Variability in the energetic electron bombardment of Ganymede

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Introduction
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Results: G8
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Discussion

Introduction

- Despite low densities compared to the *thermal* ($E < 10$ keV) plasma, *energetic* (10 keV < E < 100 MeV) particles strongly alter Ganymede's inhomogeneous surface (1, 2, 3, 4, 5)
- These energetic ions and electrons also contribute to surface sputtering (6, 7, 8) and ice state (9)
- Local Jovian magnetospheric thermal ($E < 10$ keV) plasma properties change over a synodic rotation, and the resulting interaction with Ganymede and its dipole varies in time (Fig. 1)
- Energetic ***ions*** precipitate non-uniformly across the moon's surface and are strongly affected by local electromagnetic field perturbations and Ganymede's permanent dipole (5, 8)
- But despite their contribution to surface chemistry, energetic ***electron*** precipitation patterns and fluxes onto Ganymede ***remain unconstrained***
- ***This study:*** Investigate how electron surface fluxes are affected by the non-uniform electromagnetic environment and vary over a synodic rotation, and constrain fluxes averaged over large timescales

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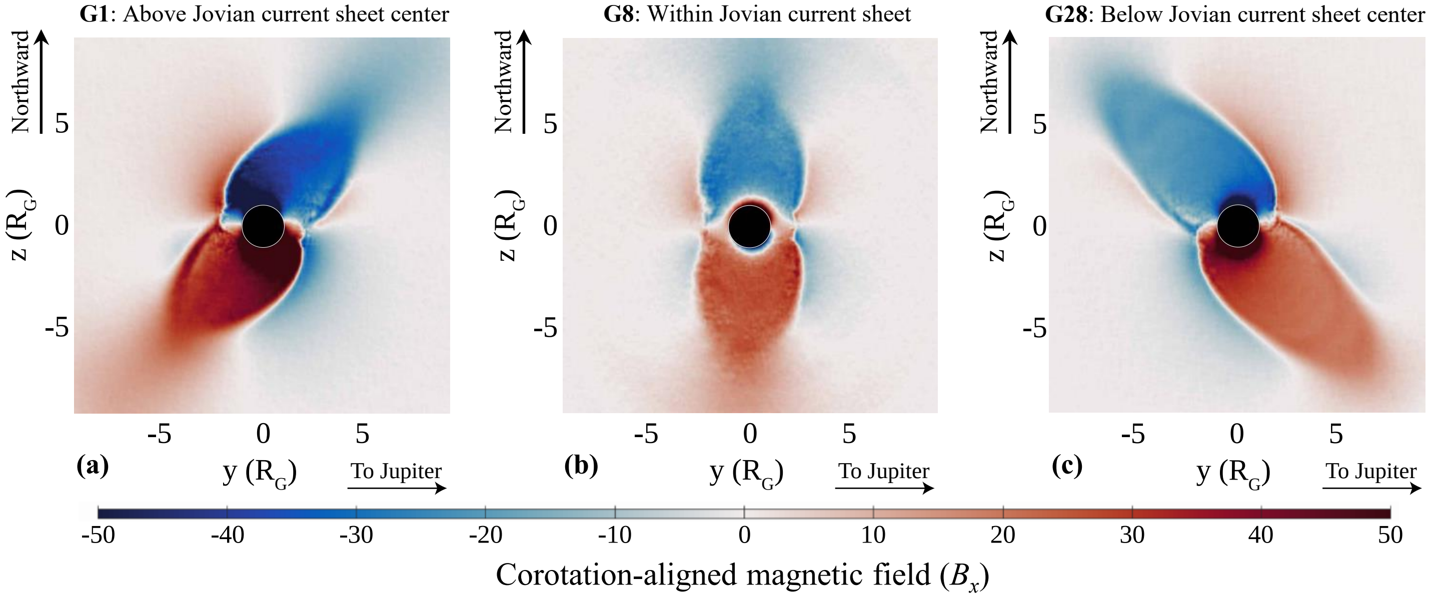

Figure 1: *Plasma interaction variability and field line draping near Ganymede (Liuzzo+ 2020).*

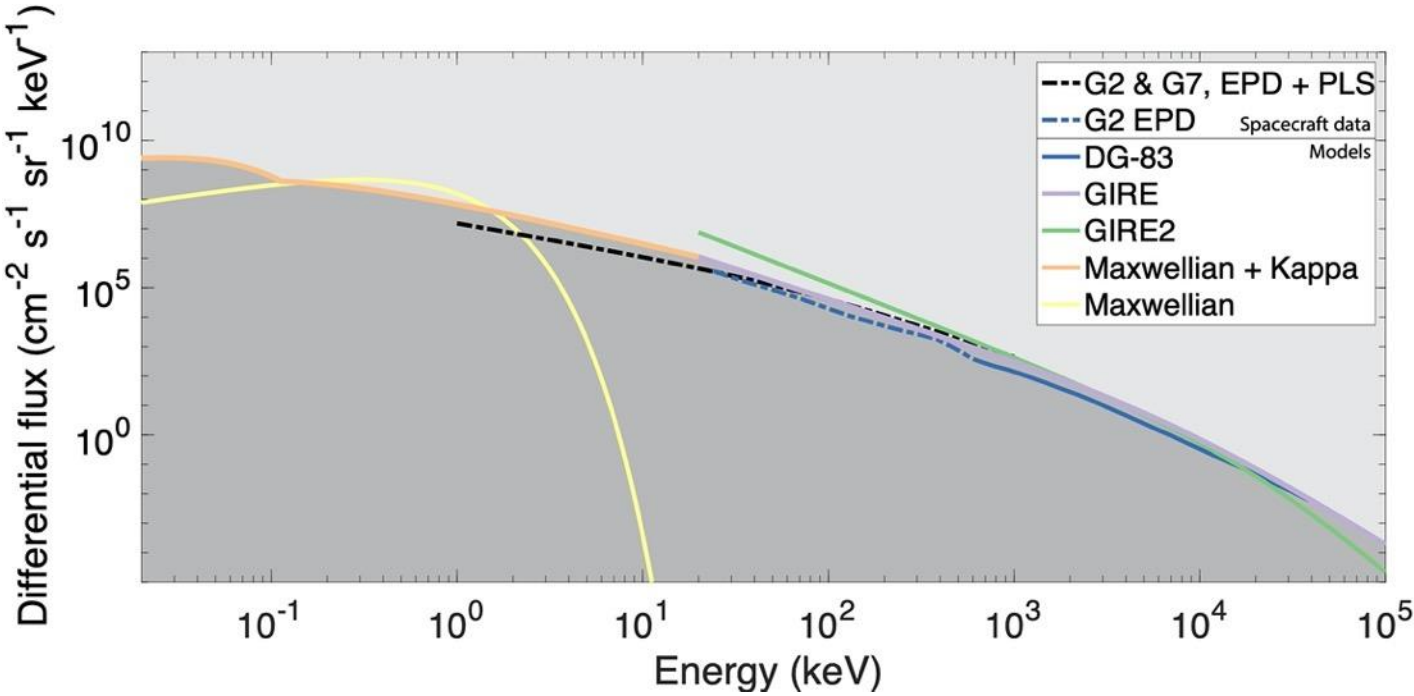

Figure 2: *Ambient electron environment near Ganymede (Liuzzo+ 2020).*

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Methods

- Use existing hybrid model (treating ions as particles, electrons as fluid) results from Fatemi+ 2016 to obtain electromagnetic fields near Ganymede for three Galileo encounters (Fig. 1):
  - G8: Ganymede ***embedded within*** Jupiter's magnetospheric current sheet
  - G1: Ganymede located at maximum distance ***above*** the current sheet
  - G28: Ganymede located at maximum distance ***below*** the current sheet
- Apply the GENTOo test-particle model (Liuzzo+ 2019a; 2019b) to propagate energetic electrons through these fields:
  - Electrons are initialized on Ganymede's surface and traced ***backward*** in time
  - Those electrons that intersect the surface at any point during tracing are "forbidden" and, in a forward-tracing picture, would *not* contribute to the surface electron flux
  - Those that do not intersect the surface are "allowed" and contribute to surface flux
- Energetic electrons near Ganymede complete a half-bounce period (from the moon's orbital plane, to their mirror point at large Jovian magnetic latitudes, and back) in ~30s.
  - ***This motion must be considered*** to determine if an electron is forbidden or allowed
  - The particle must travel to large enough azimuthal distances to ensure it does not interest the surface on a subsequent bounce to become forbidden
- Above the *critical energy* ($E_c \cong 2$ MeV) an electron's drift velocity cancels Ganymede's orbital velocity and electrons *anti-corotate* (Fig. 3)
- Using the local ambient electron distribution (Fig. 2), apply Liouville's theorem to determine surface fluxes *for allowed particles only.*

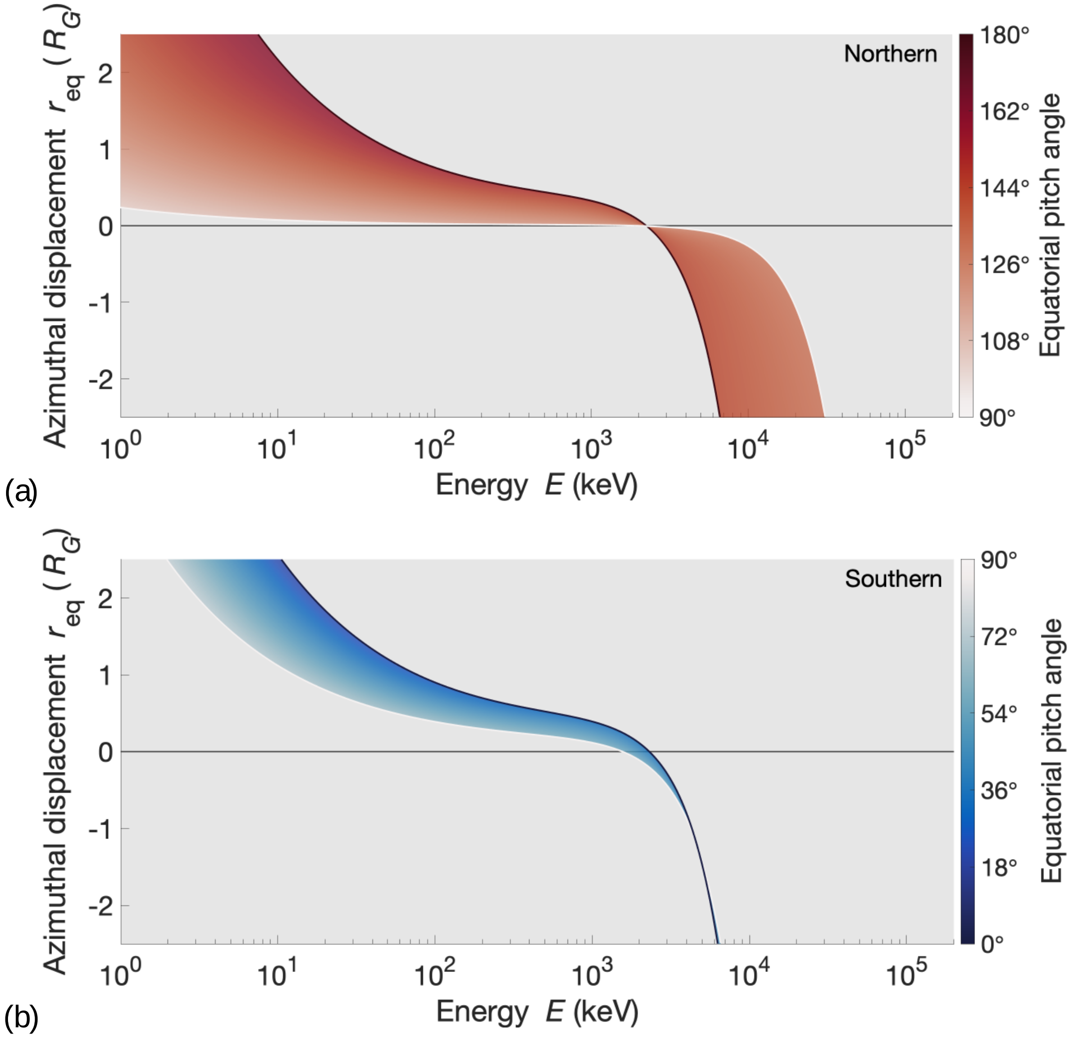

Figure 3: *Azimuthal displacement of energetic electrons (with respect to Ganymede) after a half-bounce period initially traveling (a) northward or (b) southward. Note the "critical energy" (E_c) at which electrons return with zero displacement (Liuzzo+ 2020).*

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Results: G8

- Electron precipitation with Ganymede embedded within Jupiter's magnetospheric current sheet (Fig. 4)
- Fluxes are *strongly* partitioned by latitude
- Two "bands" of enhanced flux form at high latitudes in the trailing hemisphere (Fig. 5)
- Low latitudes are shielded by Ganymede's dipole from *any* precipitating flux at energies $E < 40$ MeV
- Ganymede's dipole is *unable* to shield high-energy ($E > 40$ MeV) electrons accessing the equator; the resulting fluxes are asymmetric

High-latitude "bands" with enhanced electron flux

No precipitation!
Electrons shielded by Ganymede's dipole

Important takeaway points:

- The polar electron flux ***exceeds the net ion flux by an order of magnitude*** (cf. 1, 8)
- The equatorial electron flux is ***not zero***
- The ***entire*** surface is likely irradiated by these electrons beyond depths of 10 cm

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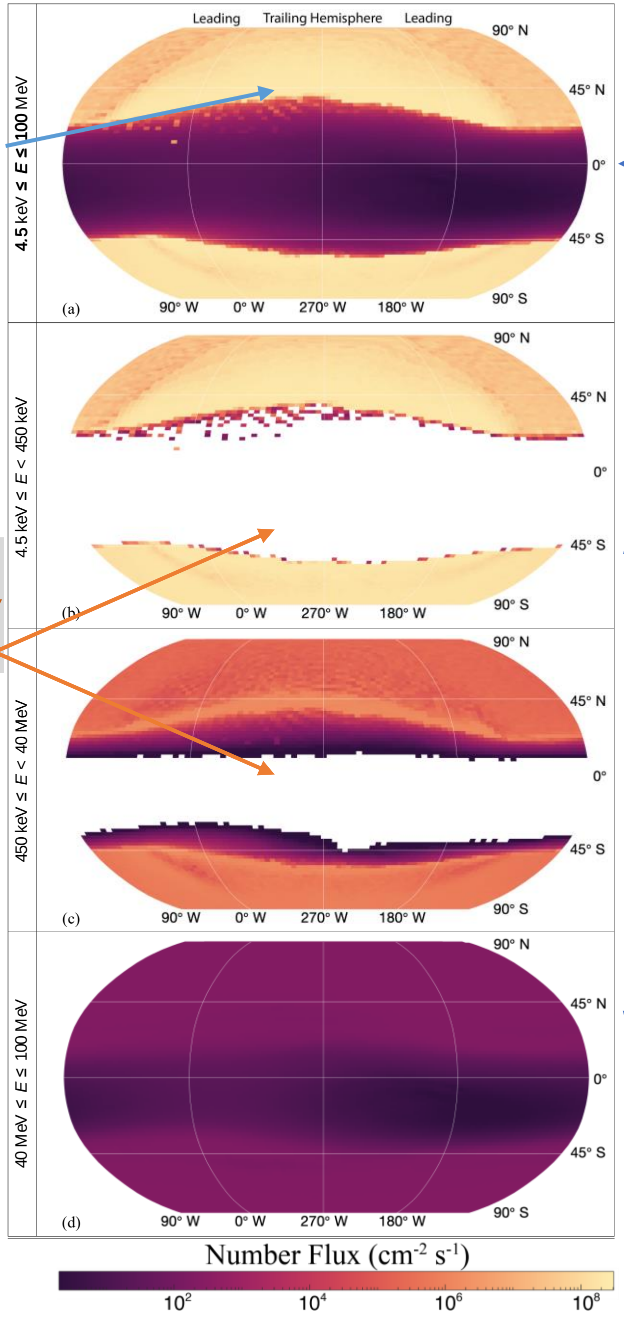

Total flux (all energies)

Narrow electron energy ranges

Figure 4: *Energetic electron number flux onto Ganymede during the Galileo G8 encounter (Liuzzo+ 2020).*

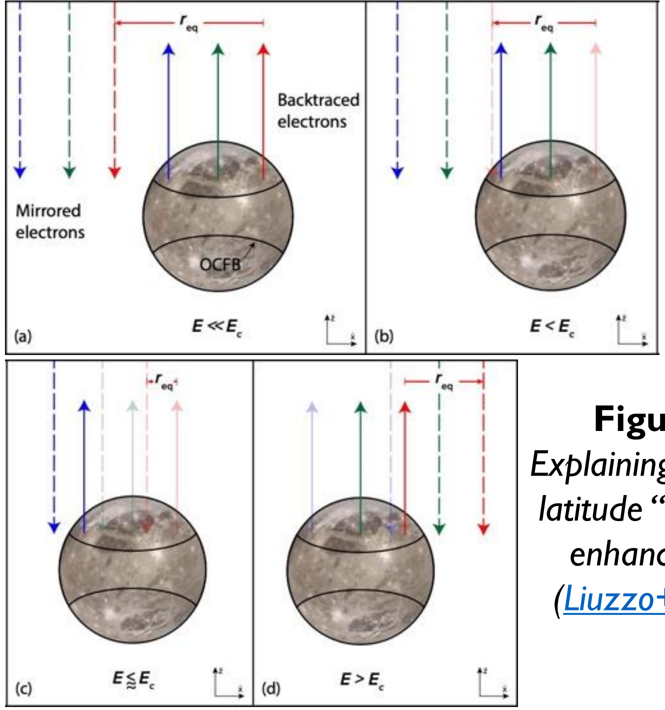

Figure 5: *Explaining the high-latitude "bands" of enhanced flux (Liuzzo+ 2020).*

- (a) *Backtraced* electrons far below the critical energy E_c are located upstream after mirroring and are "allowed"
- (b) Just below E_c, some electrons impact the moon after mirroring
- (c) At $E \lessapprox E_c$, only electrons near the trailing apex are allowed
- (d) Above E_c, the *first* allowed locations are near the leading apex
- At other moons, a "bullseye" forms; ***Ganymede's dipole prevents this low-latitude feature from forming***

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Results: G1 & G28

- Electron precipitation with Ganymede located ([Fig. 6](#) left; G1) far above the center of Jupiter's magnetospheric current sheet and ([Fig. 6](#) right; G28) far below the center of the current sheet
- Near trailing apex, electrons of all energies are ***unable to precipitate***: Ganymede's mini-magnetosphere is more expanded due to a weaker upstream pressure, and electrons are shielded from precipitating

Important takeaway points:

- While the G1/G28 precipitating fluxes are similar to during G8 (near the current sheet center), the trailing apex is now ***completely shielded***

Results: Averaged fluxes

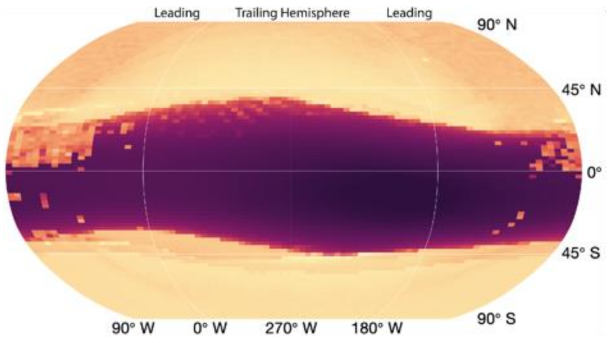

Figure 7: *Time-averaged energetic electron number flux onto Ganymede (Liuzzo+ 2020).*

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Important takeaway points:

- Promising agreement with observed asymmetries of the surface ices (4, 5)
- **Energetic electrons irradiate everywhere**: neither Ganymede's dipole nor plasma interaction can completely shield the surface

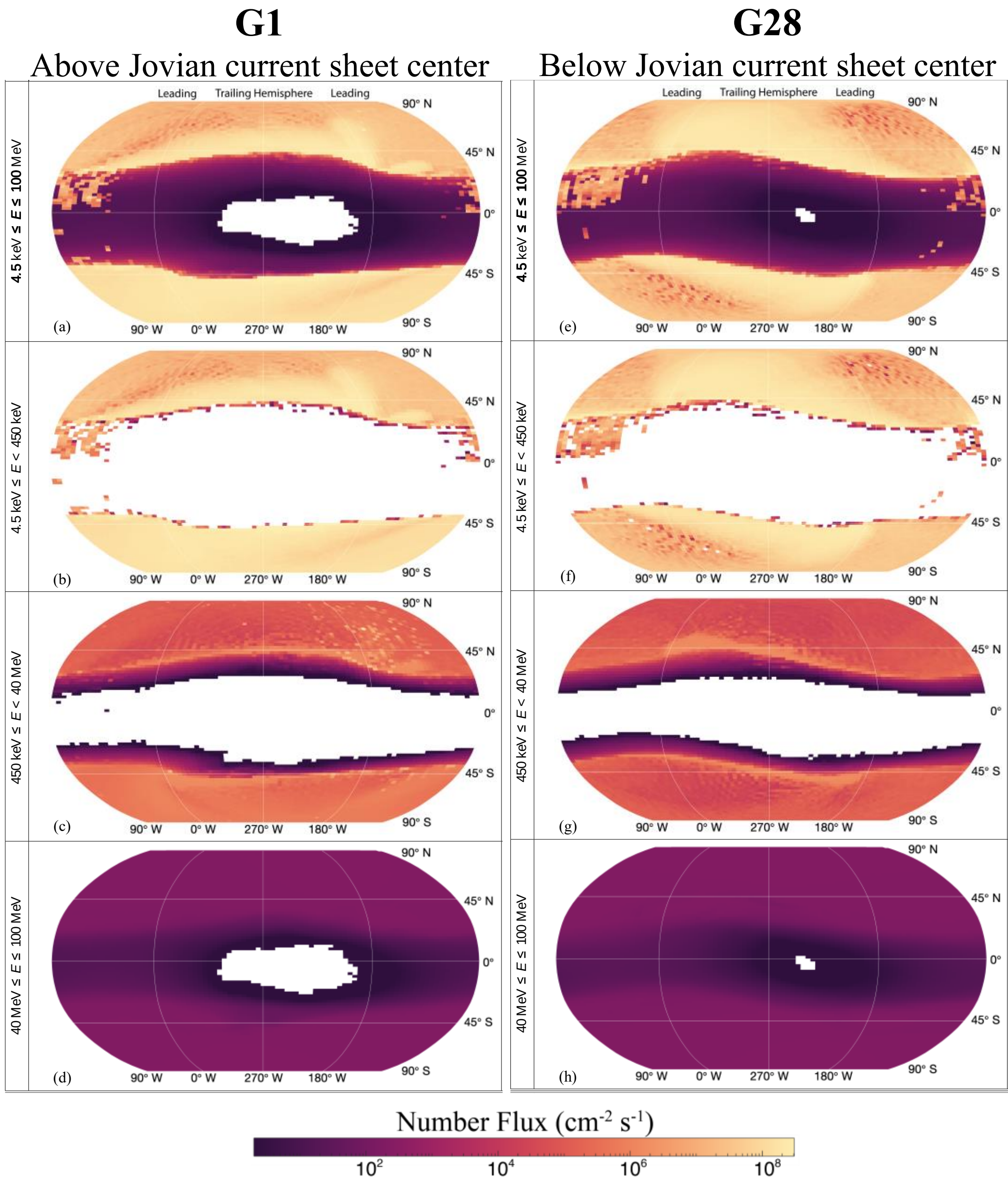

Figure 6: *Energetic electron number fluxes onto Ganymede during the Galileo (left) G1 and (right) G28 encounters (Liuzzo+ 2020).*

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- The distribution of precipitating energetic electrons onto Ganymede's surface displays a strong inhomogeneity:
  - High-latitude fluxes exceed equatorial fluxes by 5 orders of magnitude
  - The polar fluxes maximize in the orbital trailing hemisphere due to the bounce motion of electrons
  - The equator is *not* shielded from precipitating energetic electrons; fluxes are asymmetric in longitude
- Fluxes averaged over a synodic rotation agree well with surface brightness patterns
- Compared to energetic ions, electrons dominate the number and energy flux into polar latitudes, thus likely contributing to amorphization of the low-temperature ice
- Open questions include, e.g., the influence of the perturbed plasma environment on the stability of electron trajectories quasi-trapped in Ganymede's local field (10, Fig. 8)

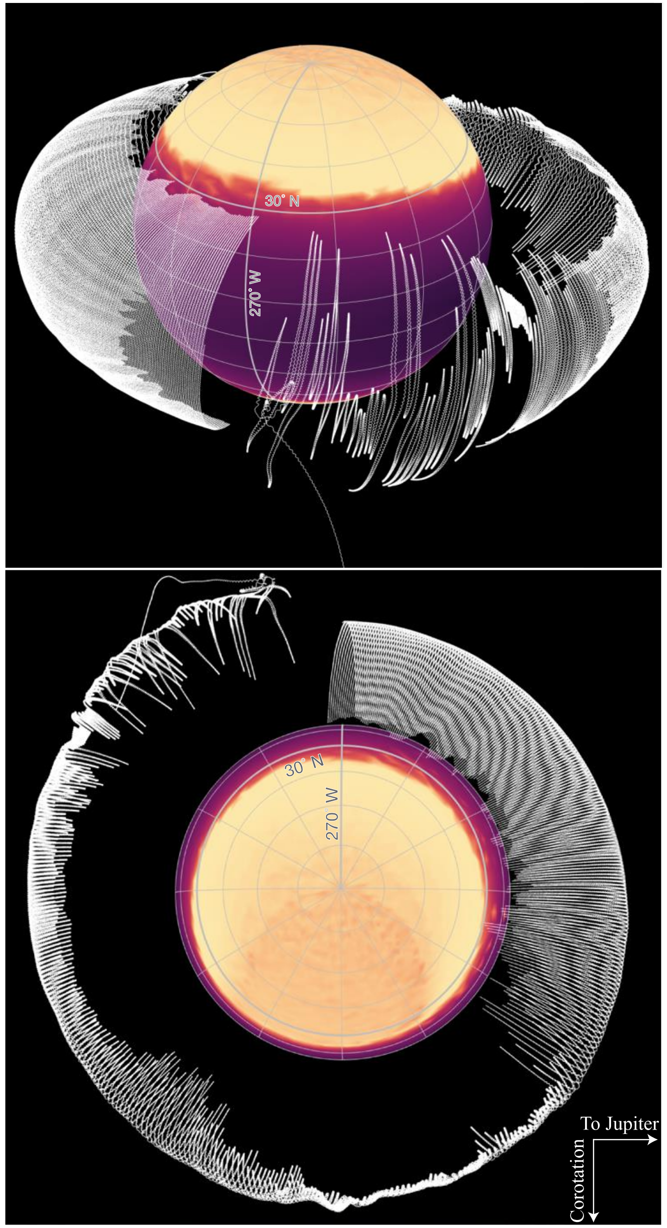

Figure 8: *Trajectory of an electron quasi-trapped in Ganymede's magnetic environment. The timescales over which such "electronic" radiation belts remain stable are unknown (Liuzzo+ 2020).*

But wait, there's more!

Our study has **even more findings** that we couldn't fit into this presentation, including:

- dynamical electron trajectories highlighting local asymmetries in Ganymede's electromagnetic environment…
- quantified effect of Ganymede's interaction with the Jovian plasma on the precipitating electron fluxes…
- surface energy fluxes…

and other exciting physical processes!

For complete details, **click here to check out our manuscript** recently published in *JGR Space Physics* (Liuzzo+ 2020)

Acknowledgements

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