Variability in the energetic electron bombardment of Ganymede

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**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.

**Discussion**

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

Figure 2: Ambient electron environment near Ganymede (Liuzzo+ 2020).
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 ($E_c \approx 2$ 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.

Discussion

G1/G28/average

Results: G8

Methods

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).
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

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

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 $E \lesssim E_c$, 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
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

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

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

• 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])

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)

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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).