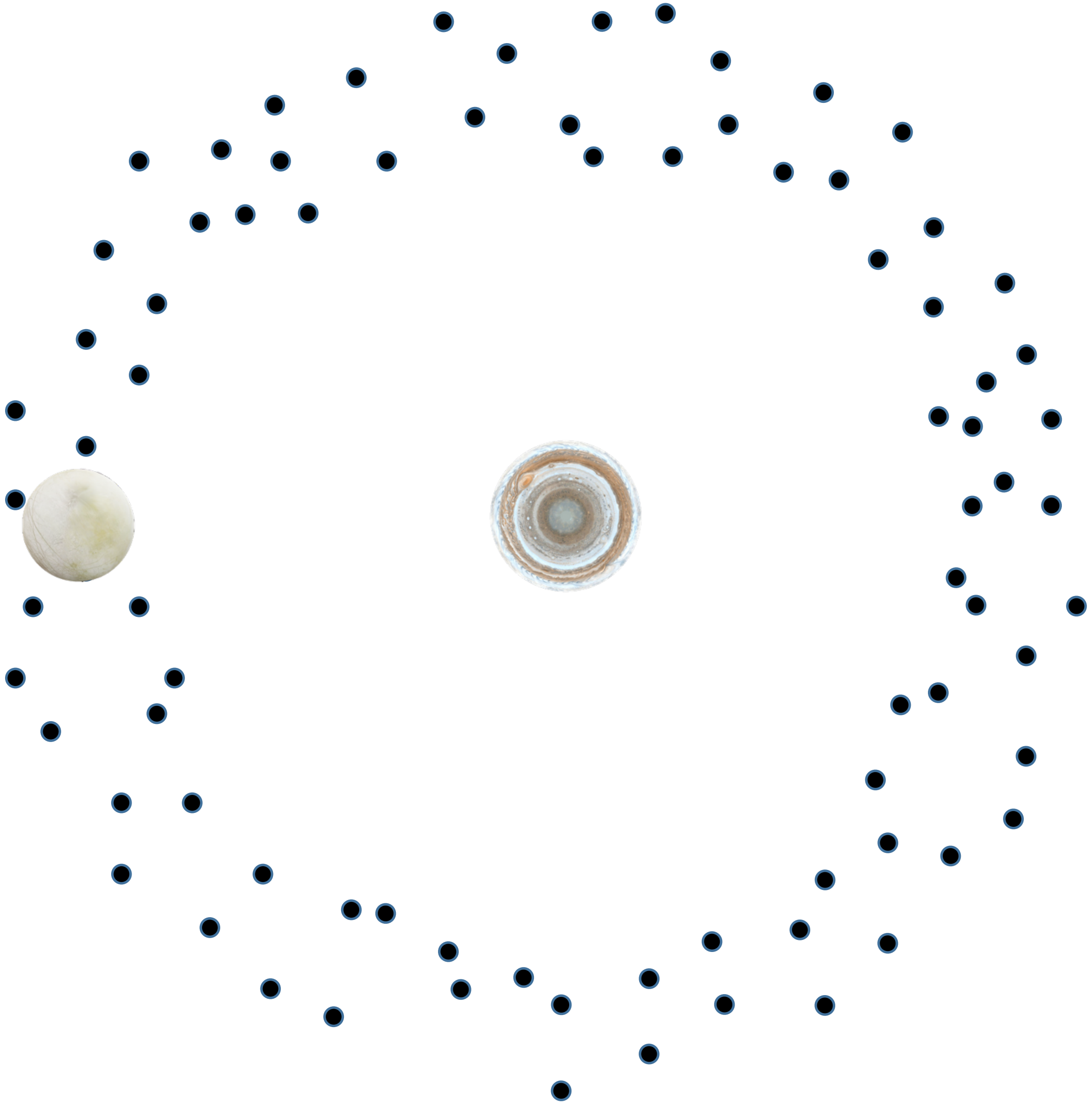
- **How do surface fluxes change over time?**

- **Approach:**
  1. **Investigate different points along a synodic rotation of Jupiter**
  2. **Compute maps of ion surface flux**
  3. **Average over a full synodic rotation**



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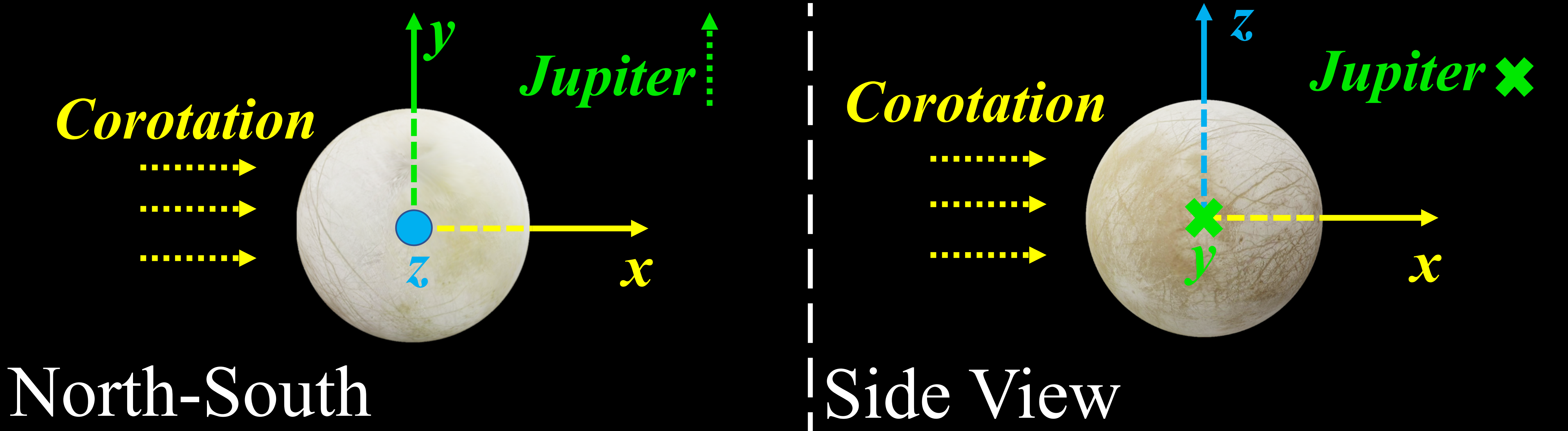
"EPhiO System"



Background magnetic field:

$$\mathbf{B}_0(t) = -84\,\mathrm{nT}\,\sin(\Omega t)\,\hat{\mathbf{x}} - 210\,\mathrm{nT}\,\cos(\Omega t)\,\hat{\mathbf{y}} - 410\,\mathrm{nT}\,\hat{\mathbf{z}}$$

(Kivelson et al., 1999; Schilling et al., 2007)

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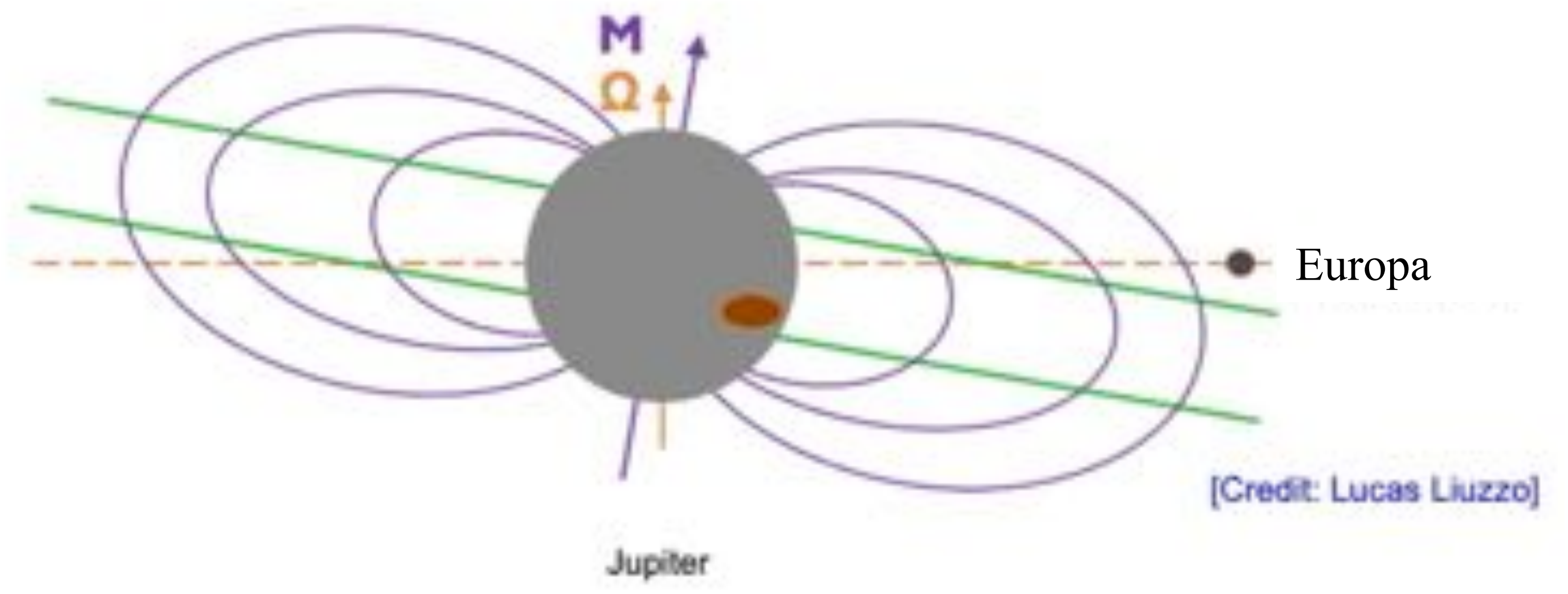

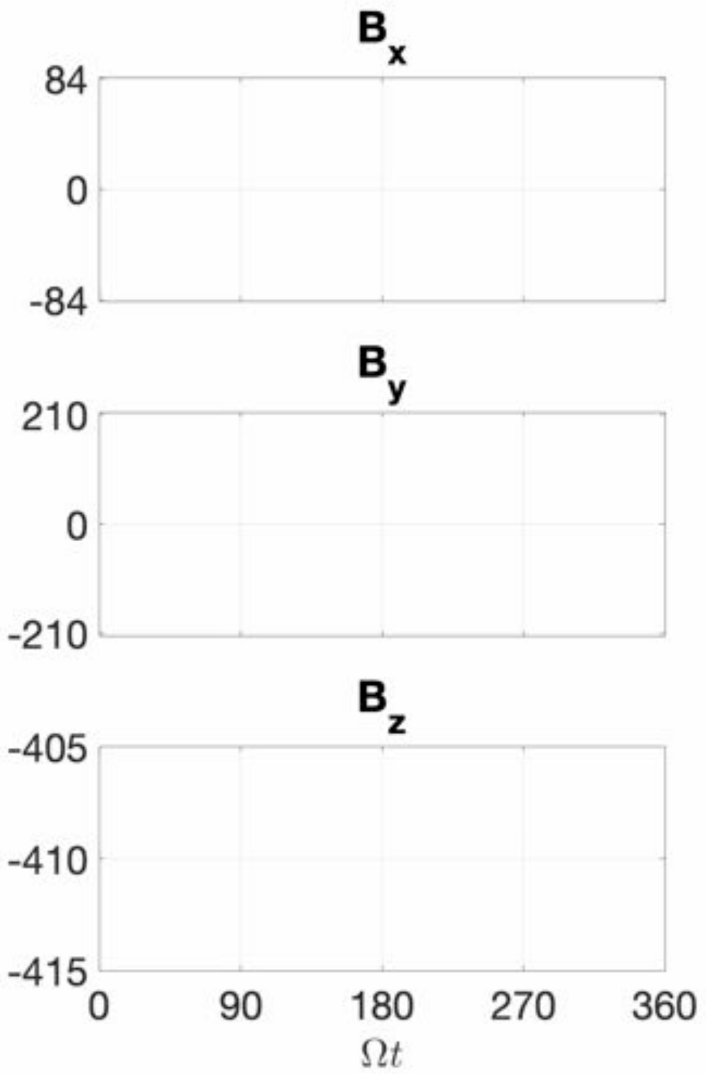

The magnetospheric conditions at Europa's orbit change periodically!

Case (1): Center of the Plasma Sheet

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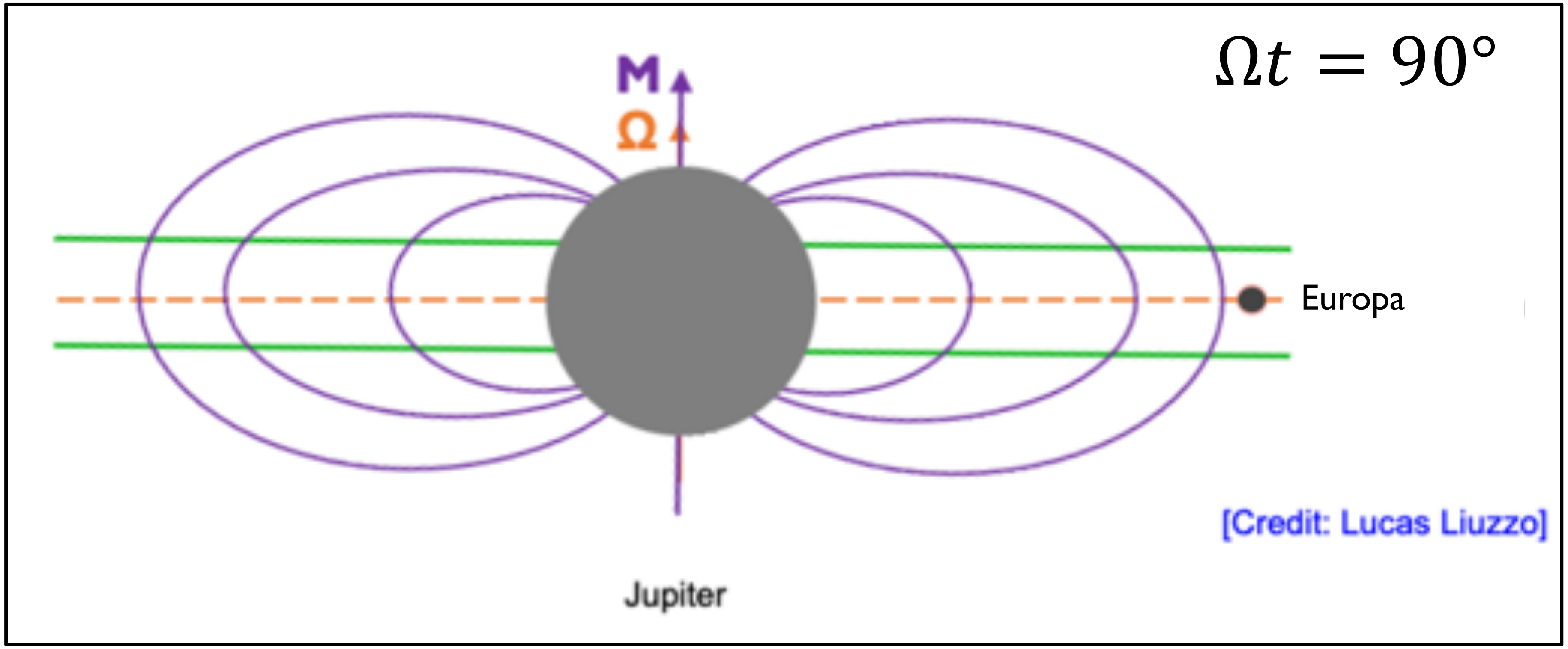

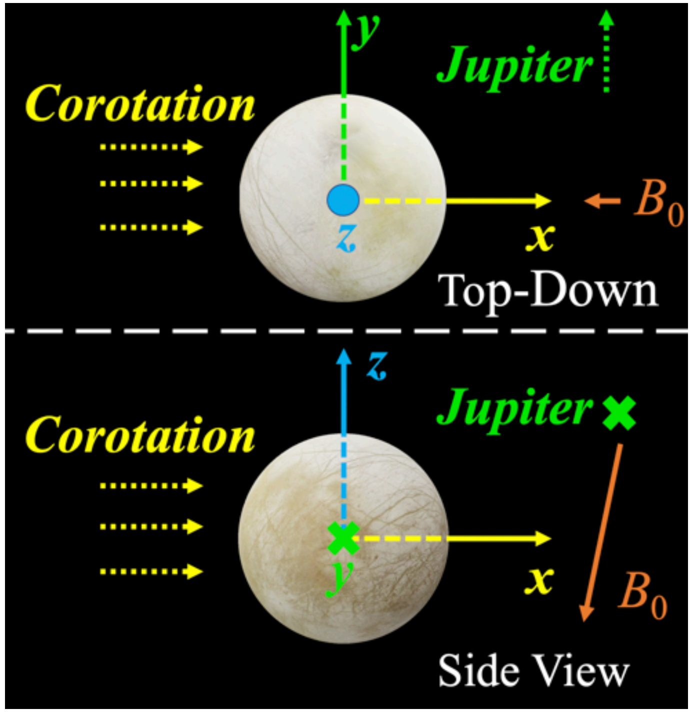

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$$B_0 = -84\,\mathrm{nT}\,\hat{x} - 410\,\mathrm{nT}\,\hat{z}$$

Case (2): North of the Plasma Sheet

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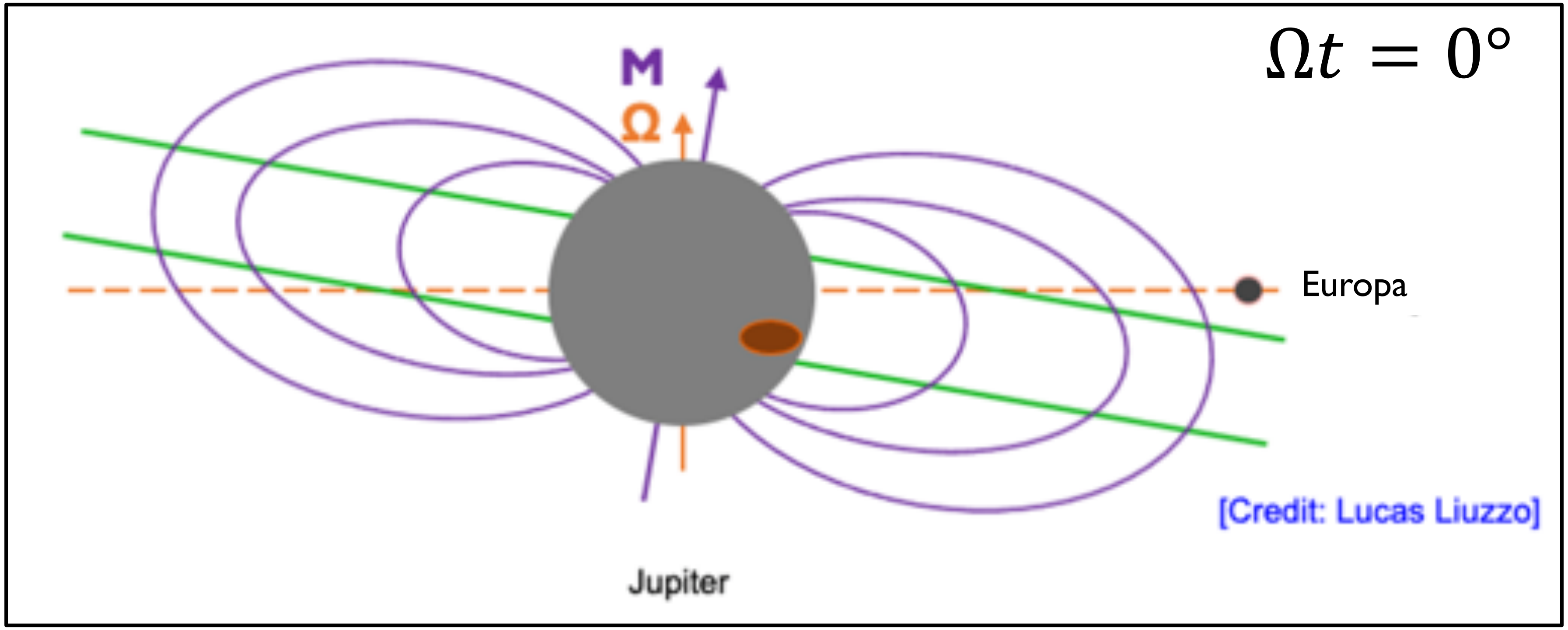

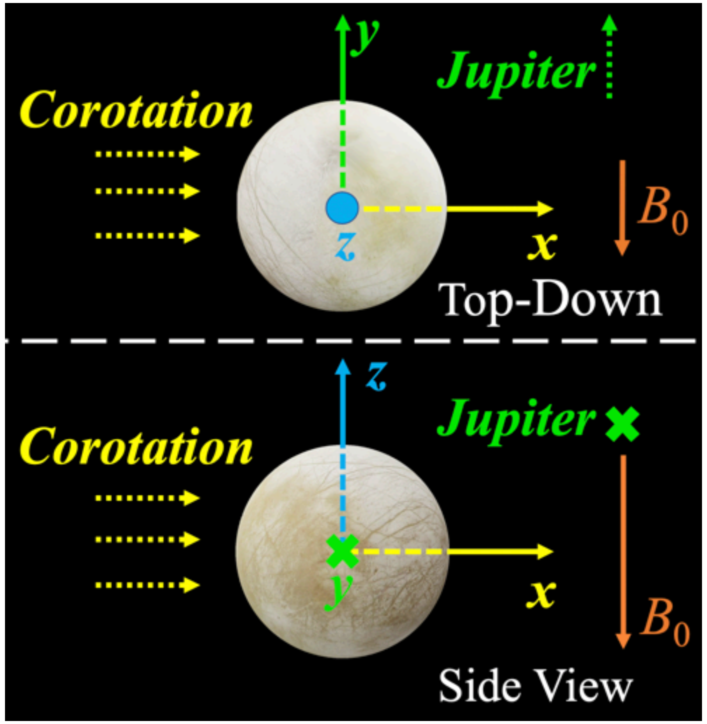

$$\mathbf{B}_0(t) = -84\,\mathrm{nT}\sin(\Omega t)\,\hat{\mathbf{x}} - 210\,\mathrm{nT}\cos(\Omega t)\,\hat{\mathbf{y}} - 410\,\mathrm{nT}\,\hat{\mathbf{z}}$$

$$B_0 = -210\,\mathrm{nT}\,\hat{\boldsymbol{y}} - 410\,\mathrm{nT}\,\hat{\boldsymbol{z}}$$

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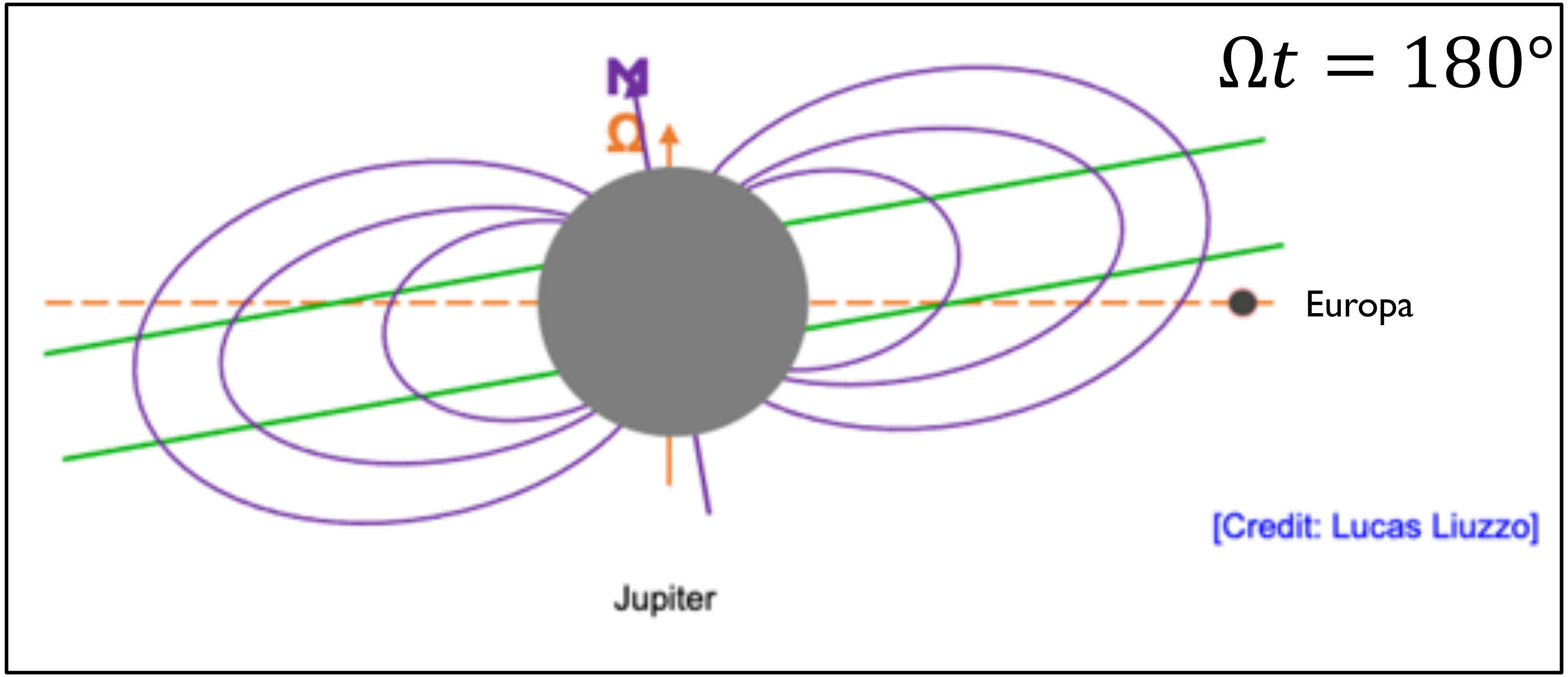

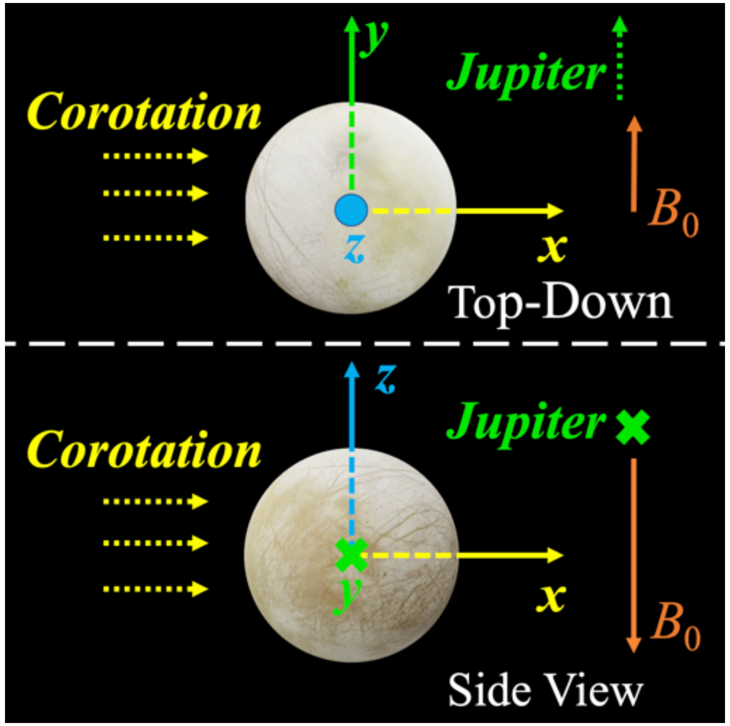

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$$B_0 = 210\ \mathrm{nT}\ \hat{\boldsymbol{y}} - 410\ \mathrm{nT}\ \hat{\boldsymbol{z}}$$

Overview: Cases (1), (2), (3)

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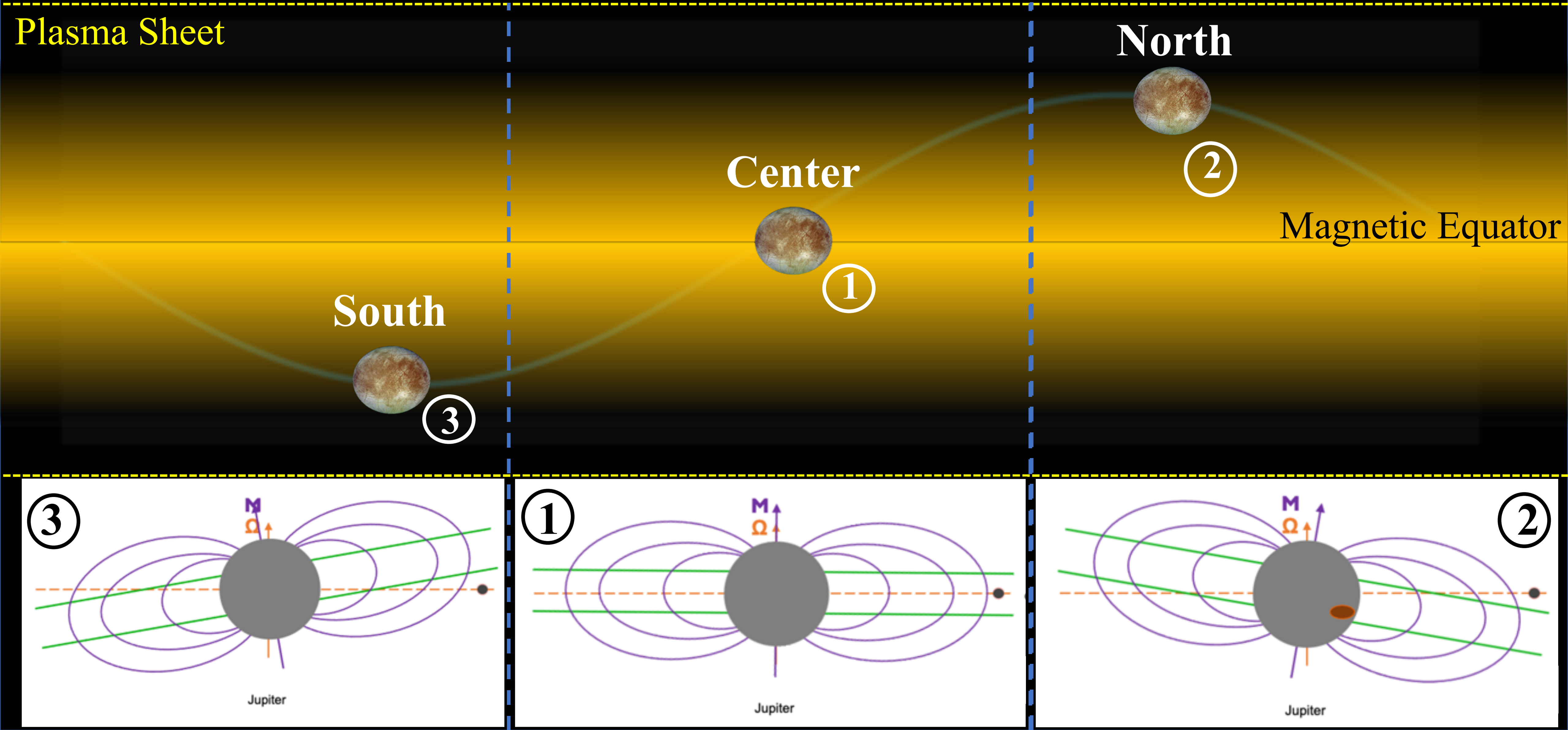
Three locations relative to the magnetospheric plasma sheet:



Upstream Ion Distributions

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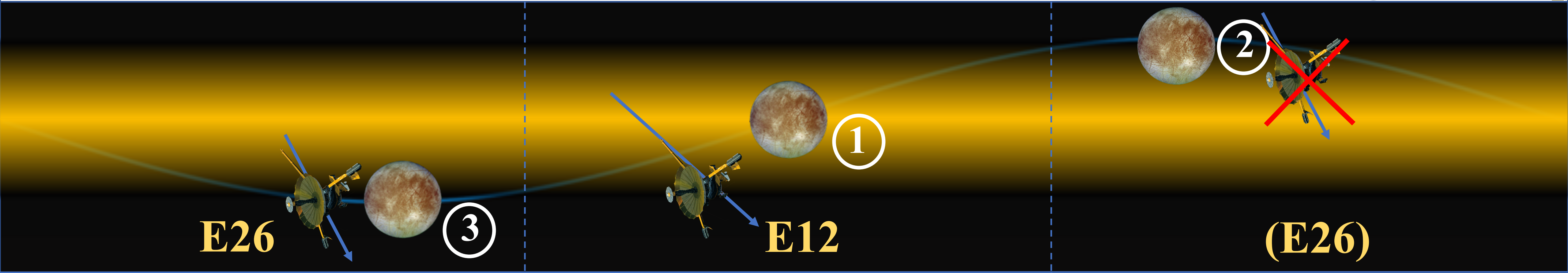
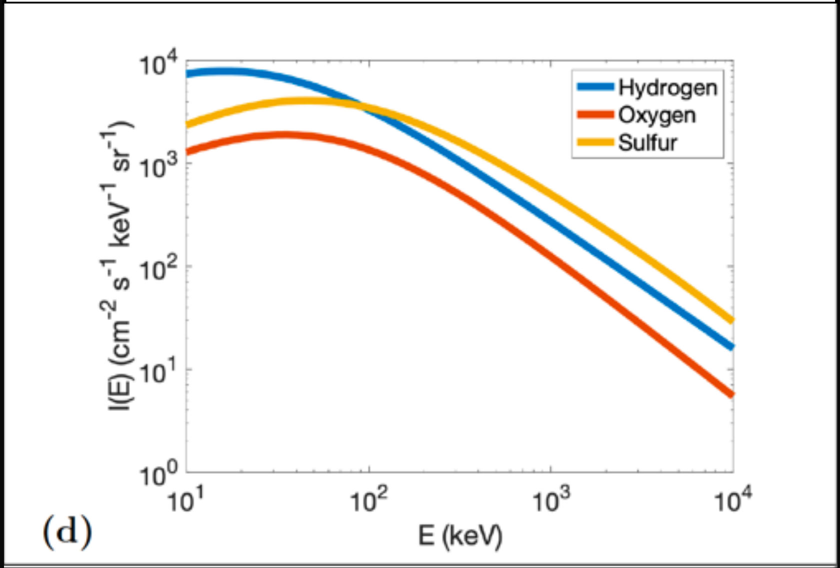
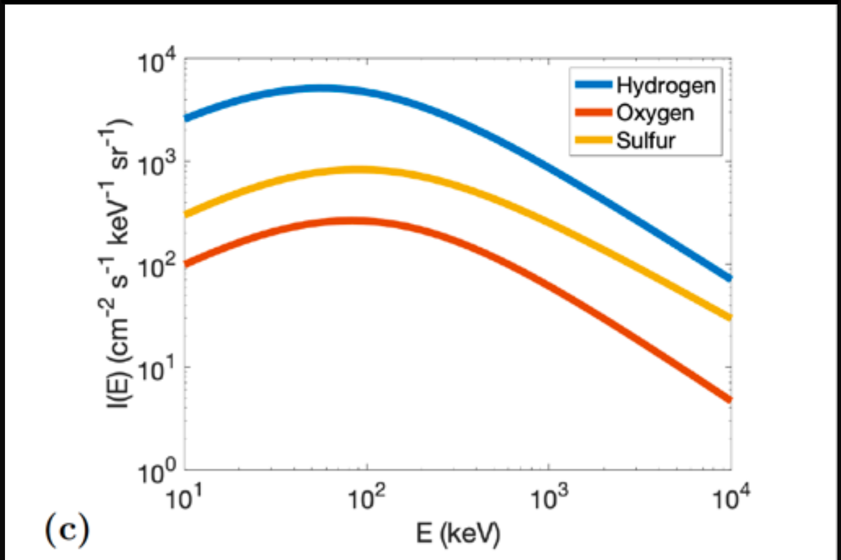


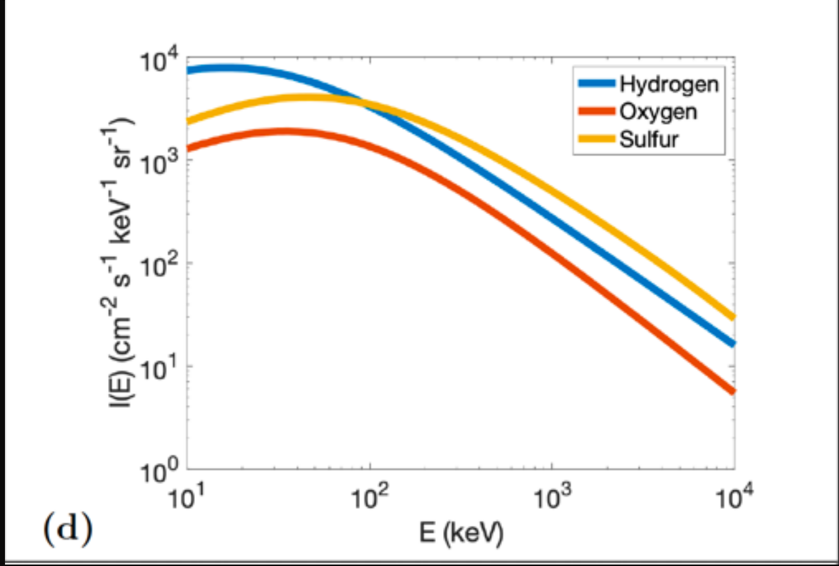
Energetic Distribution, South



Energetic Distribution, Center



Energetic Distribution, North



- **Energetic ions: in-situ measurements by Galileo EPD (*Paranicas et al., 2000, 2009; Mauk et al., 2004*)**
- **Thermal ions: drifting Maxwellian distribution**

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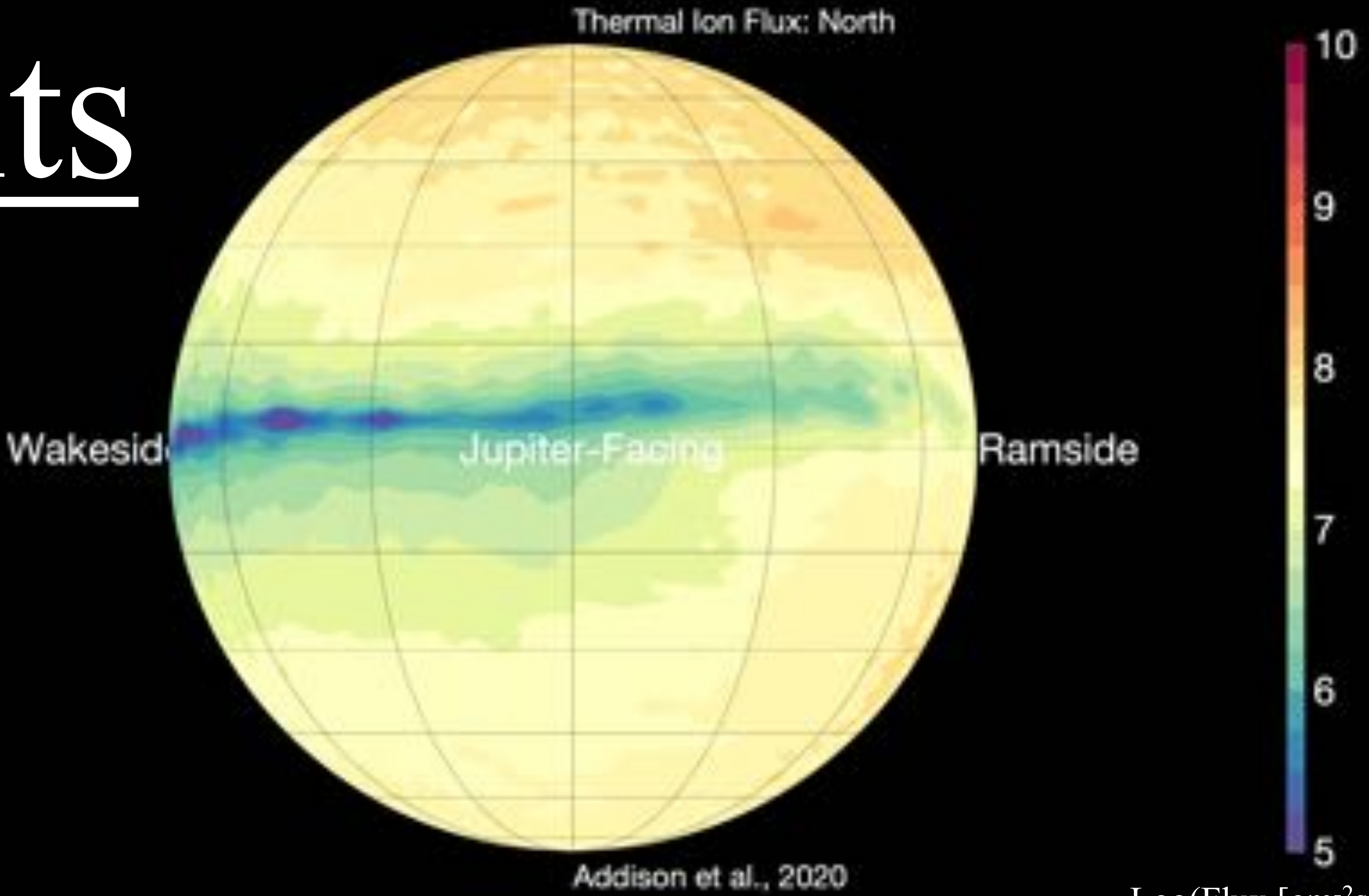
Results



Log(Flux [$cm^{-2}s^{-1}$])

Addison et al., submitted to JGR 12/2020

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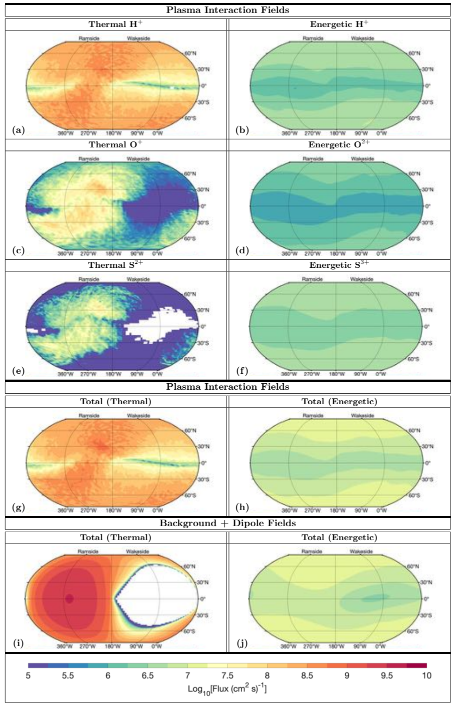
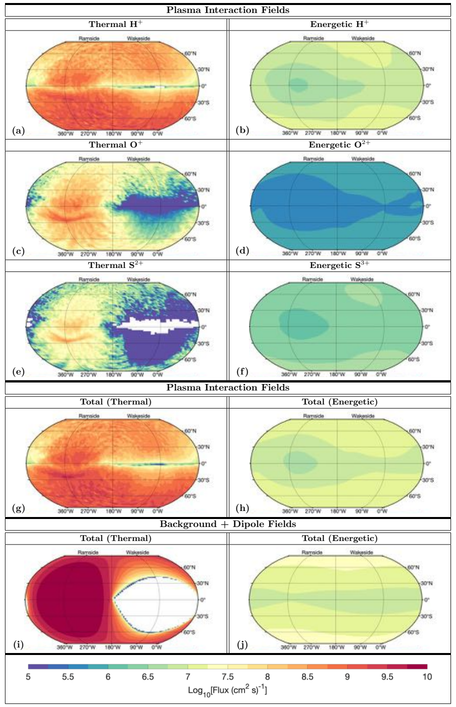
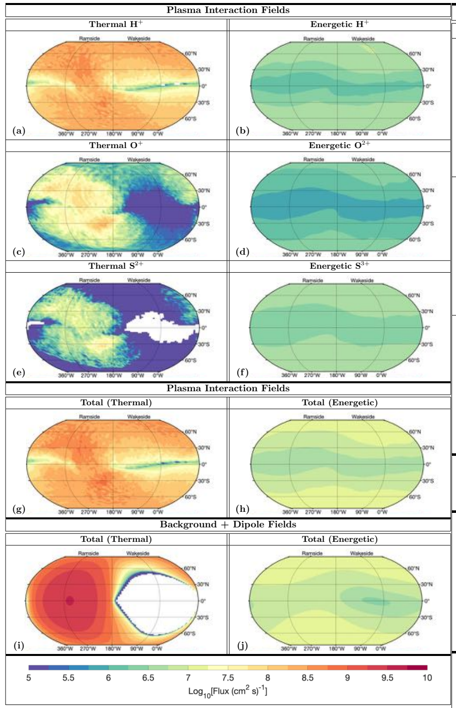
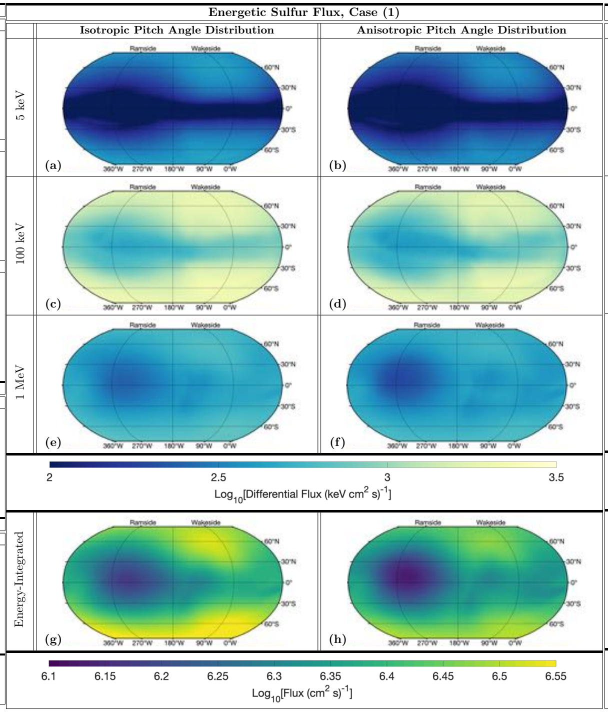
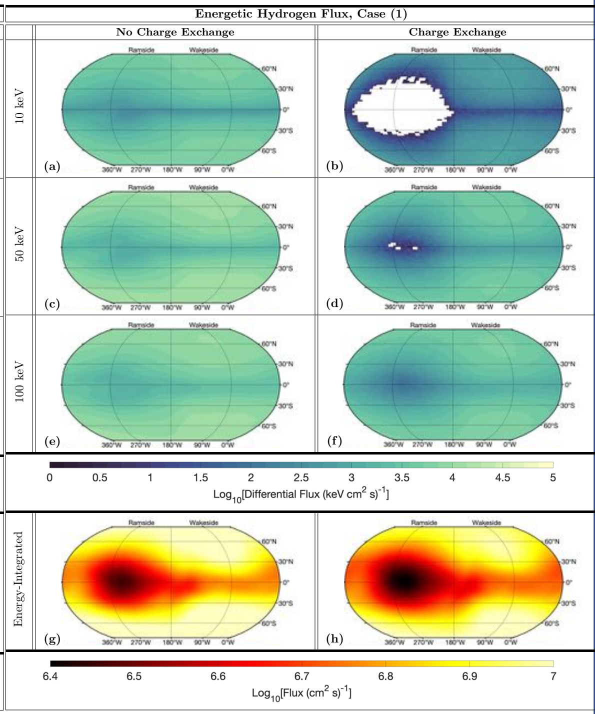
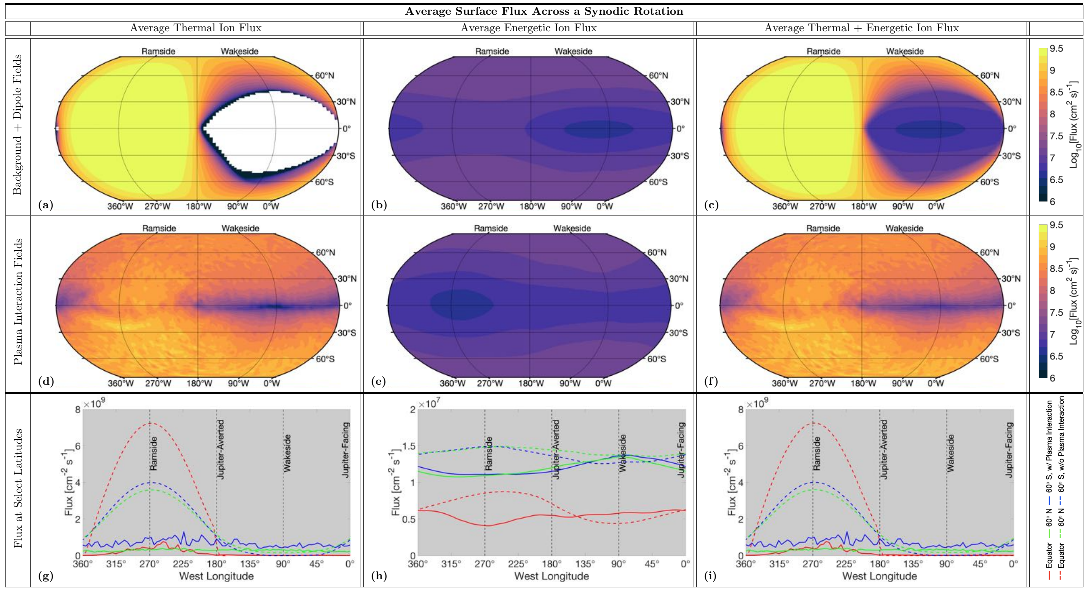








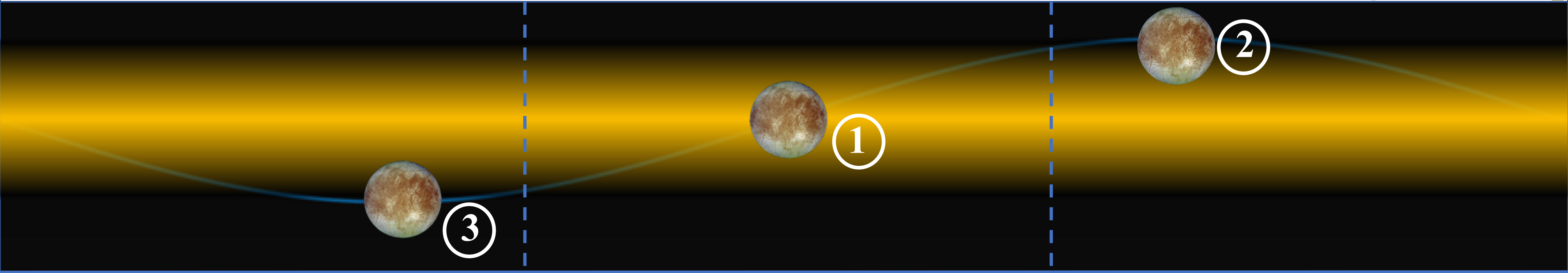


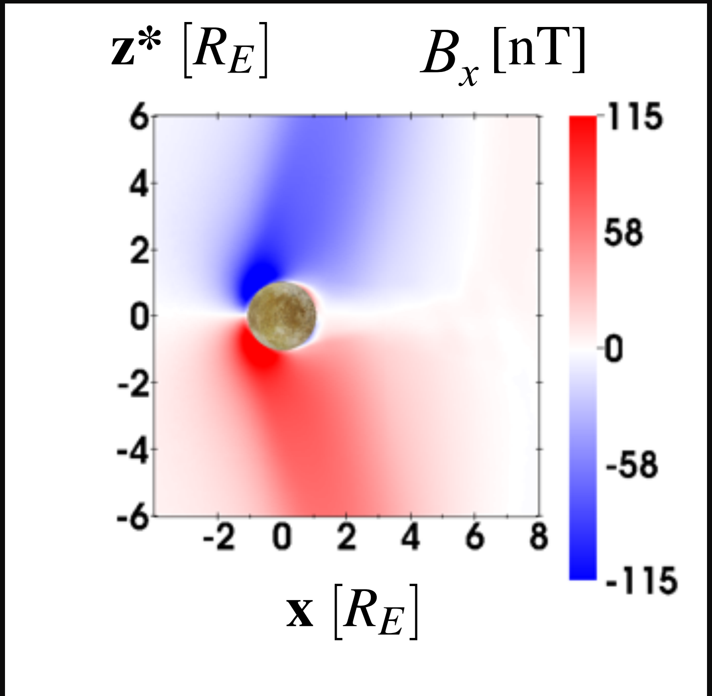


- Over 100 maps of magnetospheric ion flux generated!
- Resolved by species: hydrogen, oxygen, sulfur
- Resolved by energy range: thermal and energetic
- Only select results presented today.

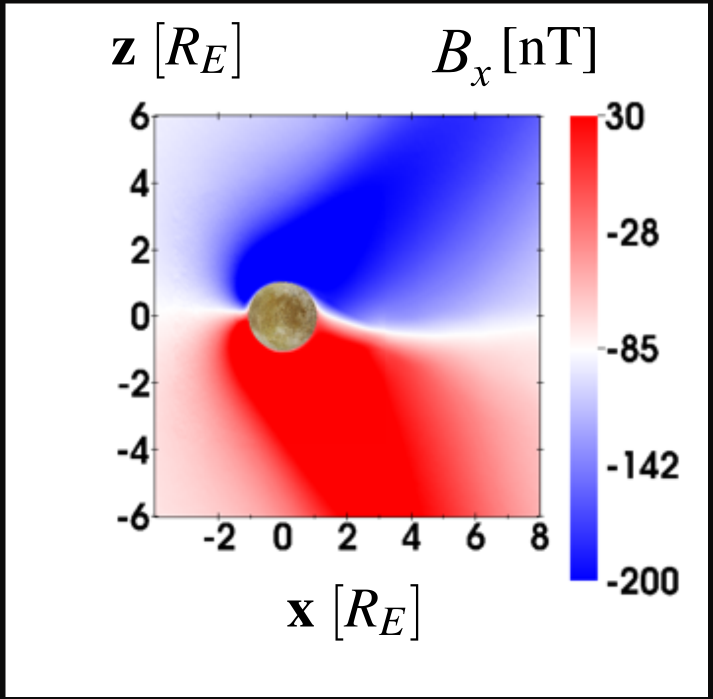
Variability of Magnetic Field

(paddison6@gatech.edu)

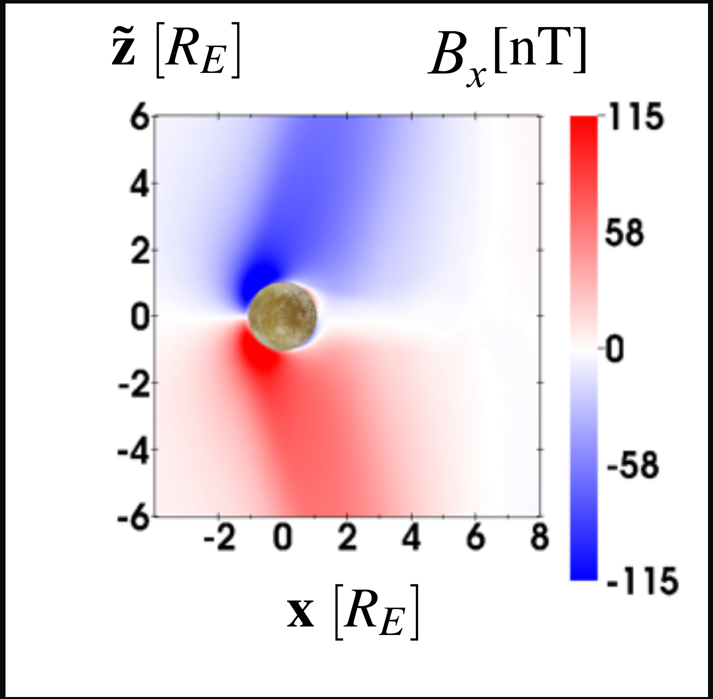




Weak draping, $M_A = 0.33$



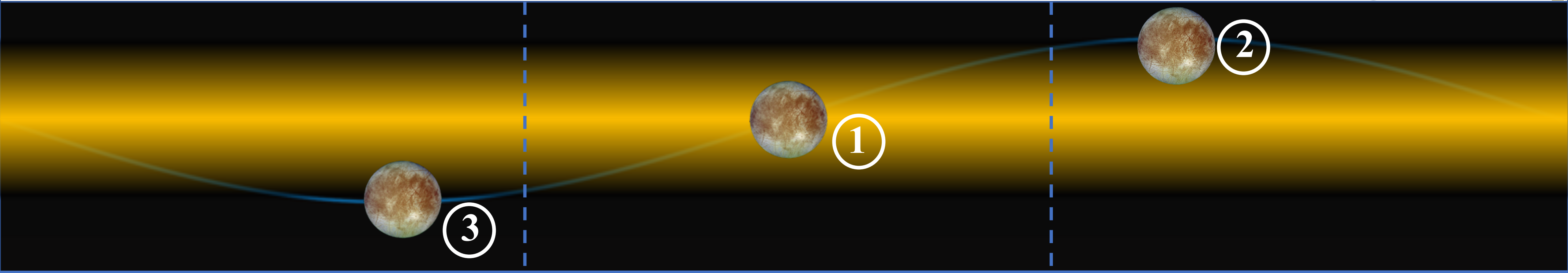
Strong draping, $M_A = 0.66$

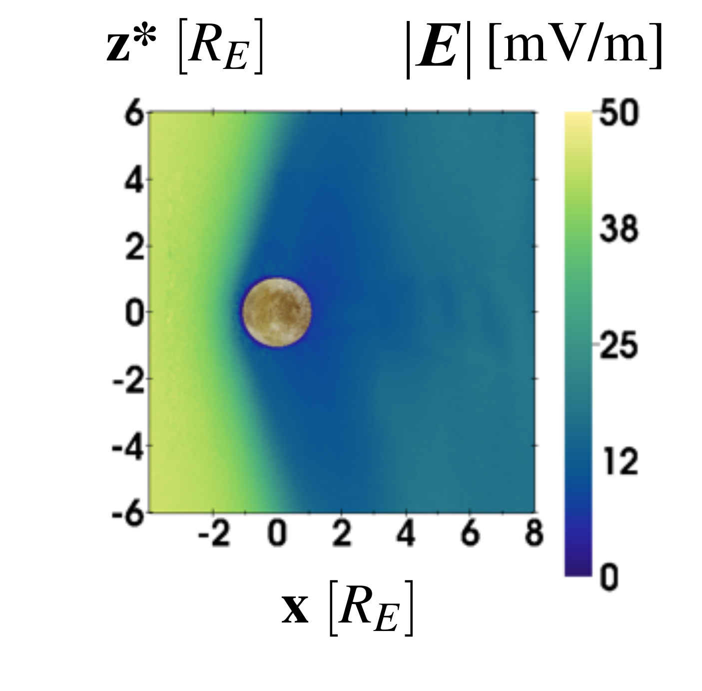


Weak draping, $M_A = 0.33$

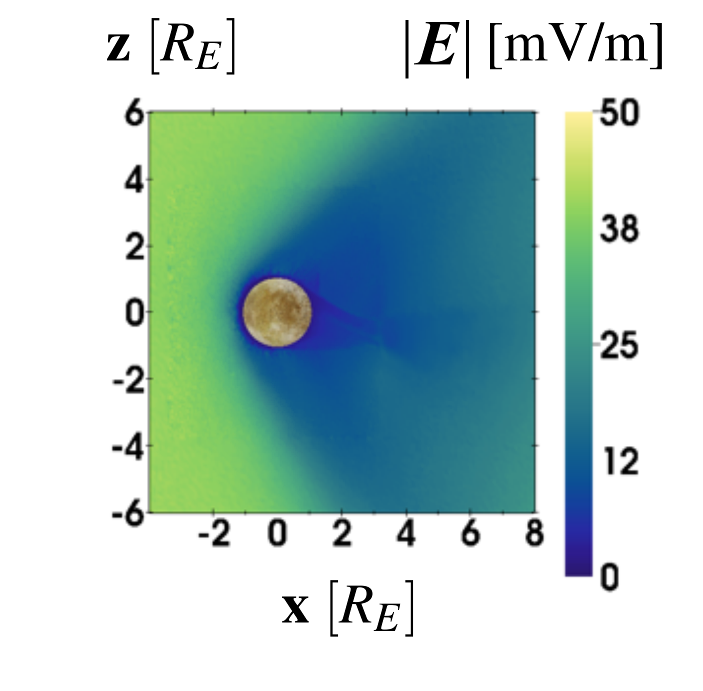
Variability of Electric Field

(paddison6@gatech.edu)

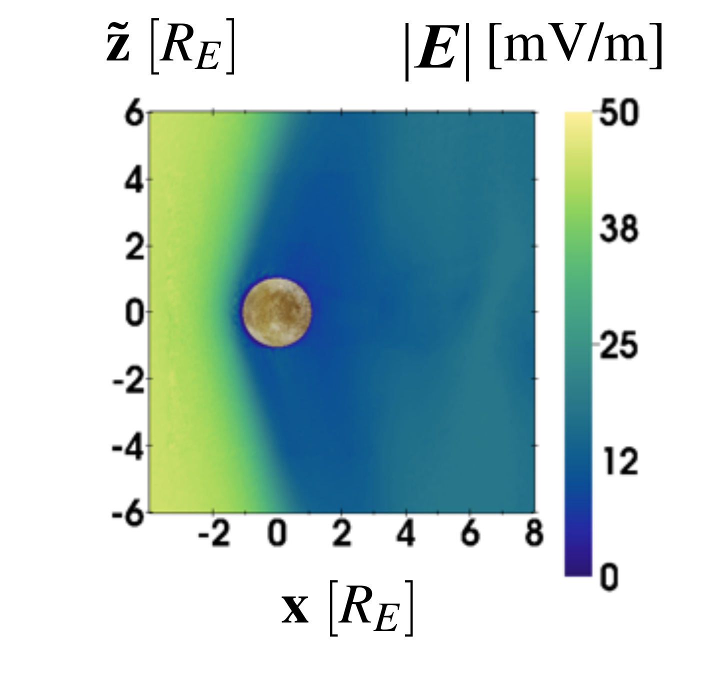




Weak draping, $M_A = 0.33$



Strong draping, $M_A = 0.66$

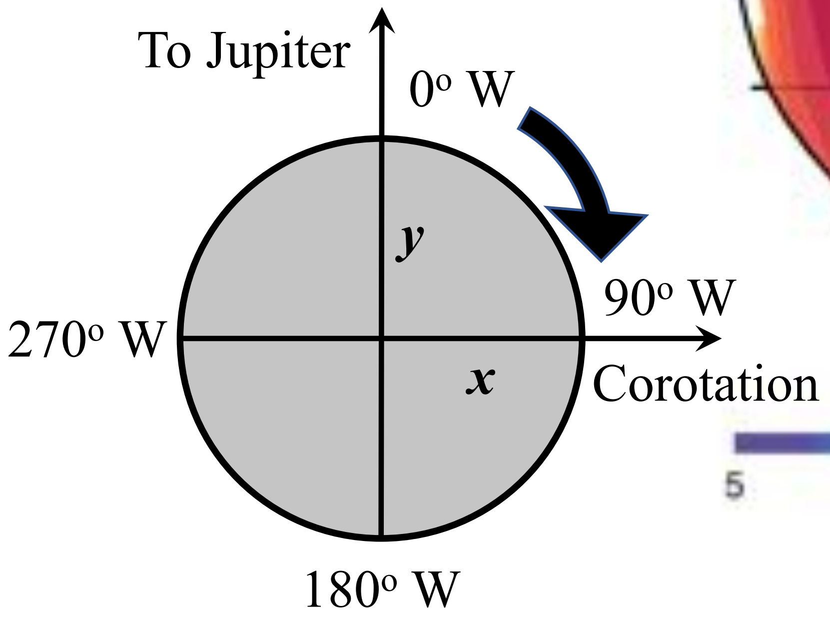


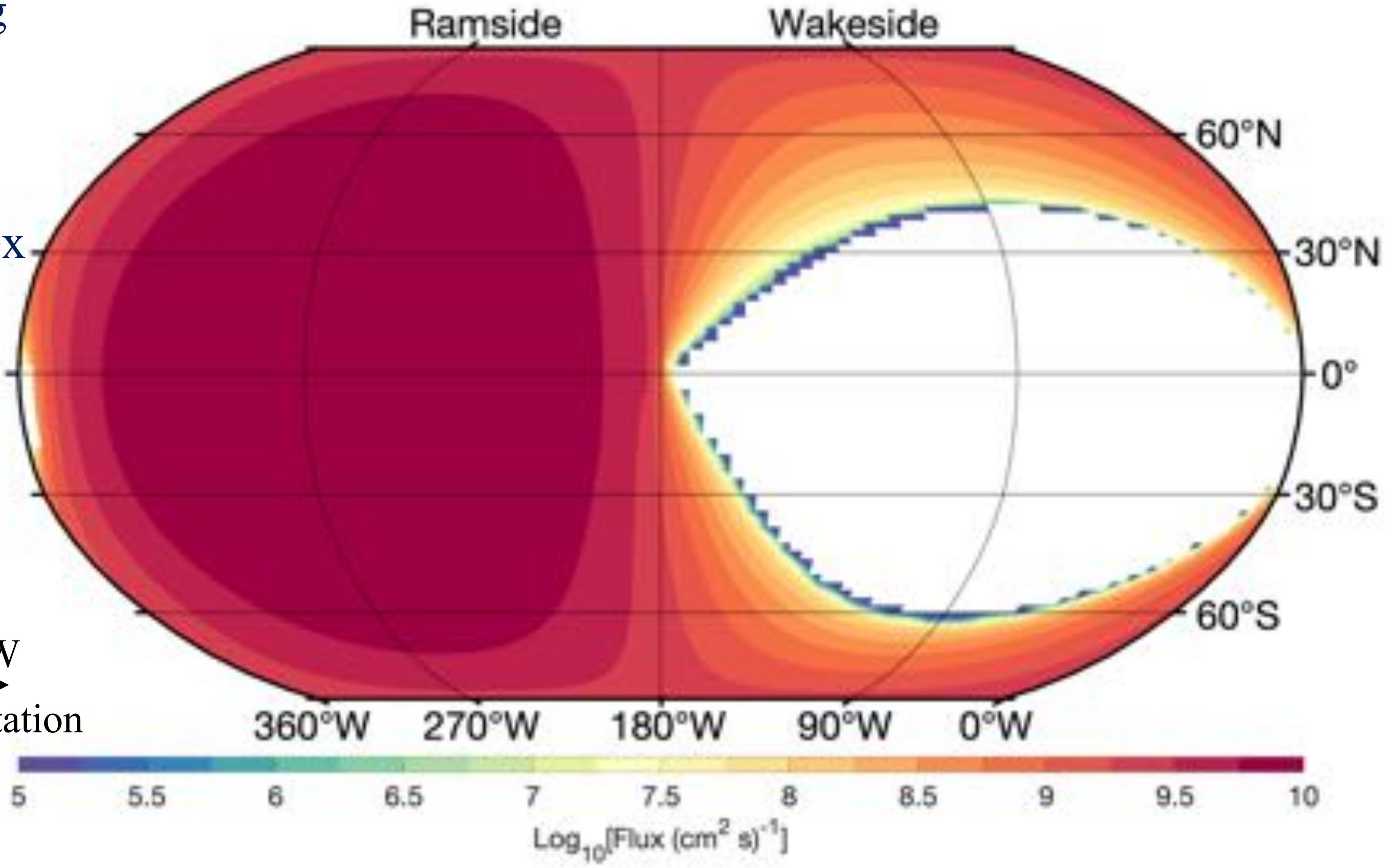
Weak draping, $M_A = 0.33$

Thermal Ions: Layout of Flux Maps

(paddison6@gatech.edu)

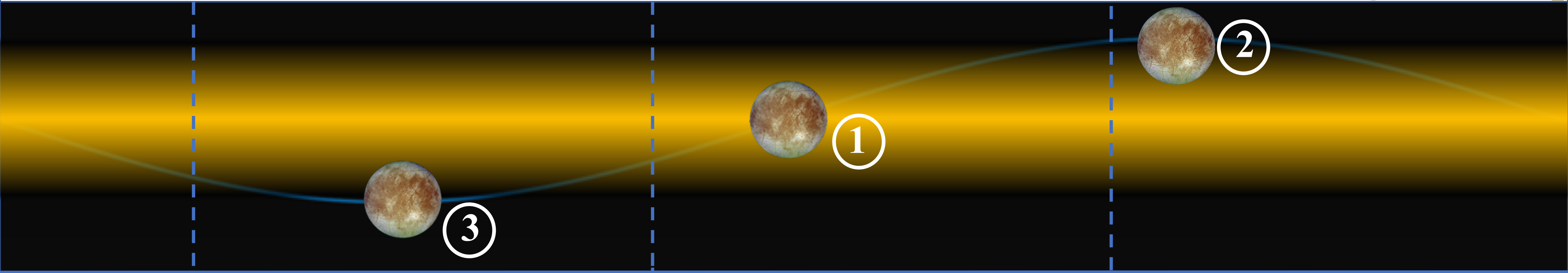
- 0/360° W: Jupiter-facing apex
- 270° W: Trailing apex (Ramside)
- 180° Jupiter-averted apex
- 90° W: Leading apex (Wakeside)



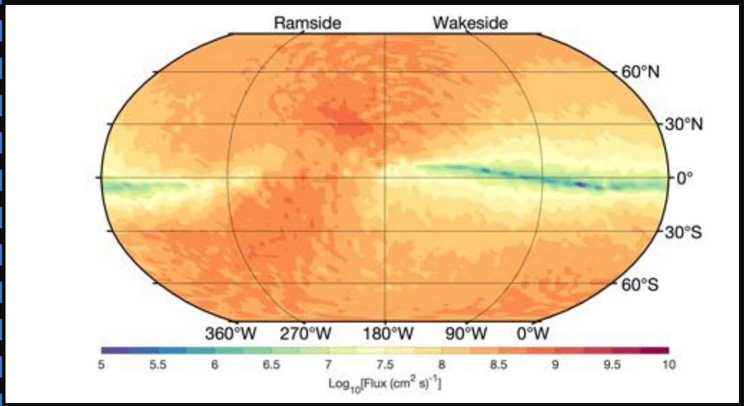


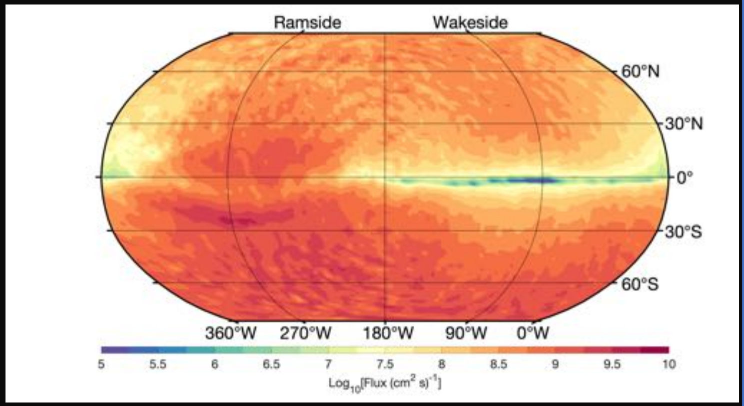
Thermal Ion Surface Flux

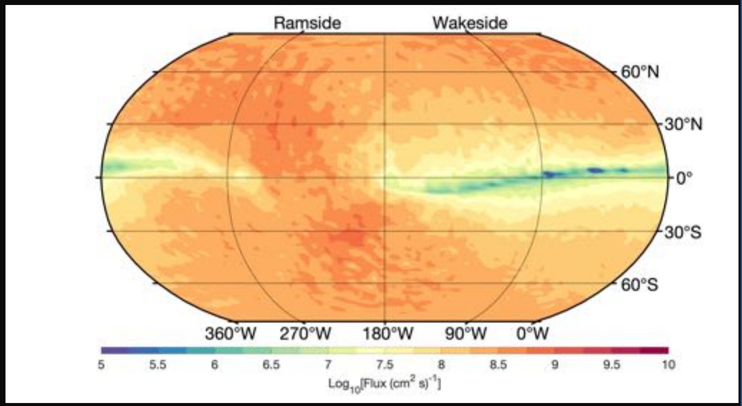
(paddison6@gatech.edu)



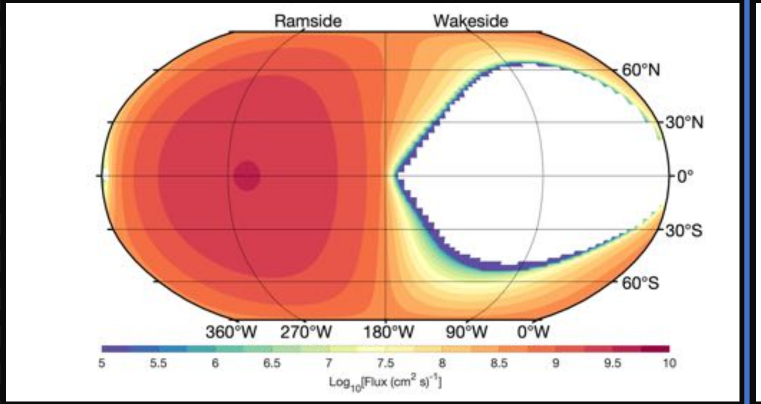
Draped magnetic fields

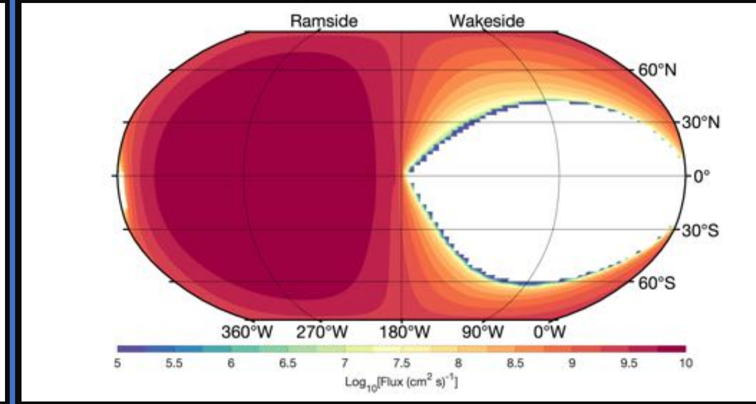


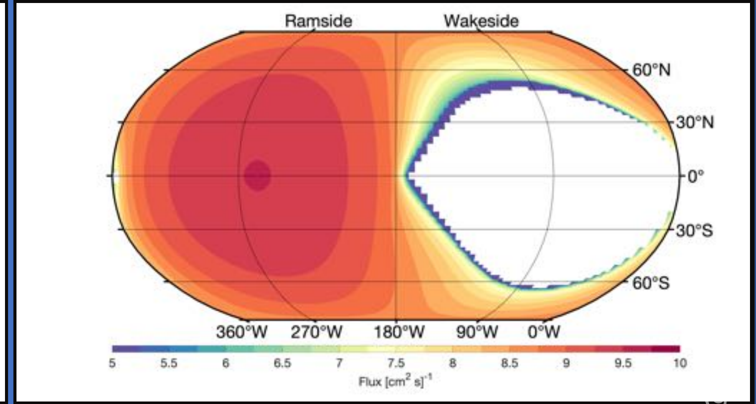




Uniform magnetic fields

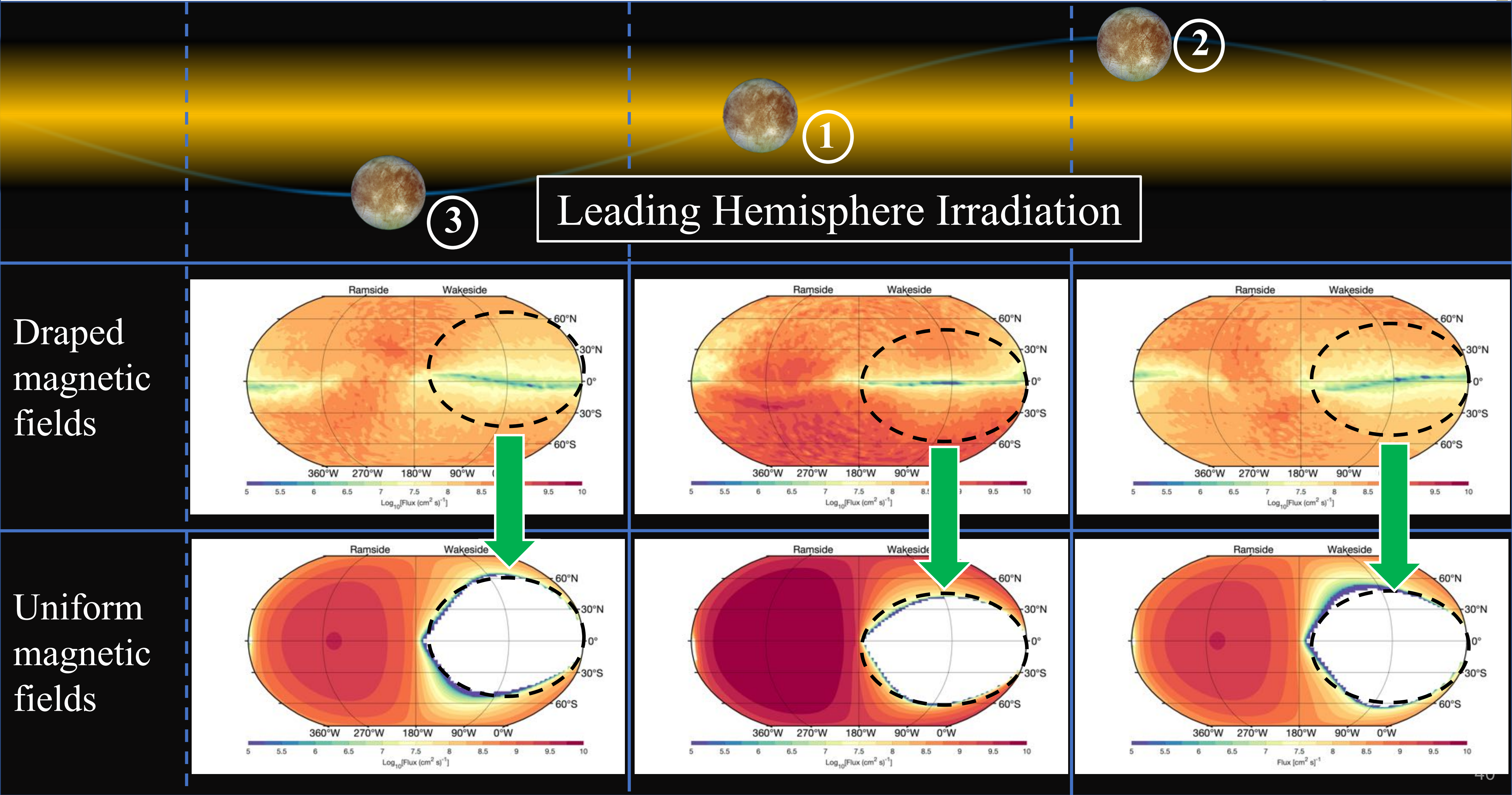




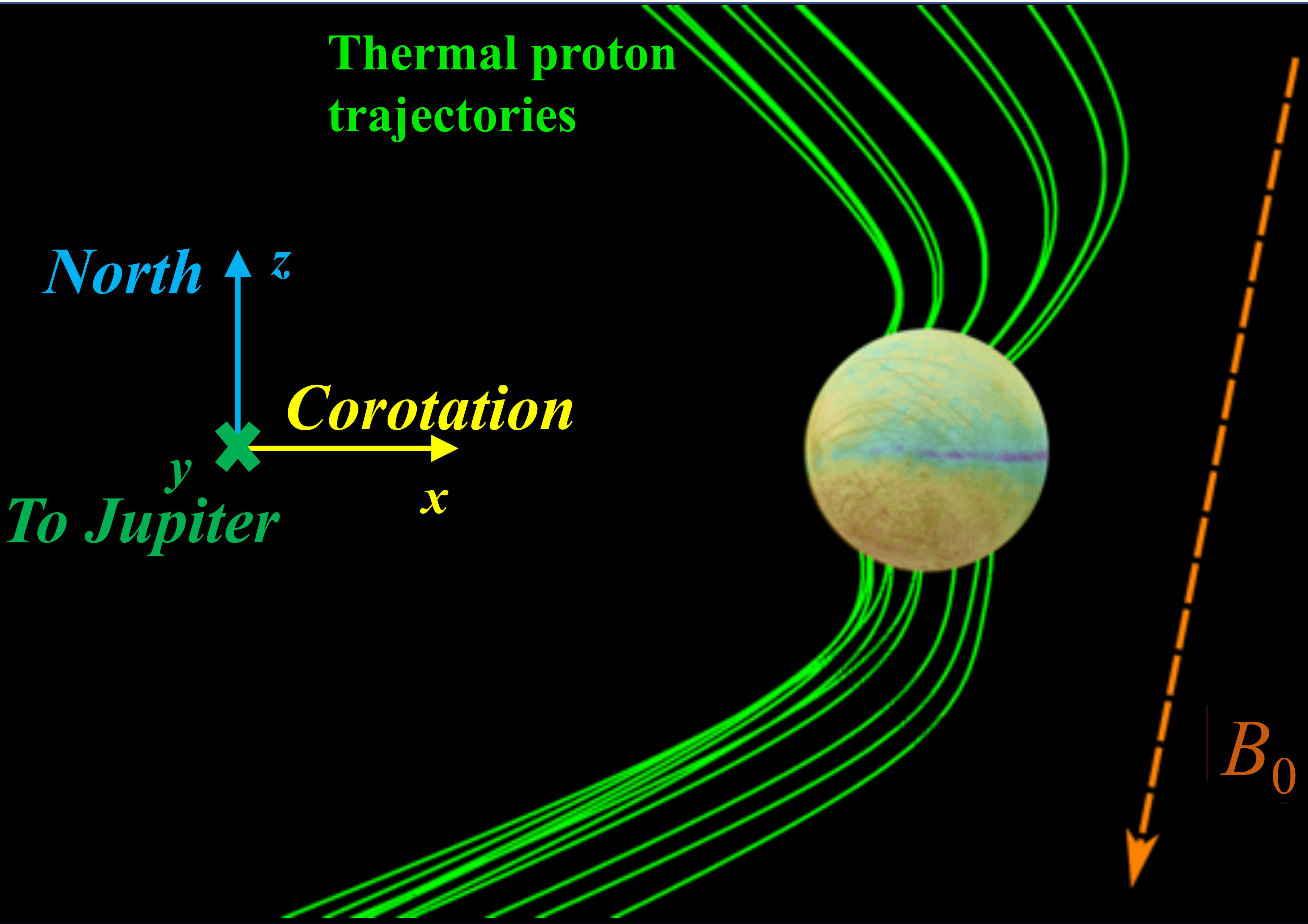


Thermal Ion Surface Flux

(paddison6@gatech.edu)



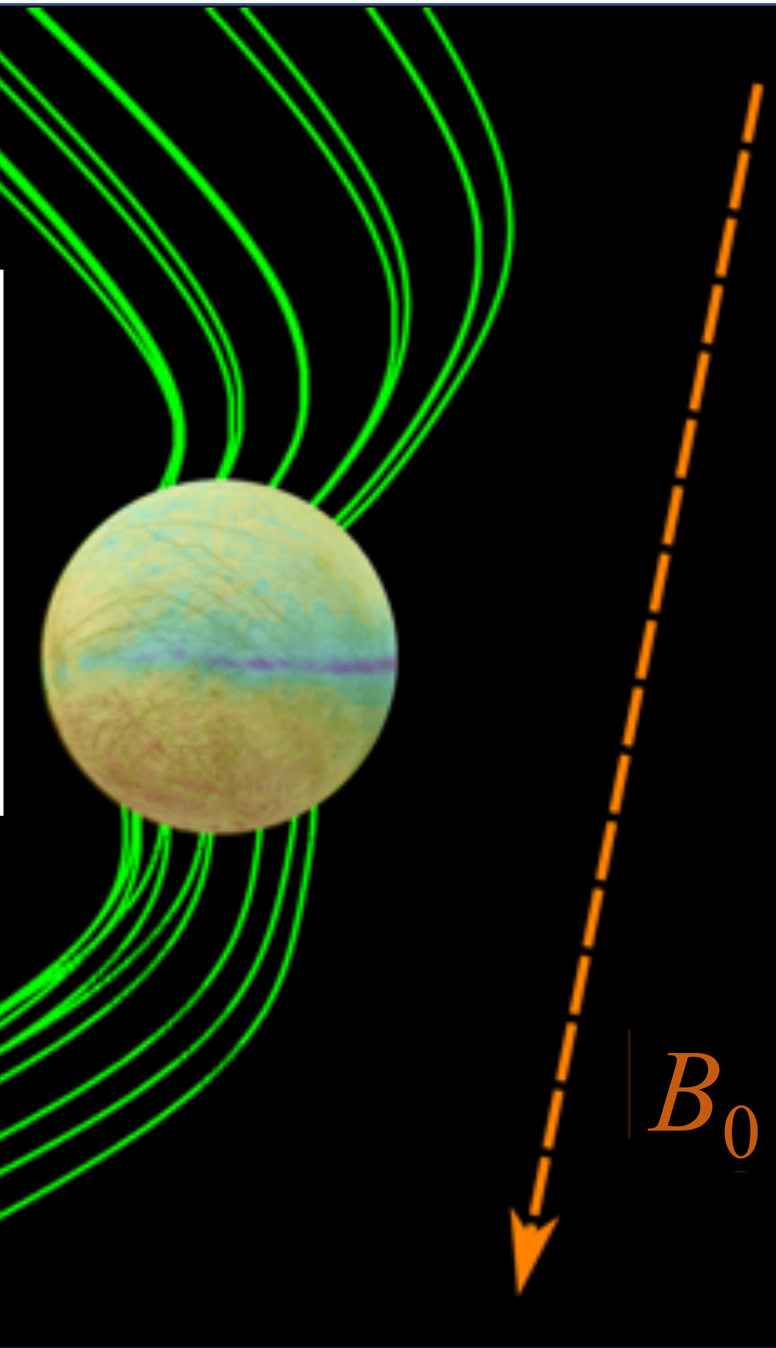
(paddison6@gatech.edu)



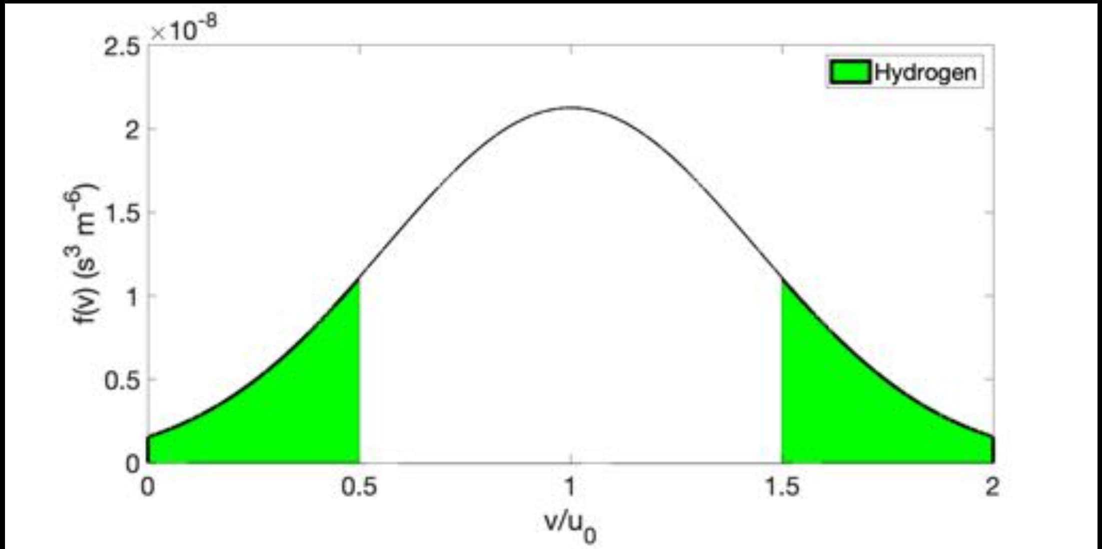
Draped field lines divert ions back into leading hemisphere!

Leading Hemisphere Irradiation

(paddison6@gatech.edu)



Thermal proton trajectories

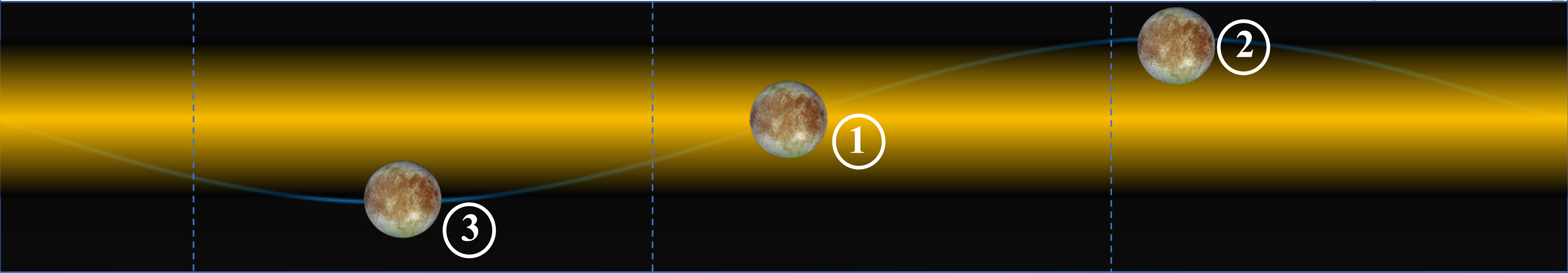


High thermal velocity of proton distribution: many particles along the "wings" of the distribution!

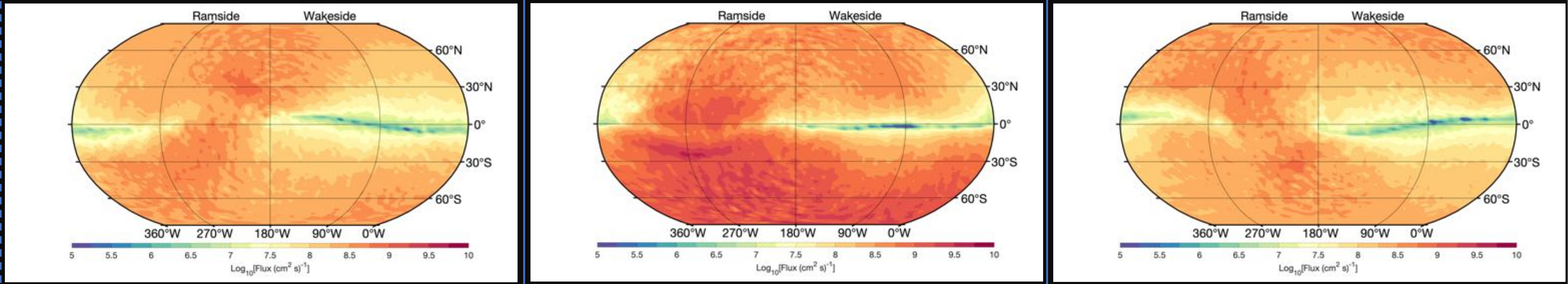
- Significant flux contribution from highly inclined trajectories: **thermal ion flux onto Europa is a kinetic problem!**

Thermal Ion Surface Flux

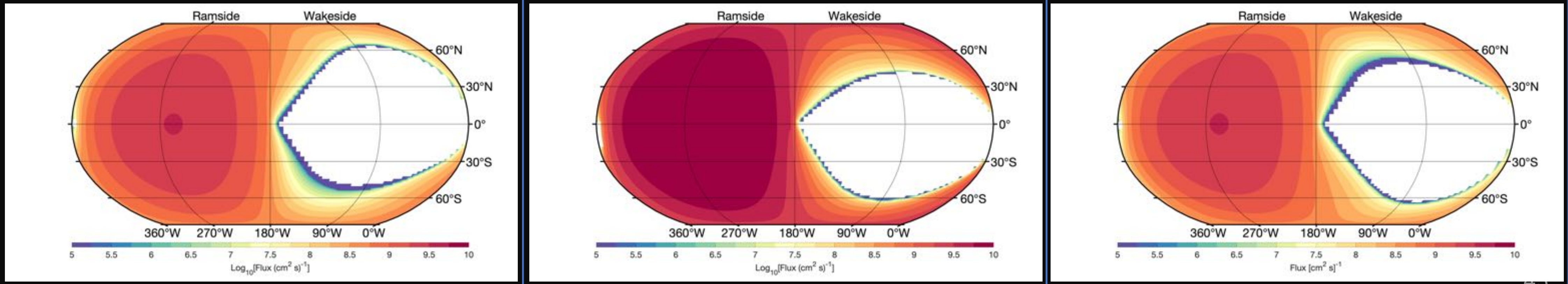
(paddison6@gatech.edu)



Draped magnetic fields

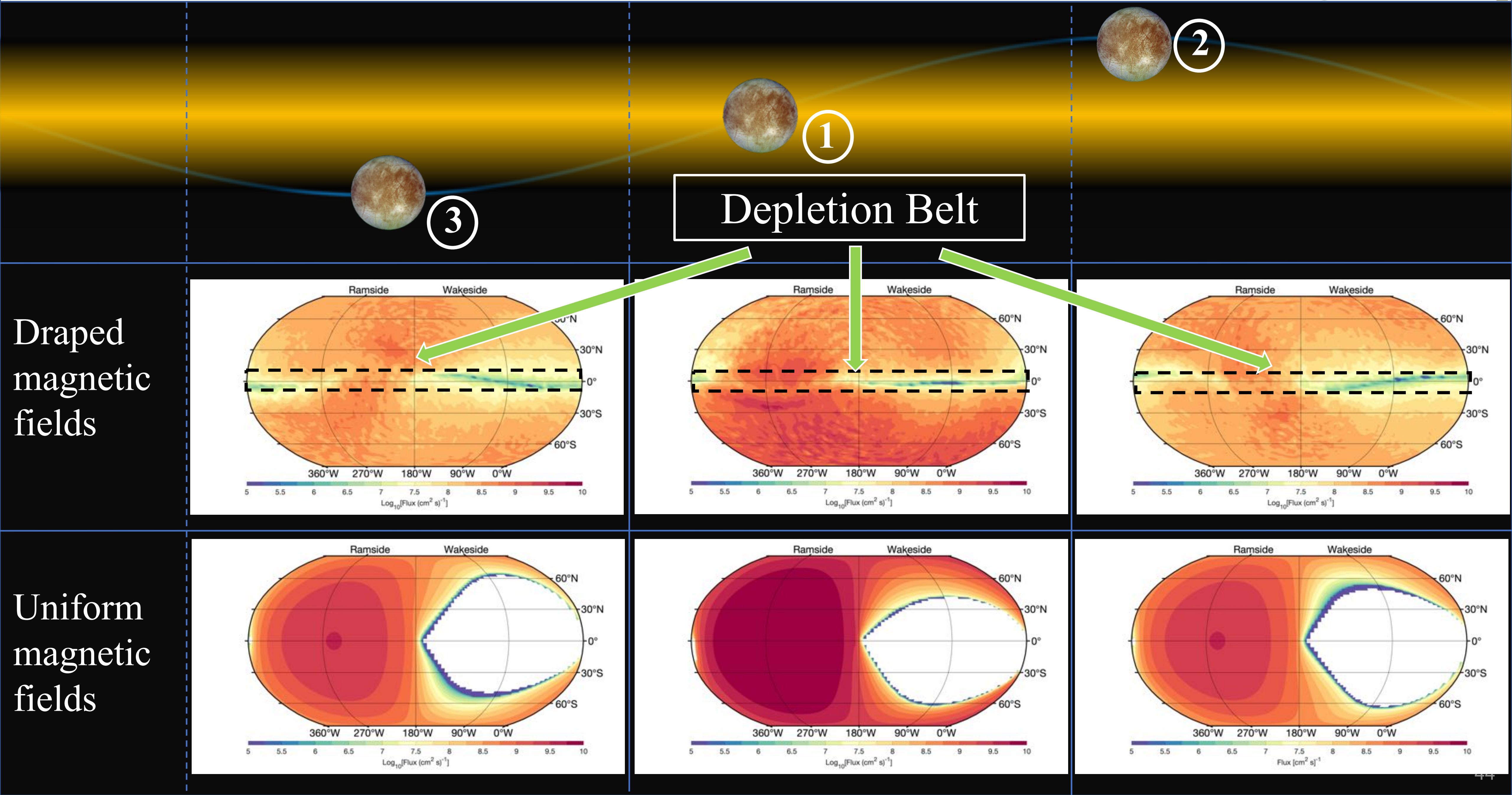


Uniform magnetic fields



Thermal Ion Surface Flux

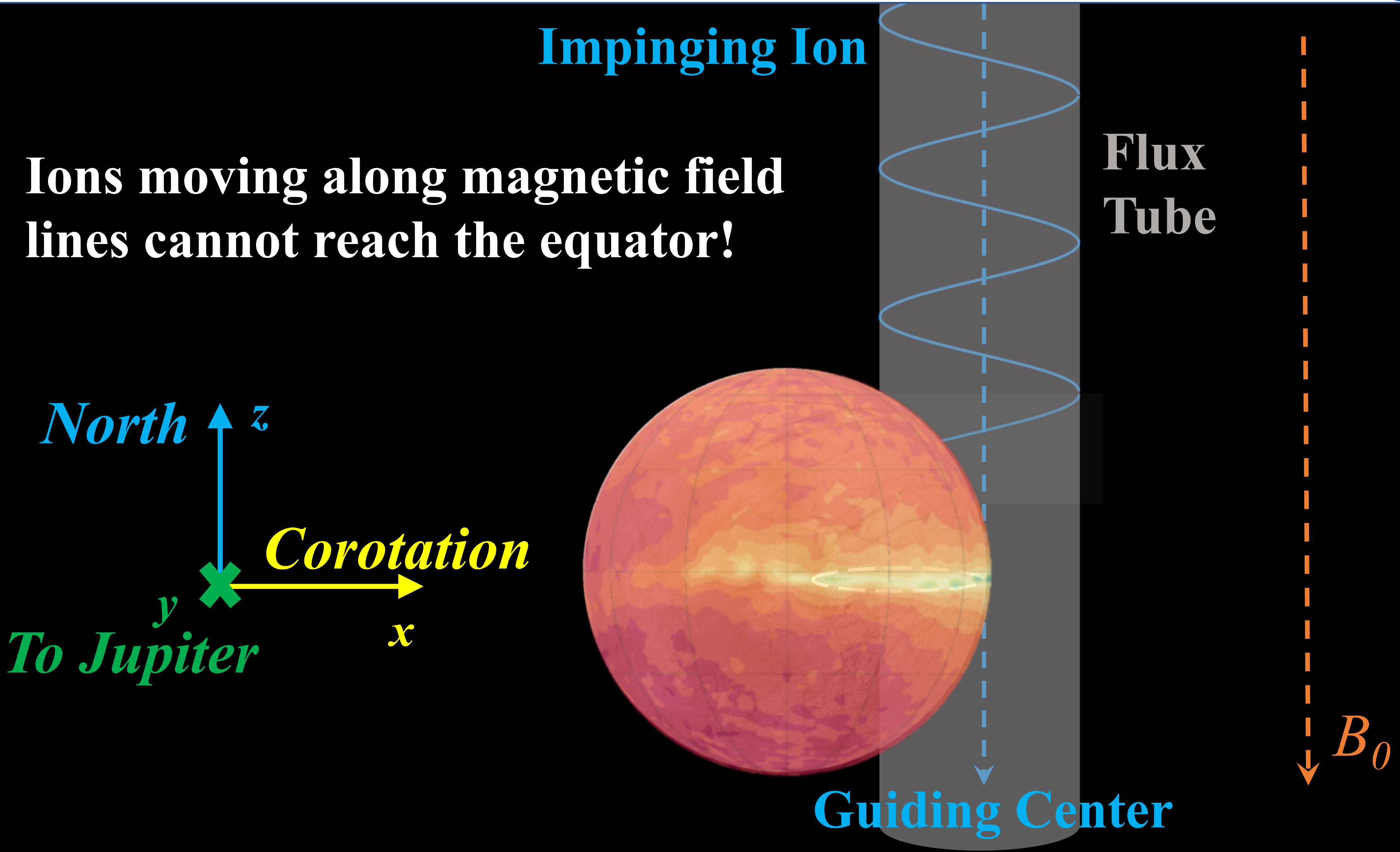
(paddison6@gatech.edu)



Equatorial Depletion Belt

(paddison6@gatech.edu)

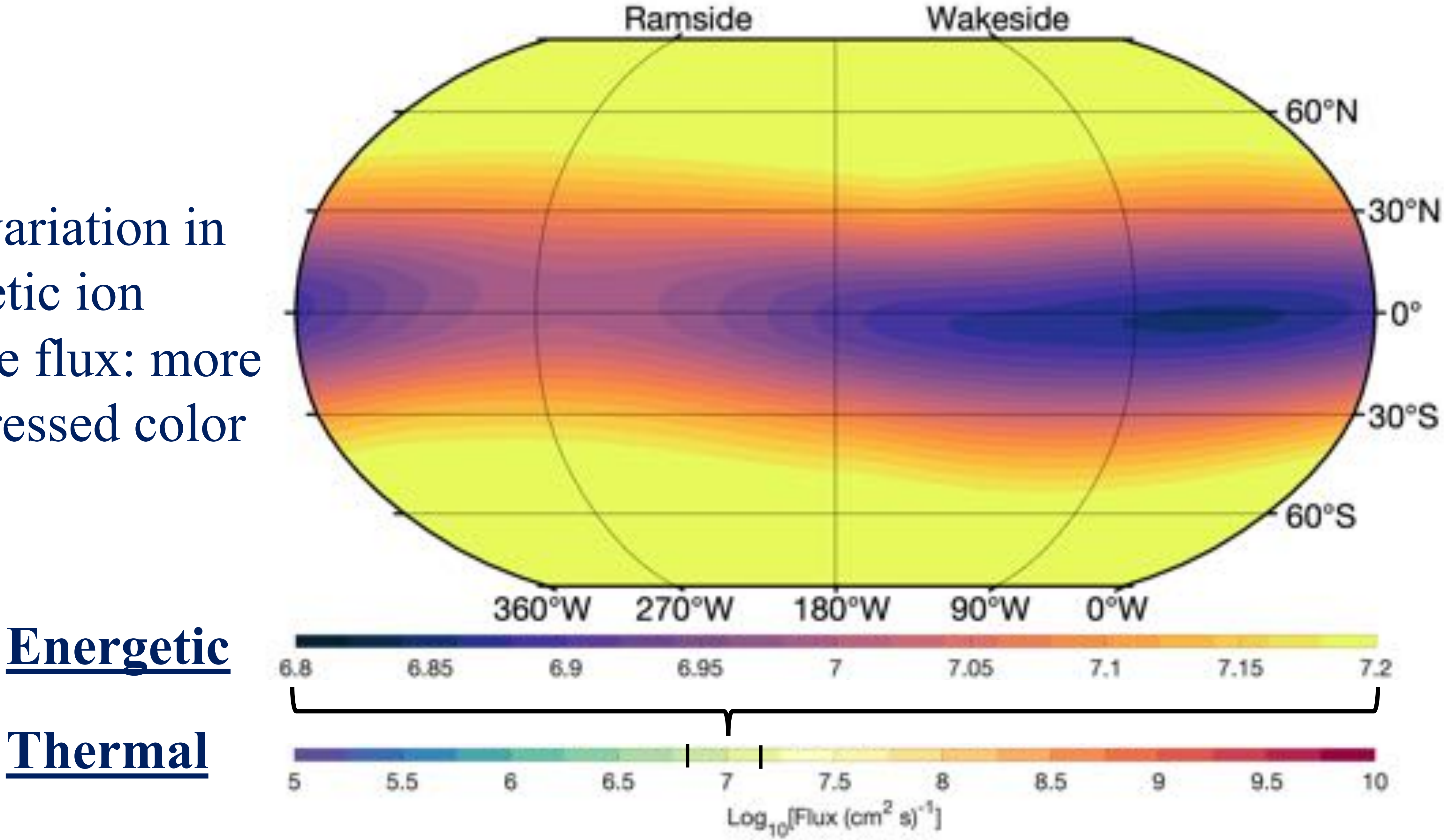
Ions moving along magnetic field lines cannot reach the equator!



Energetic Ions: Layout of Flux Maps

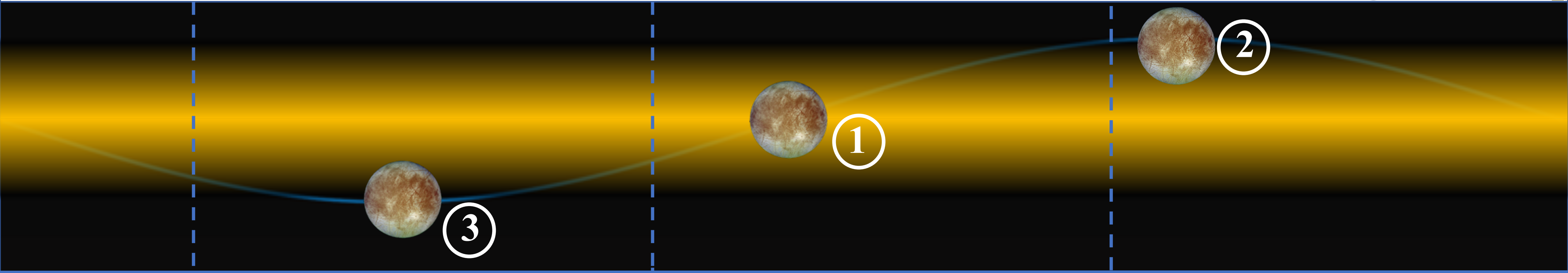
(paddison6@gatech.edu)

- Less variation in energetic ion surface flux: more compressed color scale!

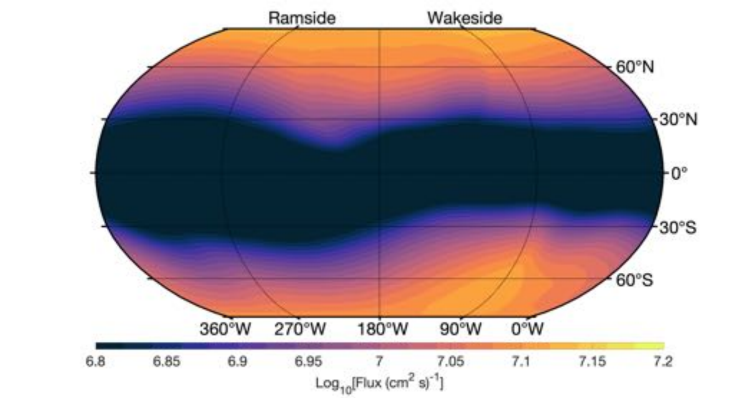


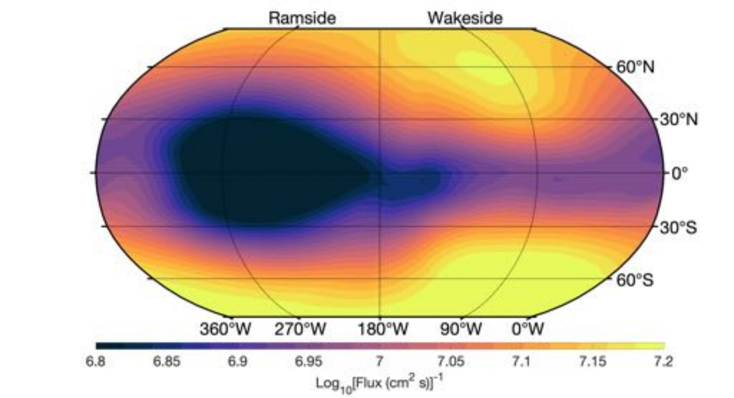
Energetic Ion Surface Flux

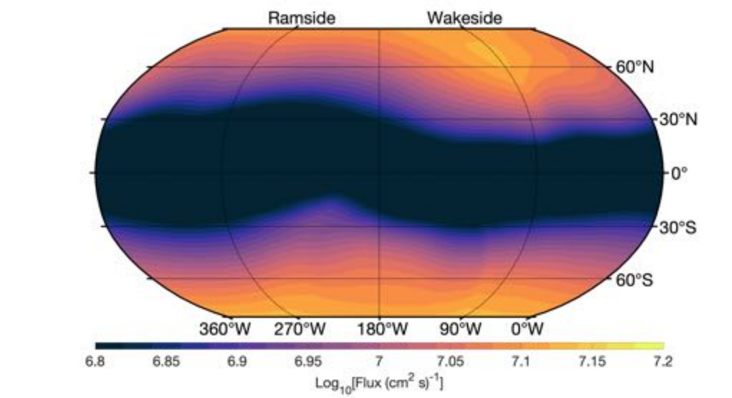
(paddison6@gatech.edu)



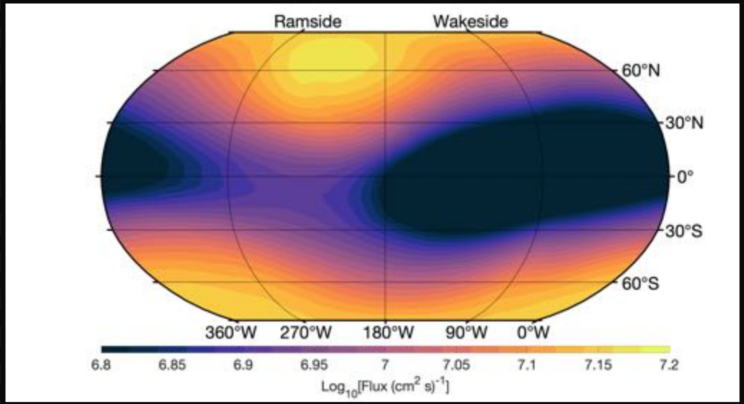
Draped magnetic fields

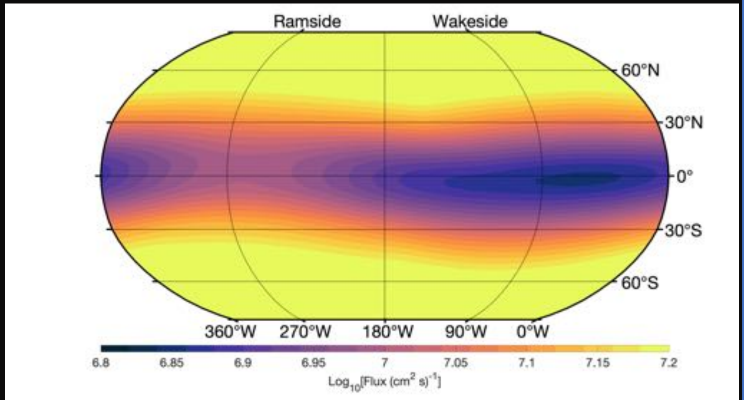


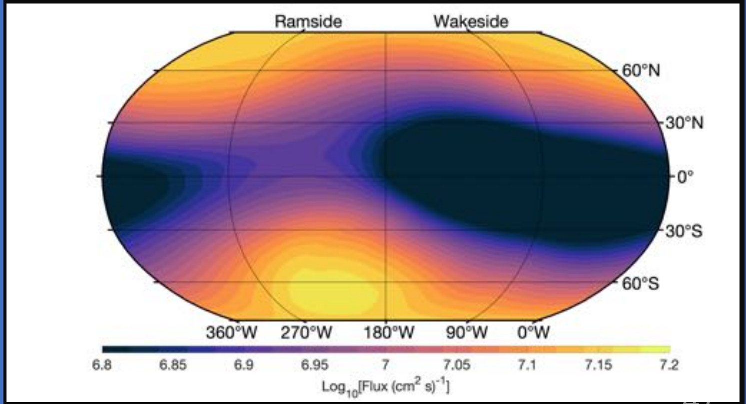




Uniform magnetic fields

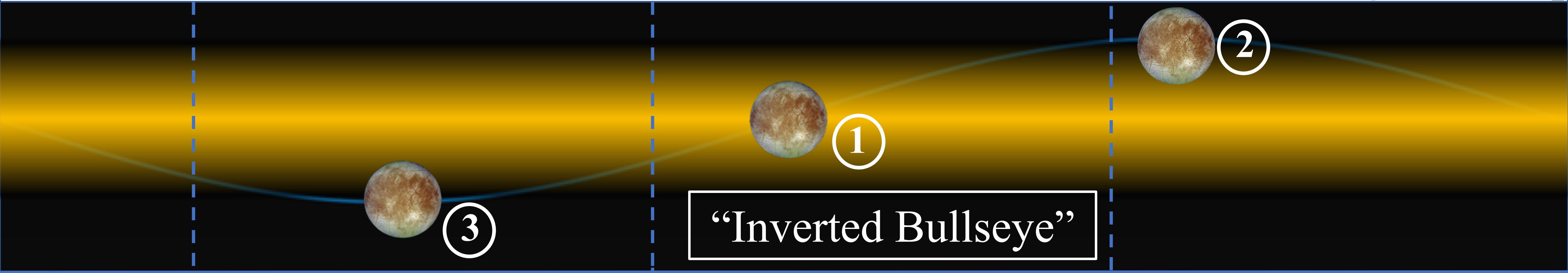






Energetic Ion Surface Flux

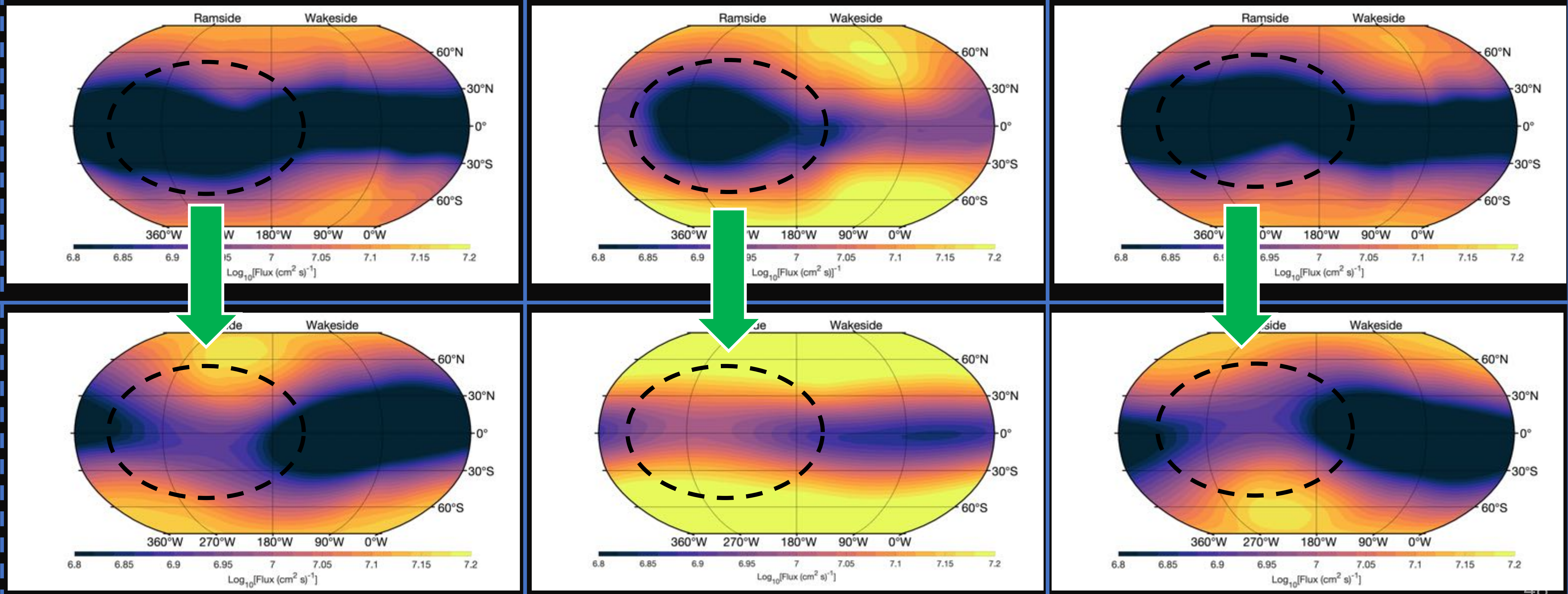
(paddison6@gatech.edu)



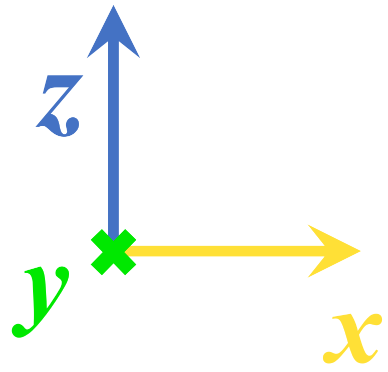
"Inverted Bullseye"

Draped magnetic fields

Uniform magnetic fields

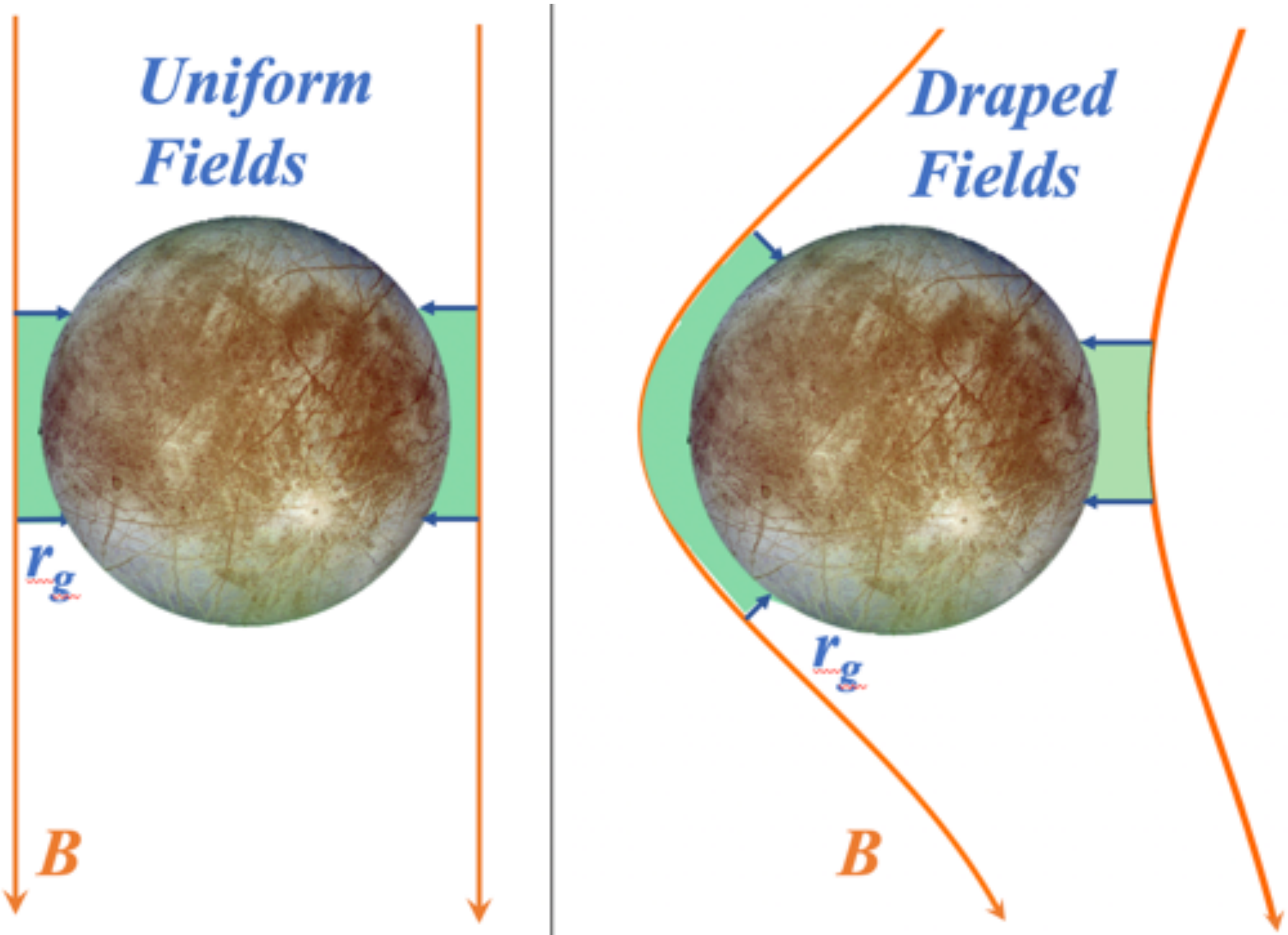


(paddison6@gatech.edu)



- **Energetic ions: "Valley of death" within one gyroradius of Europa's surface.**

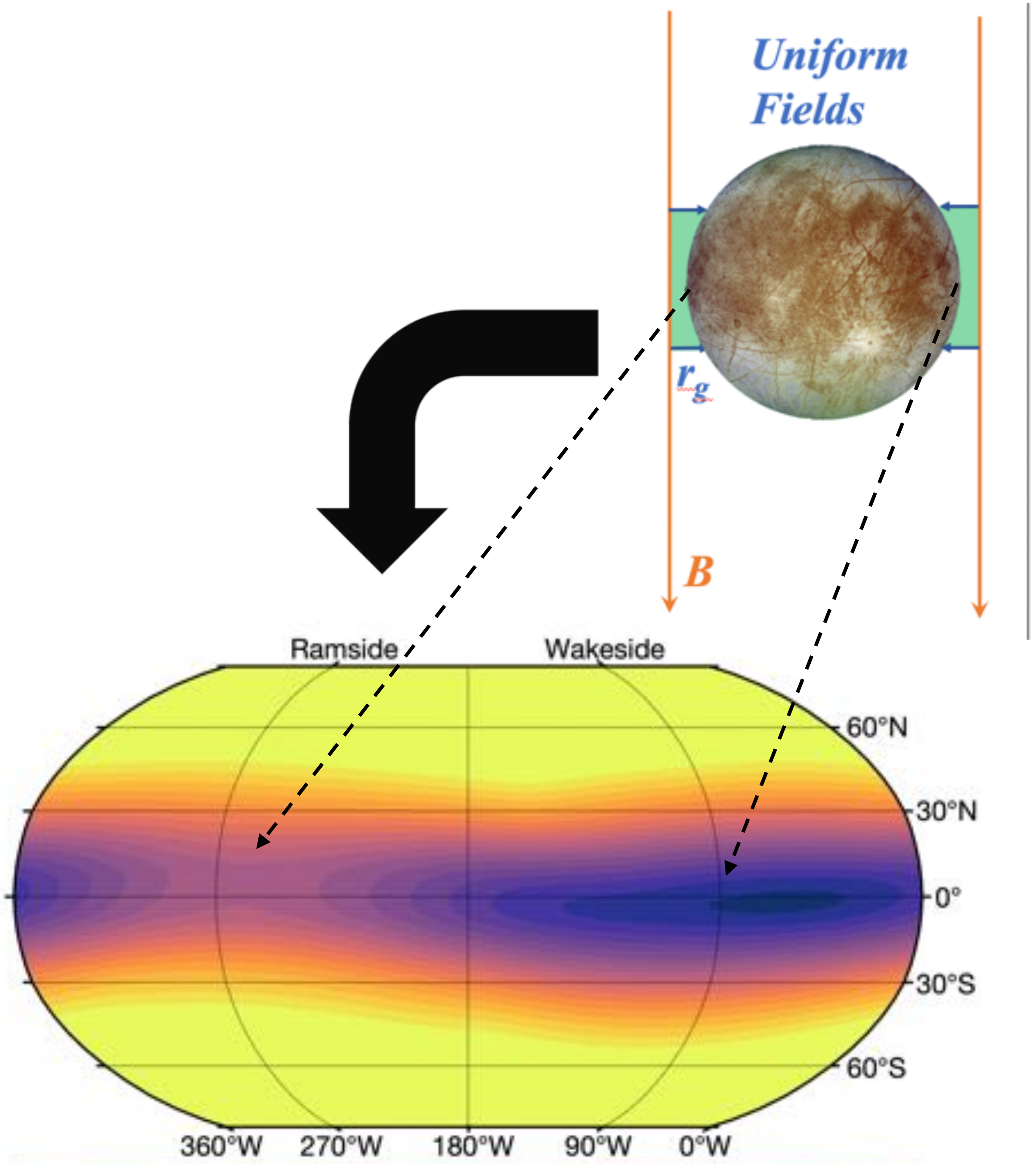
- **Field draping alters the extent of this region**

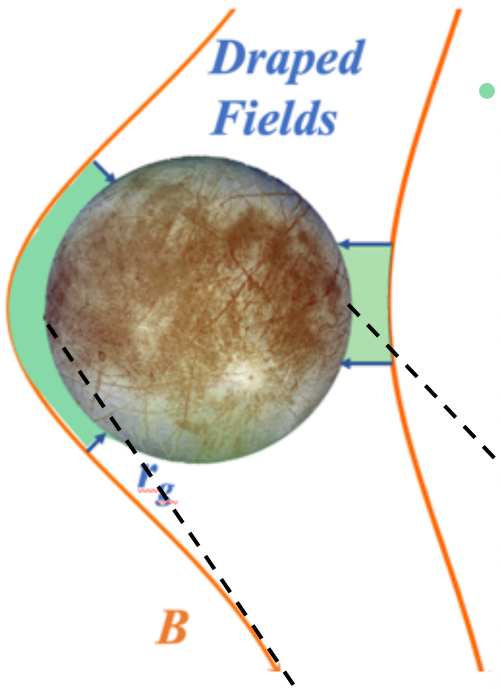


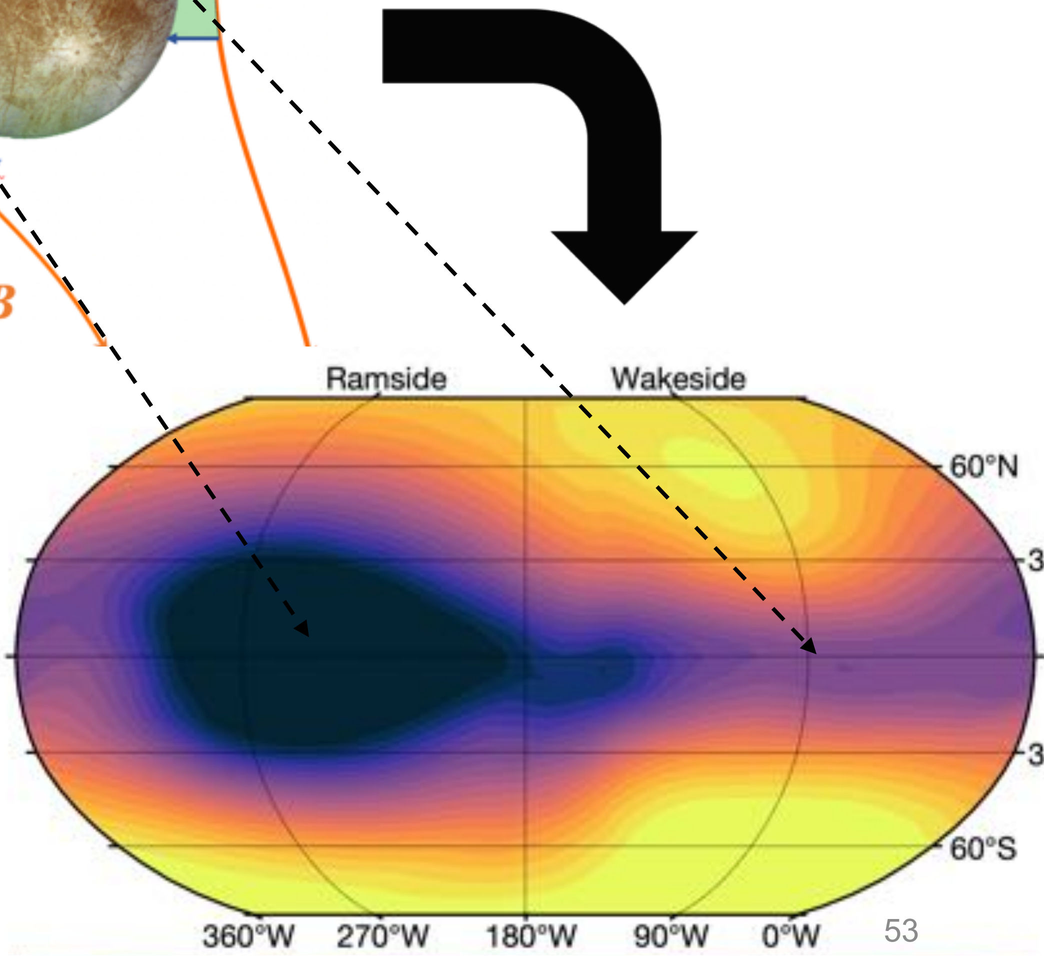
Formation of Inverted Bullseye

(paddison6@gatech.edu)

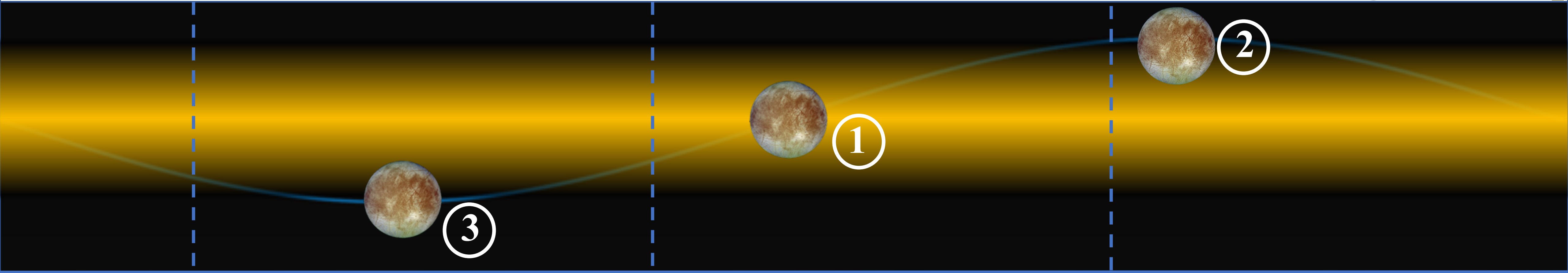
- **“Valley of Death” grows at ramside and shrinks at wakeside**







(paddison6@gatech.edu)



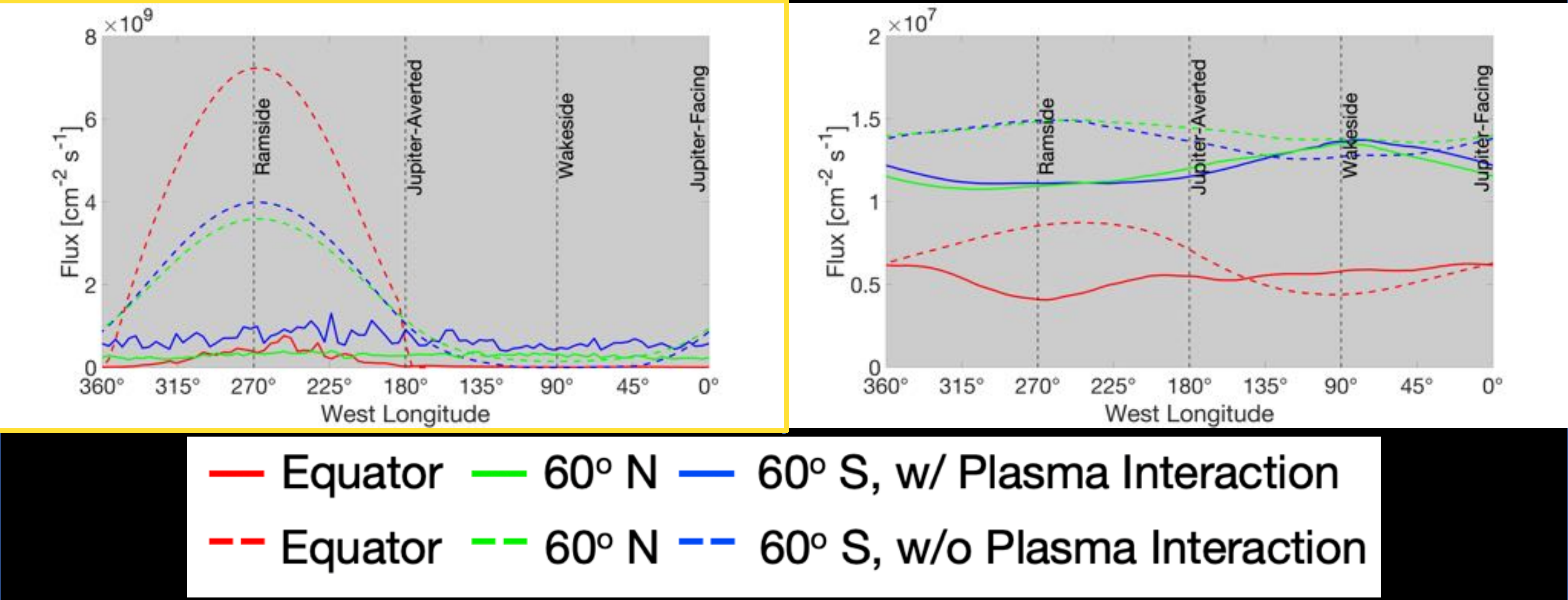
What does the average ion surface flux pattern look like?

$$\text{Average} = \frac{\text{Case (1)} + \text{Case (2)} + \text{Case (3)}}{3}$$

Synodic Rotation: Averaged Ion Flux

(paddison6@gatech.edu)

Thermal Surface Flux	Energetic Surface Flux

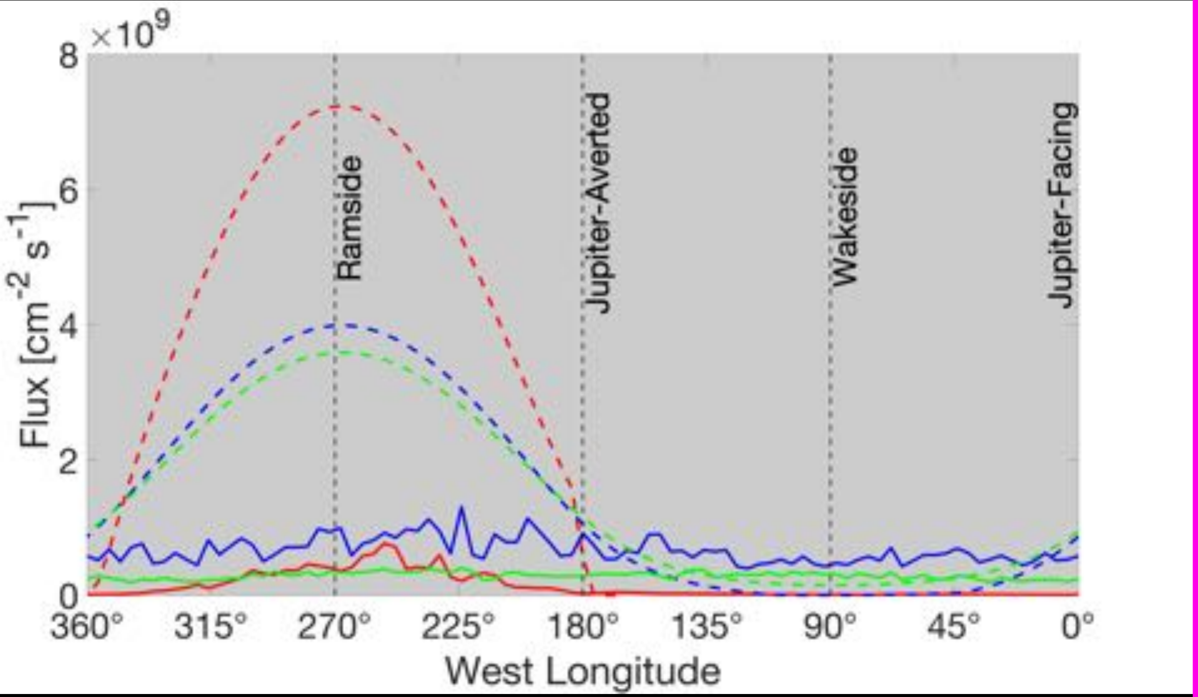


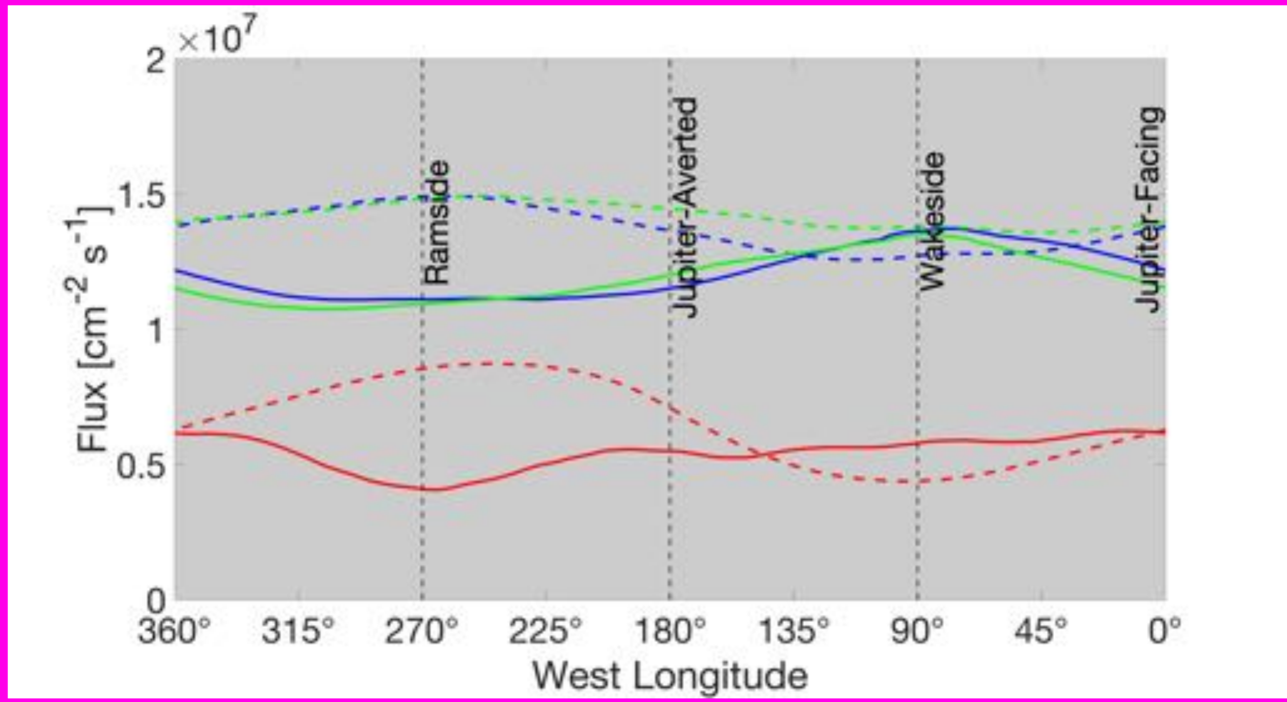
Plasma interaction: more even distribution of thermal surface flux!

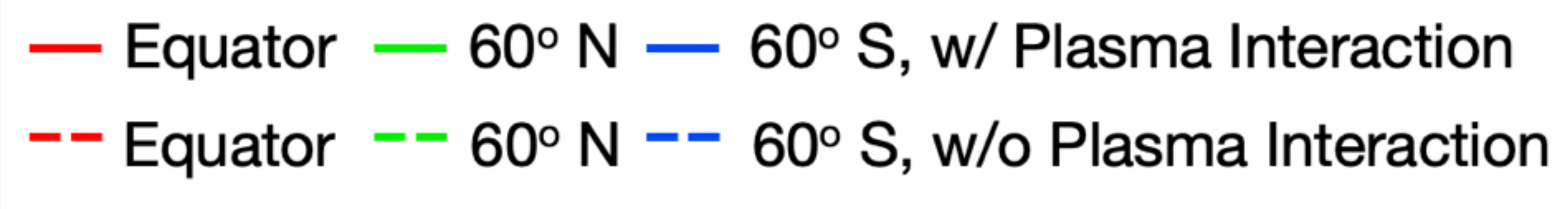
Synodic Rotation: Averaged Ion Flux

(paddison6@gatech.edu)

Thermal Surface Flux	Energetic Surface Flux



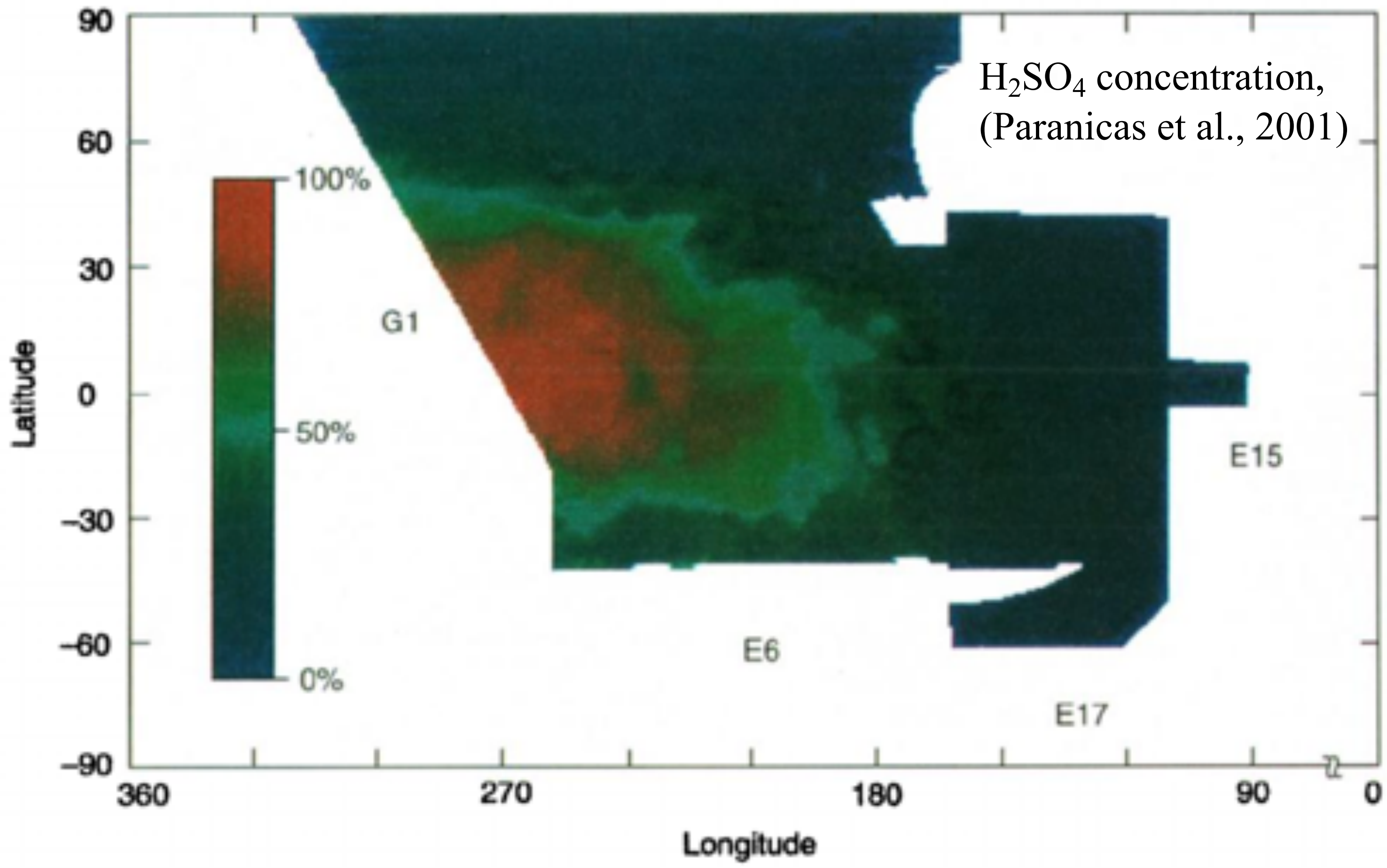




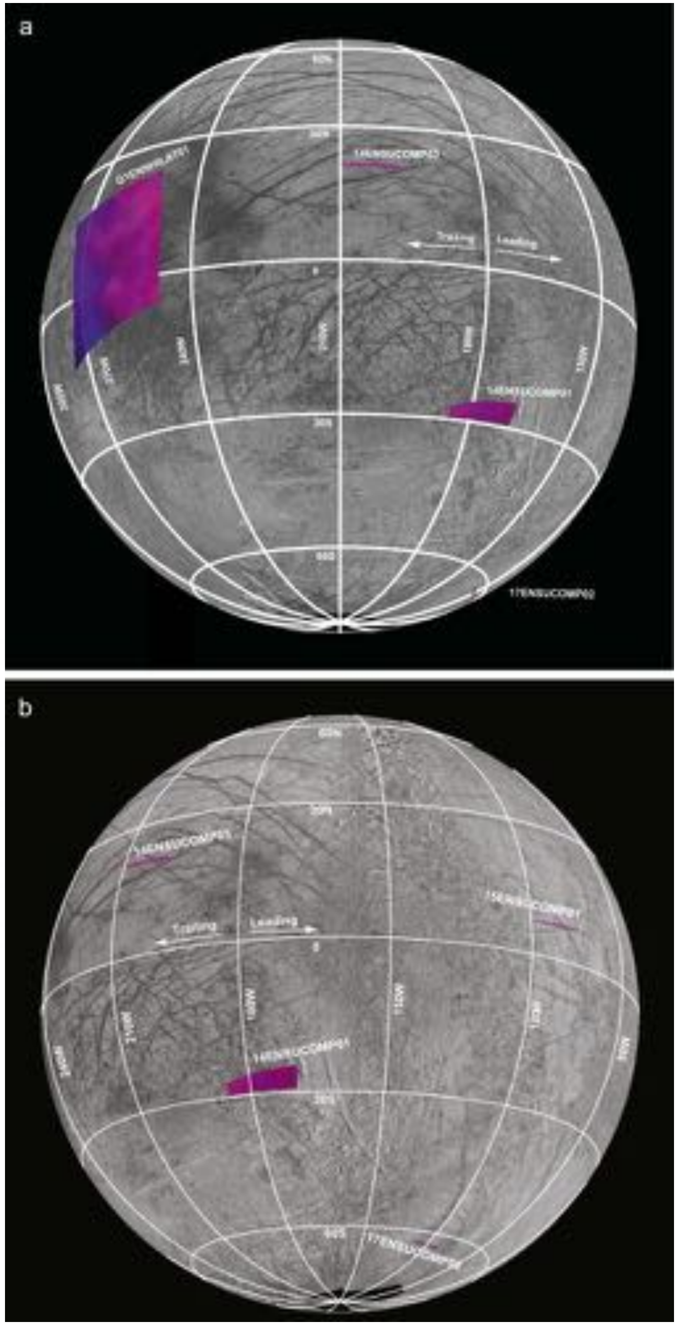
Plasma interaction included: energetic flux pattern reversed!

Surface Composition vs. Sulfur Ion Flux Pattern I

(paddison6@gatech.edu)



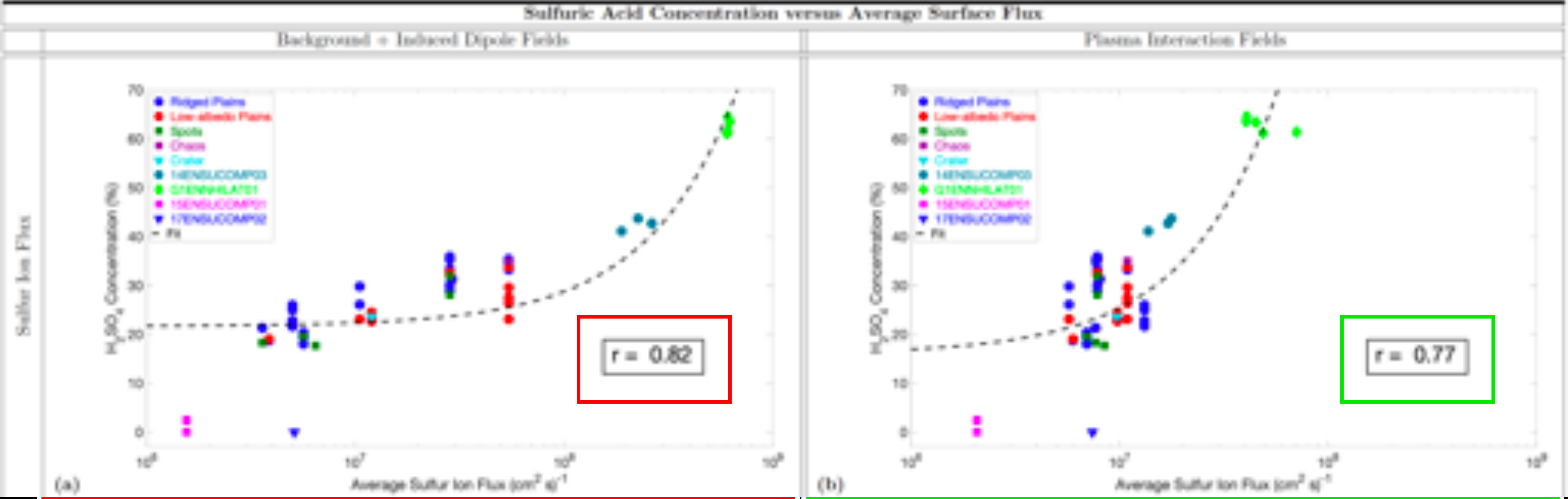
H_2SO_4 concentration, (Paranicas et al., 2001)



Surface locations of measured H_2SO_4 concentration, (Dalton et al., 2013)

Can exogenic sulfur ion flux explain the H_2SO_4 distribution?

Surface Composition vs. Sulfur Ion Flux Pattern II (paddison6@gatech.edu)



Uniform fields

Draped fields

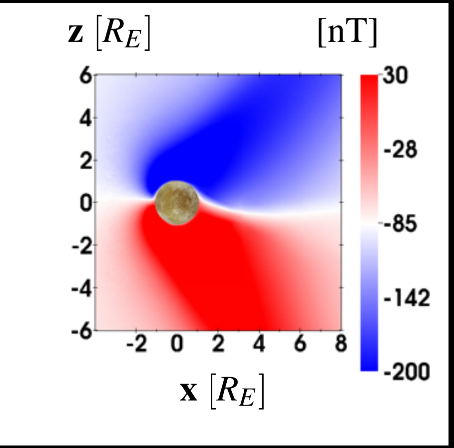
- **MEASURED H_2SO_4 concentrations correlate tightly with MODELED sulfur ion flux!**
- **Despite flux changes imposed by field perturbations, correlation remains!**

Conclusions

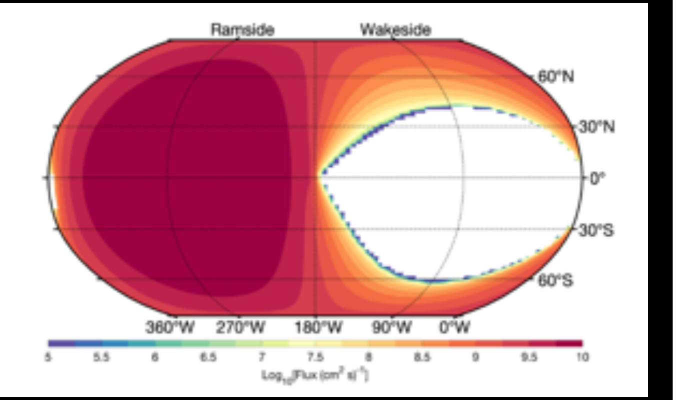
(paddison6@gatech.edu)

- Goal: calculate spatial distribution of ion surface flux at Europa
- Method: combination of hybrid plasma model and particle tracing tool

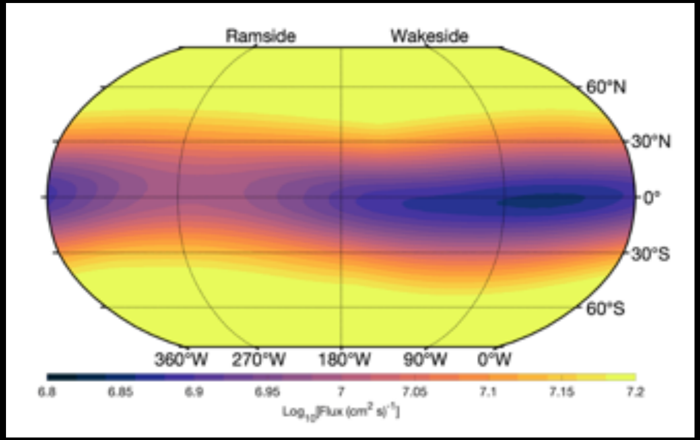
1. Europa: highly perturbed electromagnetic environment.



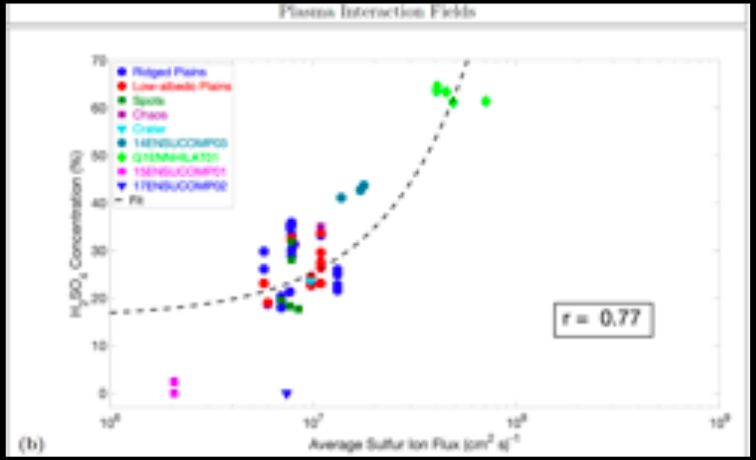
2. Field perturbations **significantly alter** ion surface fluxes!



3. Longitudinal energetic ion flux pattern is reversed when perturbations are included!



4. Ion bombardment pattern can explain **surface composition**.



Manuscript submitted to JGR: Space Physics

Influence of Europa's Time-Varying Electromagnetic Environment on Magnetospheric Ion Precipitation and Surface Weathering

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[2]Space Sciences Laboratory, University of California, Berkeley, CA, USA

Key Points:

- Magnetic field draping around Europa reduces ion surface flux onto the upstream hemisphere and enhances flux onto its downstream hemisphere
- Europa's upstream hemisphere receives the least amount of flux from energetic