# Effects of Europa's Atmosphere on Its Magnetic and Plasma Environment: Application of Multi-Fluid MHD Simulations to Spacecraft Flybys

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## Induction at Europa

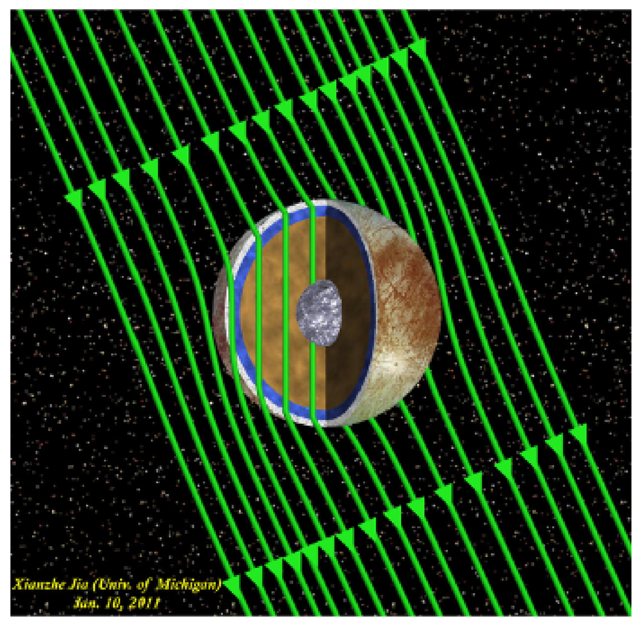



Figure 1. A diagram showing how the Jovian magnetic field is altered by Europa's conducting interior (Westlake et al., 2023).

- Europa's subsurface ocean may contain clues about the habitability of other worlds (Howell and Pappalardo, 2020).
- One of the best techniques by which we can constrain the ocean's properties is by observing the magnetic induction response of the ocean to Jupiter's time-varying magnetic field.
- However, the interaction of Europa's thin oxygen atmosphere with the plasma in the surrounding environment can obscure this signal.

## Atmospheric Asymmetry

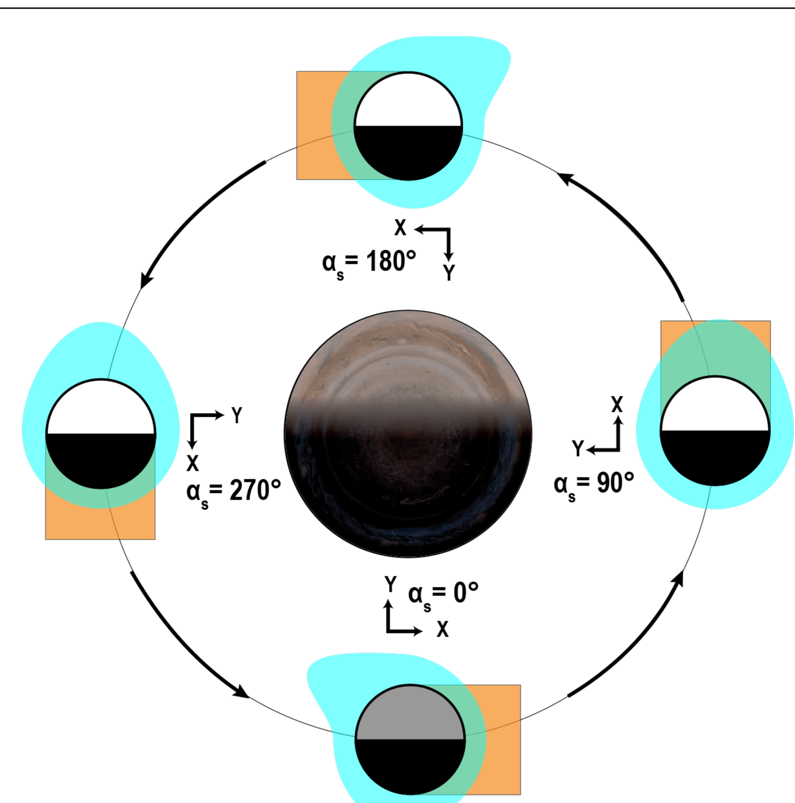



Figure 2. Representation of Europa's asymmetric plasma-atmosphere interaction as a function of orbital phase. The blue is an idealized atmosphere, and the orange represents the plasma wake.

- The moon-plasma interaction results in the generation of an Alfvèn wing and a wake behind the moon, as flux tubes and field lines are diverted and distorted by Europa's presence (Neubauer, 1998).
- The processes which produce Europa's atmosphere are highly variable in time and in space. Two major asymmetries result from:
  - The variance of the density and inclination of Jupiter's plasma sheet with respect to Europa [~ 11 hrs] (Bagenal et al., 2015)
  - The changing geometry of the sunlit hemisphere relative to the hemisphere receiving preferential plasma bombardment, along with the moon's rotation [~ 80 hrs] (Plainaki et al., 2012; Oza et al., 2019)
- The overall complexity of this interaction necessitates the use of high-fidelity numerical models to accurately simulate it.

## BATS-R-US for Europa

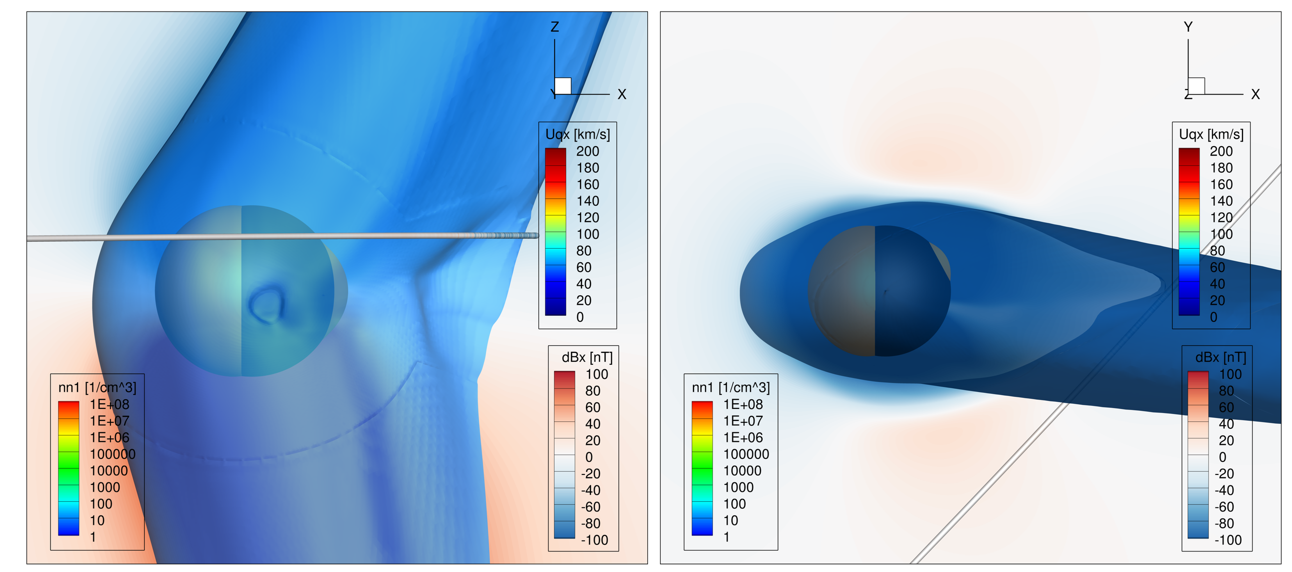
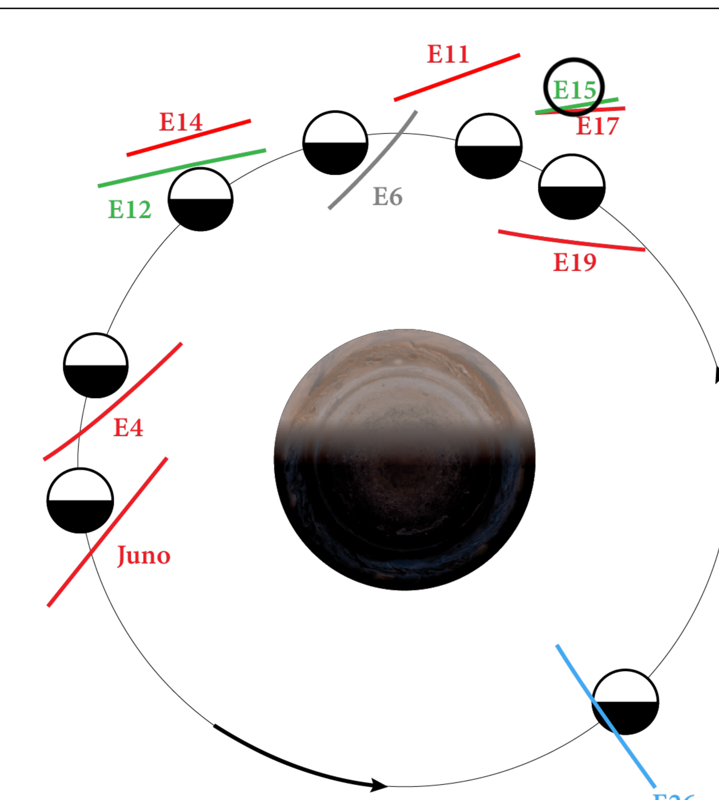


Figure 3. BATS-R-US simulation output for the E15 flyby. Left: A cut in the xz plane. Right: a cut looking down on the plane of that flyby.

- To model the interaction at Europa, we use the Space Weather Modeling Framework's BATS-R-US model to solve the MHD equations for 3 ion fluids:
  - One $O^+$ fluid with a charge state of +1.5, which represents the magnetospheric plasma flowing by Europa
  - Two fluids primarily produced by the plasma-atmosphere interaction: $O_2^+$ and $O^+$
- To achieve the most accurate results, we incorporate the Hall effect into the Ohm's Law calculation, as well as self-consistent electron temperature evolution and a resistive interior profile.

## Observations of Europa




| Quantity | E15 |
|---|---|
| Magnetic Latitude | -0.5° |
| Jovian Magnetic Field (nT) | (-65,32,-380) |
| Induced Dipole Field (nT) | (33,-18,0) |
| Jovian Local Time | 10.1 |
| Closest Approach Altitude (km) | 2519 |
| $Z_{EPO}$ ($R_E$) | 0.67 |

Figure 4. Left: A diagram showing the locations of all close spacecraft flybys of Europa. Right: Characteristics of the E15 flyby.

Our model's initial conditions are informed by data gathered from Galileo orbiter flybys and Hubble Space Telescope campaigns. In this study, we use the E15 Galileo close flyby, and use estimates from Hubble to bound the scale and density of our atmosphere.

## Study Objectives

1. What is the effect that different forms of atmospheric asymmetry have on the form of the plasma interaction?
2. How do those effects change under different upstream plasma conditions?
3. To what extent does accounting for atmospheric asymmetries improve data-model agreement in modeling Europa flybys?

## Results: Upstream Variance

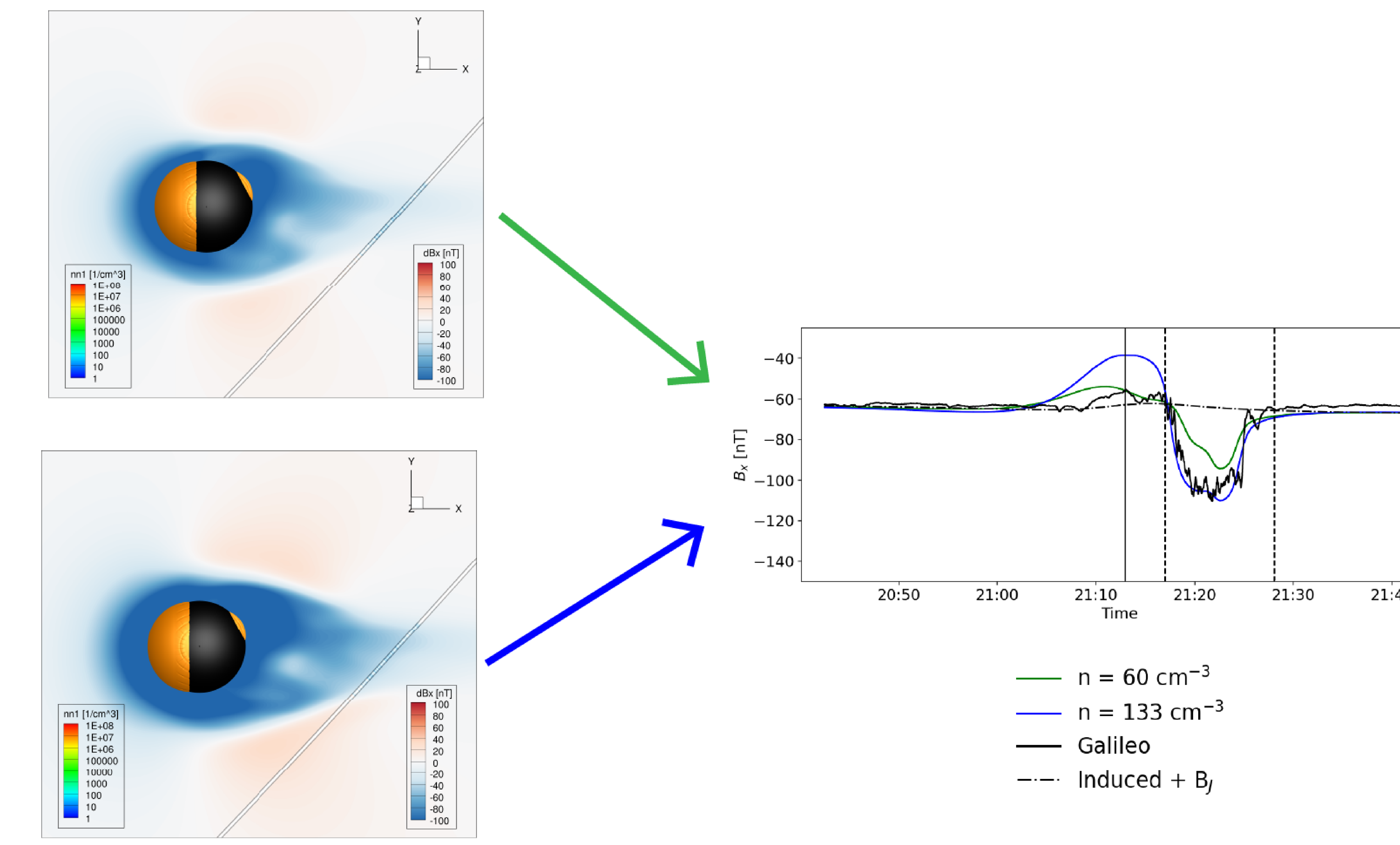



Figure 5. Diagram showing three simulations with different upstream plasma densities. The left panels are shaded by $\delta B_x$ and are in the plane of the E15 flyby. The right shows the actual $B_x$ as seen by Galileo, with the simulations along the spacecraft trajectory plotted for comparison.

## Results: Atmosphere Variance

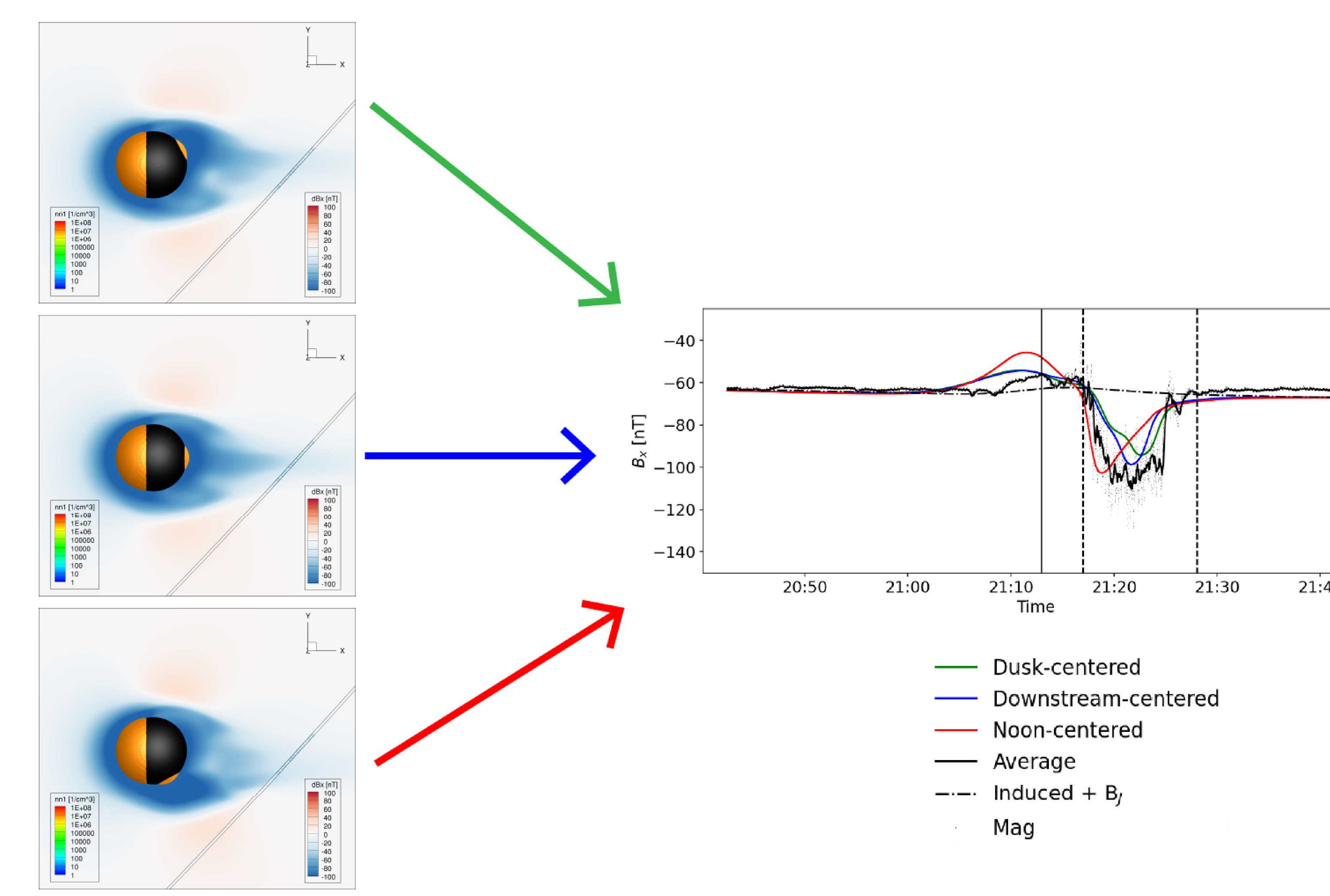



Figure 6. Diagram showing three simulations with different atmospheric profiles. The left panels are shaded by $\delta B_x$ and are in the plane of the E15 flyby. The right shows the actual $B_x$ as seen by Galileo, with the simulations along the spacecraft trajectory plotted for comparison.

## References

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