Influence of Europa’s Time-Varying Electromagnetic Environment on Energetic Ion Precipitation

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Goals of this study:

- Calculate and map energetic ion flux onto Europa’s surface
- Evaluate how surface flux is influenced by electromagnetic perturbations at Europa
- Determine if any locations on Europa’s surface are consistently shielded from energetic ion flux over geologic timescales

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Europa's Electromagnetic Environment

- The inclination of Jupiter's magnetic moment against its rotational axis results in an oscillatory magnetic field at Europa (radius R_E=1560 km).
- Time variation of the horizontal magnetic field components induces currents in Europa's conducting subsurface ocean, generating a secondary dipolar field centered at the moon.
- Europa's dilute oxygen exposphere faces continual ionization from the impinging magnetospheric plasma.
- Europa orbits within the magnetospheric plasma sheet, and as such experiences strong Alfvénic plasma interactions.

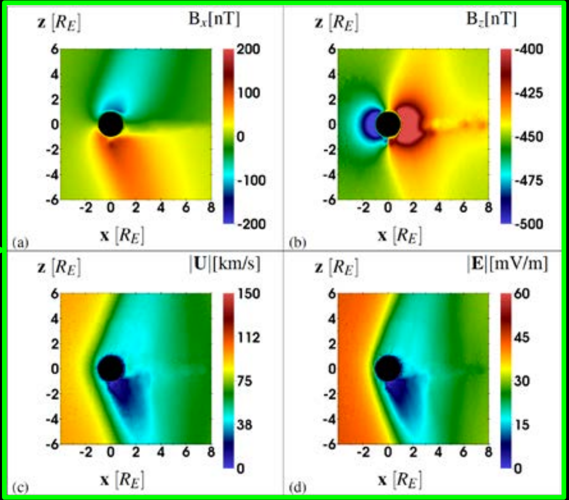


Figure 1: Perturbed electromagnetic fields near Europa, showing the effects of the plasma interaction. (Arnold et al., 2020)

- Previous studies of energetic ion flux onto Europa (e.g., Pospieszalaksa and Johnson, 1983; Cassidy et al., 2013) have treated the fields around Europa as uniform, i.e., no plasma interaction or induced dipole were included!
- A recent study by Breer et al., (2019) found that the induced dipole and plasma interaction have significant shielding effects on ion precipitation! **However, only precipitation patterns, not fluxes, were calculated!** Likewise, Huybrighs et al., 2020 showed significant influence of the non-uniform field on energetic ion trajectories!
- This is the first study to calculate energetic ion surface flux at Europa using a three-dimensional picture of the perturbed electromagnetic environment **and** in-situ measurements of ion spectra!

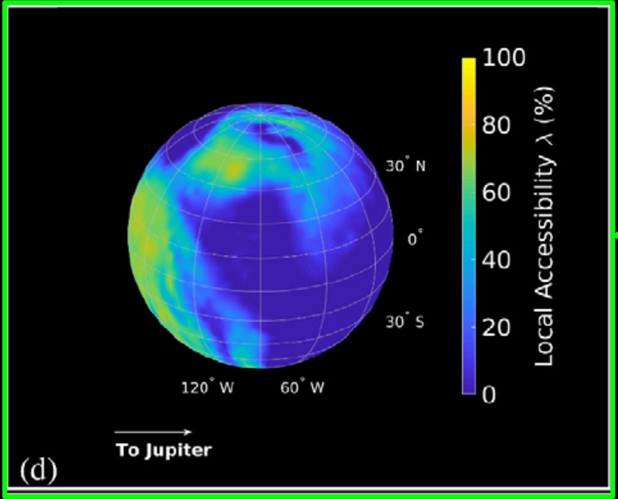


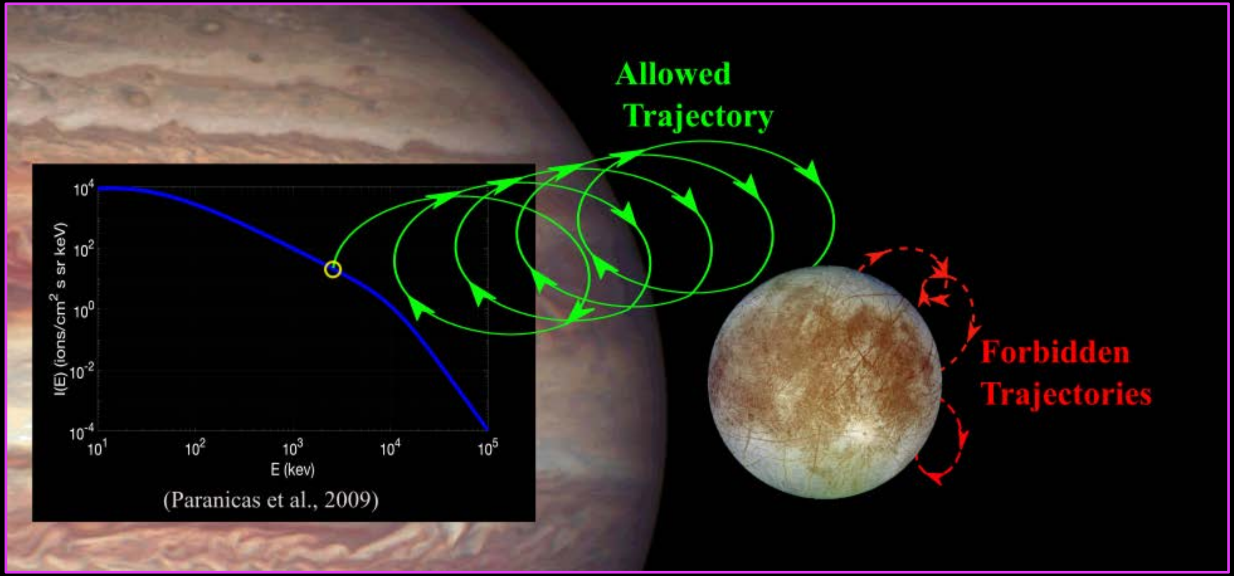
Figure 2: Accessibility of Europa's surface to 10 keV oxygen ions, as modeled by Breer et al., (2019)

Technical Approach and Methodology

Hybrid Code AIKEF

- We use the established hybrid plasma simulation code AIKEF (Müller et al., 2011) to calculate the <u>three-dimensional electromagnetic field configuration</u> around Europa.
- The hybrid approach allows <u>small-scale features</u> such as the ionospheric Hall effect to be resolved.
- AIKEF has been successfully applied previously to Europa (Breer et al., 2019; Arnold et al., 2019, 2020) as well as Callisto (Liuzzo et al., 2015, 2016, 2017, 2018, 2019a,b).

Particle-Tracing Tool GENTOo GEN-2



- To model the <u>trajectories of energetic ions</u> as they pass near/impact Europa, we use a variant of the established particle-tracing tool GENTOo (Liuzzo et al., 2019a,b), called GENTOo GEN-2.
- GENTOo has been <u>previously applied</u> to Europa (Breer et al., 2019), Callisto (Liuzzo et al., 2019a,b), and Ganymede (Liuzzo et al., 2020).
- A <u>backtracing</u> approach is used, where ions are initialized on Europa's surface and <u>traced backwards in time</u>. Ions that re-encounter Europa are deleted ("Forbidden Trajectories").
- Once a particle is escaped ("Allowed Trajectory"), the associated surface flux is calculated using <u>**ion energy spectra gathered by the Galileo *Energetic Particles Detector* (EPD)**</u>.

Results 1: Hybrid Simulations

- When Europa is in the center of the plasma sheet, it is exposed to a very dense, corotating thermal plasma population ($n \approx$ 50-200 cm^{-3}).
- At this position, the magnetic field component that points along the Jupiter-Europa line disappears, while the component along the flow direction maximizes (Kivelson et al., 1999).
  - The induced dipole moment therefore points along the flow direction of the corotating plasma.
- No study to date has modeled the electromagnetic field environment **or** surface precipitation at Europa with such a high upstream density **or** a flow-oriented dipole.

Background Field + Plasma Interaction

- Interaction of Europa's atmosphere with the impinging plasma creates significant perturbations, most notably a strong Alfvén wing.
- Pileup of magnetic field at the ramside ($x = -1\ R_E$) creates a local field enhancement, along with a local weakening of the field at the wakeside ($x > 1\ R_E$).
- Electric field is drastically reduced in the wake due to the pickup of slow exospheric ions.
- The inclusion of an x component in the background field rotates the system clockwise about the y axis by approximately $\theta = \arctan\left(\frac{B_x}{B_z}\right)$.

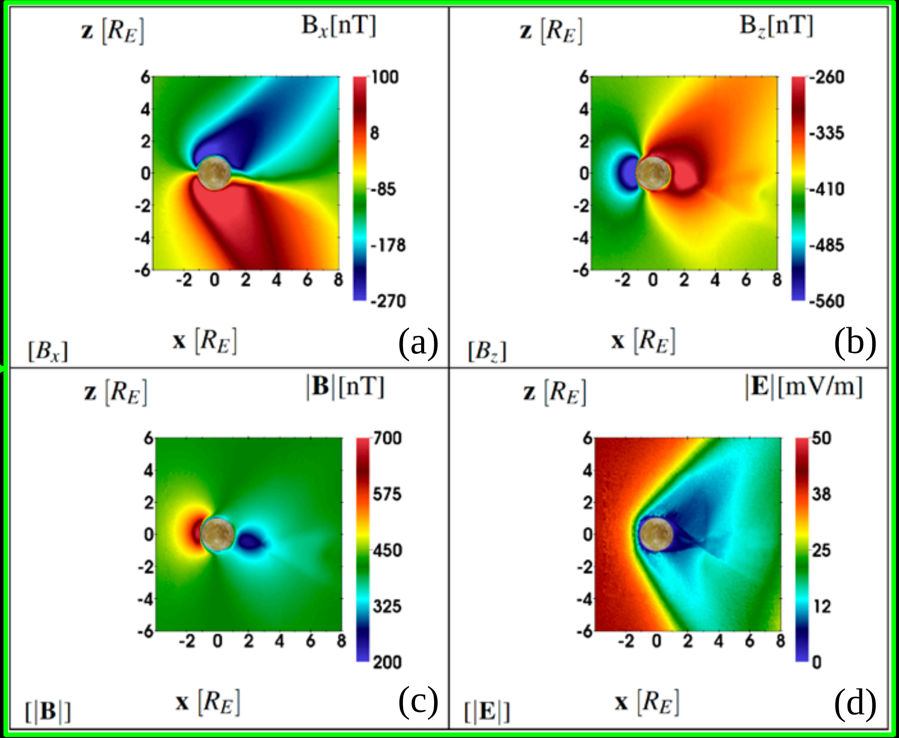
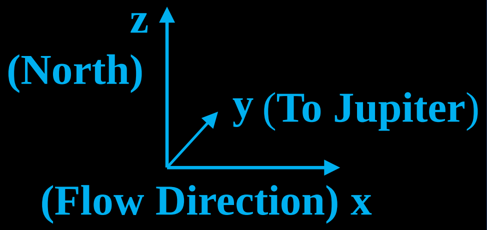


Figure 3. (a) x component, (b) z component, and (c) magnitude of the magnetic field, (d) electric field magnitude. The background field is ***B*** = (-84, 0, -410) nT, and the upstream density is $n_0 = 200\ cm^{-3}$.

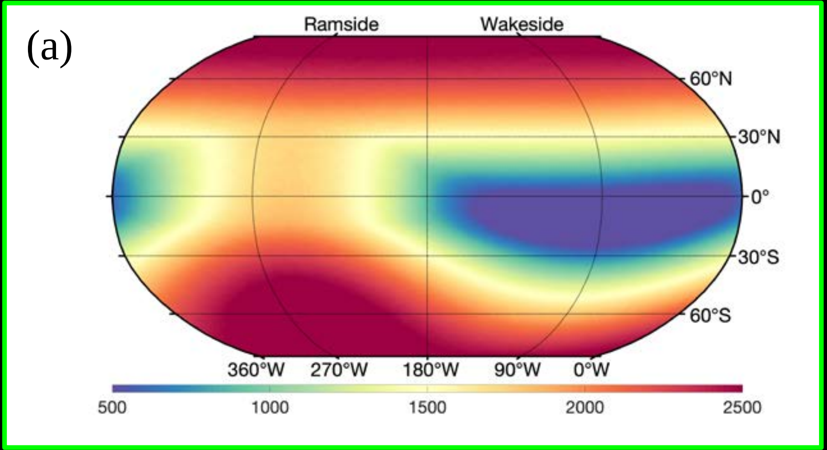


Results 2: Influence of the Thermal Plasma Interaction on Surface Precipitation

Uniform Background Field

For a 3D animation of these results, see here.

Background + Plasma Interaction



Plasma Interaction

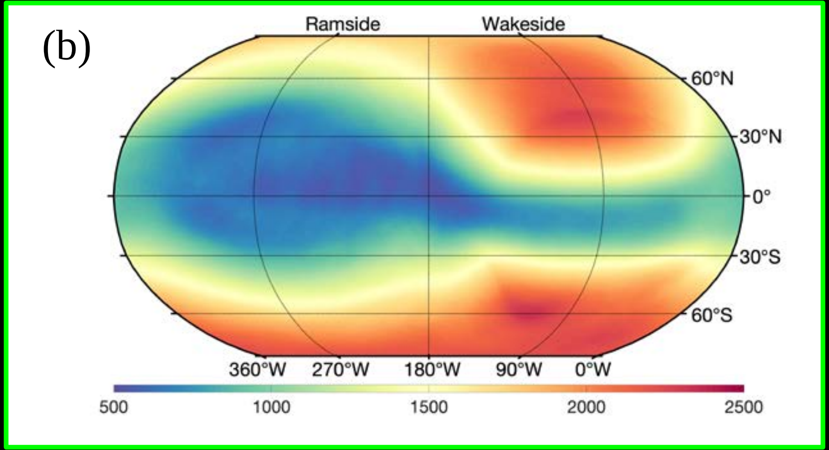


Figure 4 (above): Surface flux in [cm^{-2} sr^{-1} kev] of 100 keV S^{3+} ions for (a) uniform background field and (b) background field with the plasma interaction included, as described in Figure 3.

- Including the thermal plasma perturbations **shifts the region of highest flux from the upstream face to the downstream face!**
- Pileup of magnetic field lines at the ramside (270°W) protects the ramside hemisphere from energetic ion bombardment!
- This ramside depletion **has been seen in Galileo EPD data** (Paranicas et al., 2000; see Fig 5).
- **Including plasma perturbations is critical to understanding surface erosion at Europa!**

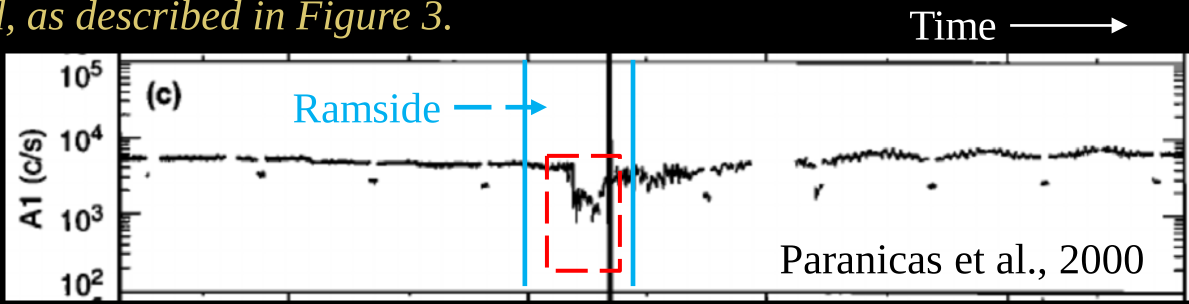
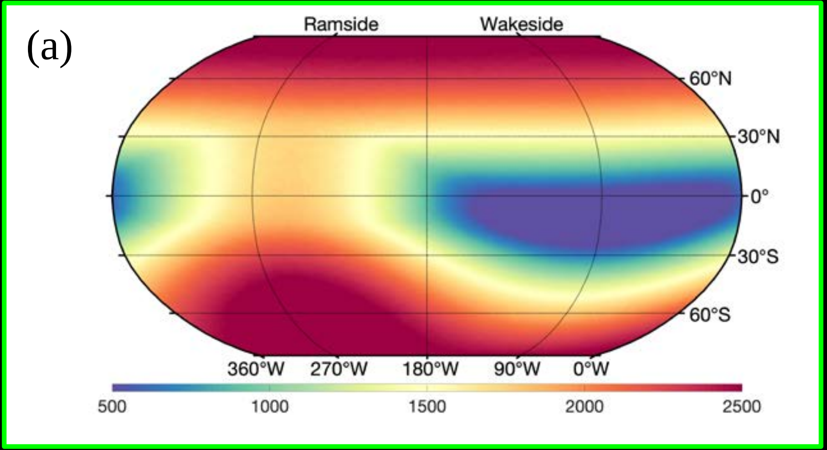


Figure 5: Time series of particle counts per second during the E12 flyby for the A1 channel of the Galileo EPD instrument, which measured ions with energies from 42-180 keV. Note the depletion in count rate (red) during the close approach to Europa's ramside (blue).

Results 3: Influence of the Induced Dipole on Surface Precipitation

Uniform Background Field



For a 3D animation of these results, see here.

Induced Dipole

Background + Dipole

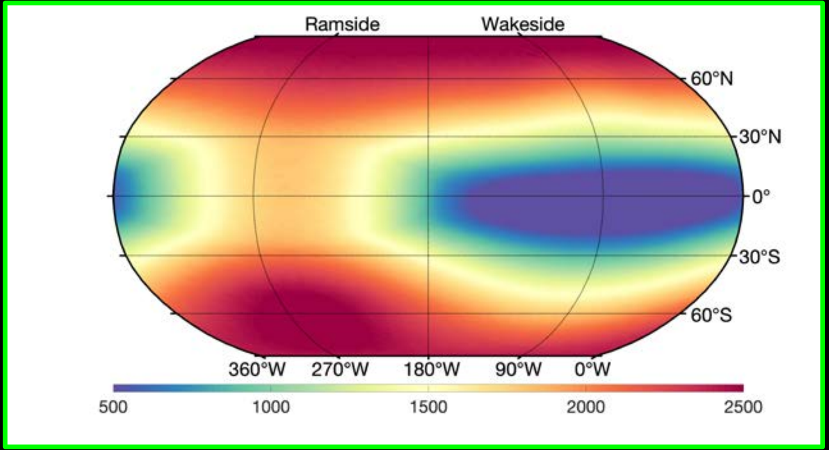


Figure 6 (above): Surface flux in [cm^{-2} sr^{-1} kev] of 100 keV S^{3+} ions for (a) uniform background field and (b) background field with the induced dipole included.

- Induced dipole provides a limited protection of the surface from energetic ion bombardment.
- Unlike the plasma perturbations, the dipole does not shift the highest flux region away from the ramside apex.
- The protection of the surface by the induced dipole is weak compared to that of the plasma interaction.

Click here for a list of studies referenced in this presentation.

Conclusions

- Perturbations from Europa's induced dipole and plasma-exosphere interaction drastically affect energetic ion surface precipitation!
- The thermal plasma interaction shields the upstream face from ion bombardment, **contrary to what is predicted by models that treat the fields at Europa as uniform**! This effect can be seen in spacecraft data!
- The influence of the induced dipole is small compared to that of the plasma interaction.