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# Geophysical Research Letters<sup>®</sup>



## RESEARCH LETTER

## Electron Beams at Europa

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F. Allegrini<sup>1,2</sup> , J. Saur<sup>3</sup> , J. R. Szalay<sup>4</sup> , R. W. Ebert<sup>1,2</sup> , W. S. Kurth<sup>5</sup> , S. Cervantes<sup>3</sup> ,  
H. T. Smith<sup>6</sup> , F. Bagenal<sup>7</sup> , S. J. Bolton<sup>1</sup> , G. Clark<sup>6</sup> , J. E. P. Connerney<sup>8,9</sup> , P. Louarn<sup>10</sup> ,  
B. Mauk<sup>6</sup> , D. J. McComas<sup>4</sup> , A. Pontoni<sup>1</sup> , Y. Sarkango<sup>4</sup> , P. Valek<sup>1</sup> , and R. J. Wilson<sup>7</sup> 

### Key Points:

- Powerful electron beams that significantly shape Europa's space environment are discovered during a Juno flyby
- The beams enhance electron-impact-excited emissions in Europa's atmosphere and are associated with large jumps of the magnetic fields
- The beams' proximity to Europa and their pitch angle distribution constrain the source acceleration to be near or within the plasma disk

### Supporting Information:

Supporting Information may be found in the online version of this article.

### Correspondence to:

F. Allegrini,  
fallegrini@swri.edu

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<sup>1</sup>Southwest Research Institute, San Antonio, TX, USA, <sup>2</sup>Department of Physics and Astronomy, University of Texas at San Antonio, San Antonio, TX, USA, <sup>3</sup>Institute of Geophysics and Meteorology, University of Cologne, Cologne, Germany, <sup>4</sup>Department of Astrophysical Sciences, Princeton University, Princeton, NJ, USA, <sup>5</sup>Department of Physics and Astronomy, University of Iowa, Iowa City, IA, USA, <sup>6</sup>The Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA, <sup>7</sup>Laboratory for Atmospheric and Space Physics, University of Colorado Boulder, Boulder, CO, USA, <sup>8</sup>Space Research Corporation, Annapolis, MD, USA, <sup>9</sup>NASA Goddard Space Flight Center, Greenbelt, MD, USA, <sup>10</sup>Institut de Recherche en Astrophysique et Planétologie (IRAP), Toulouse, France

**Abstract** Jupiter's moon Europa contains a subsurface ocean whose presence is inferred from magnetic field measurements, the interpretation of which depends on knowledge of Europa's local plasma environment. A recent Juno spacecraft flyby returned new observations of plasma electrons with unprecedented resolution. Specifically, powerful magnetic field-aligned electron beams were discovered near Europa. These beams, with energies from ~30 to ~300 eV, locally enhance electron-impact-excited emissions and ionization in Europa's atmosphere by more than a factor three over the local space environment, and are associated with large jumps of the magnetic fields. The beams therefore play an essential role in shaping Europa's plasma and magnetic field environment and thus need to be accounted for electromagnetic sounding of Europa's ocean and plume detection by future missions such as JUICE and Europa Clipper.

**Plain Language Summary** A recent Juno spacecraft close flyby of Jupiter's moon Europa revealed the presence of powerful electrons beams. Based on previous observations and modeling of electron beams at the moon Io, such beams were not expected to be observed so close to Europa. Overall, the proximity of the beams to Europa indicates that the acceleration of these electrons takes place much closer to Europa than anticipated and that these beams, therefore, stem from a new and previously unknown acceleration mechanism. The beams are predicted to have an outsized influence on the ionization of the constituents of Europa's tenuous atmosphere and are accompanied with large magnetic field perturbations. Hence, these electron beams are an important ionization source that modify the moon's ionosphere, the electric current systems, and the magnetic field environment. In particular, the presence of electron beams will affect plasma conditions that are used to infer the extent of a subsurface ocean via the magnetic induction signal. These beams significantly impact the space plasma environment around Europa which needs to be accounted for by future missions such as ESA's (European Space Agency) JUICE (Jupiter Icy Moons Explorer) and NASA's (National Aeronautics and Space Administration) Europa Clipper mission.

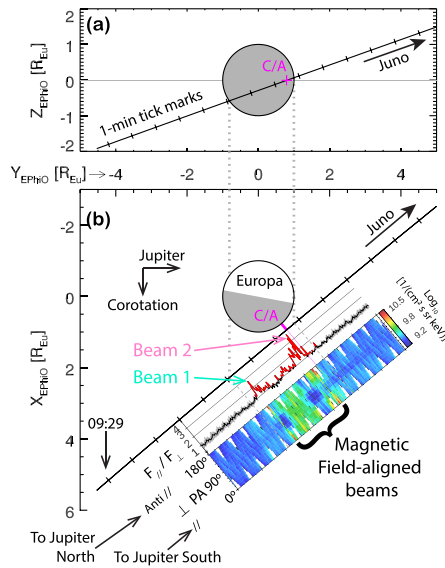
## 1. Introduction

Electron beams related to the interaction of a moon with its magnetized plasma were detected near Jupiter's satellite Io in Galileo spacecraft measurements (Frank & Paterson, 1999; Williams et al., 1996). These electron beams, observed in the downstream hemisphere and over the poles of Io, are likely a consequence of the coupling between the space environment around the moon and its electromagnetic connection to the planet's atmosphere. The electrons are accelerated within Io's Alfvén wings close to Jupiter (Szalay et al., 2018); some travel back toward Io and the rest manifest as auroral emissions associated with the moon's magnetic footprint (Clarke et al., 2002; Connerney et al., 1993). The beams near Io are an essential source of ionization, which can explain why a moon's plasma wake, such as Io's, is not empty and thus alters the moon's magnetic field environment (Dols et al., 2008; Saur et al., 2002).

The downstream location of electron beams is governed by timescales associated with the time for the plasma to convect past the moon relative to the one-way Alfvén travel time along the moon's Alfvén wings (Jacobsen et al., 2010). If the convection time is large compared to the Alfvén travel time, as is the case at Io, then the beams are observed close to the moon. But if the convection time is relatively shorter, then the beams are observed far

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**Figure 1.** Flyby geometry and location of electron beams. Panels (a, b) show two projections of Juno's trajectory on 29 September 2022 (Day of Year 272) in the Europa-Phi-Omega reference frame where the  $x$ -axis points toward Jupiter's co-rotation direction (and plasma disk flow), the  $z$ -axis is parallel to Jupiter's spin axis, and the  $y$ -axis (approximately toward Jupiter) completes the right-handed system. Closest approach (C/A) is at  $1.23 R_{Eu}$  (where  $R_{Eu}$  is Europa's average radius of 1560.8 km) at UTC 09:36:29. Magnetic field-aligned electron beams are observed where the intensity (see the pitch angle (PA) spectrogram and Figure 2c) is higher along the magnetic field direction ( $F_{\parallel}$ , which includes the parallel and anti-parallel flux) compared with the perpendicular direction ( $F_{\perp}$ ). This is illustrated with the red part of the curve where  $F_{\parallel}/F_{\perp} - 5\sigma_{(F_{\parallel}/F_{\perp})} > 1$ . We highlight two of the strongest beams (Beam 1 and Beam 2) that bound the region where most of the beams are observed, which is within the geometric wake (gray dashed lines).

downstream. Europa's convection time is expected to be about a factor of five smaller compared to that of Io (e.g., Saur et al., 1998), therefore it was expected that electron beams, if present, should be shifted further downstream compared to Io. The Galileo spacecraft had several Europa flybys about 20 years ago—one similar (at 586 km) to this Juno pass - but no low energy ( $\sim$ keV) electron data is available from those flybys and no electron beams were reported in the higher energies ( $\geq 15$  keV, which is the Galileo Energetic Particles Detector (EPD) lower energy threshold (Williams et al., 1992).

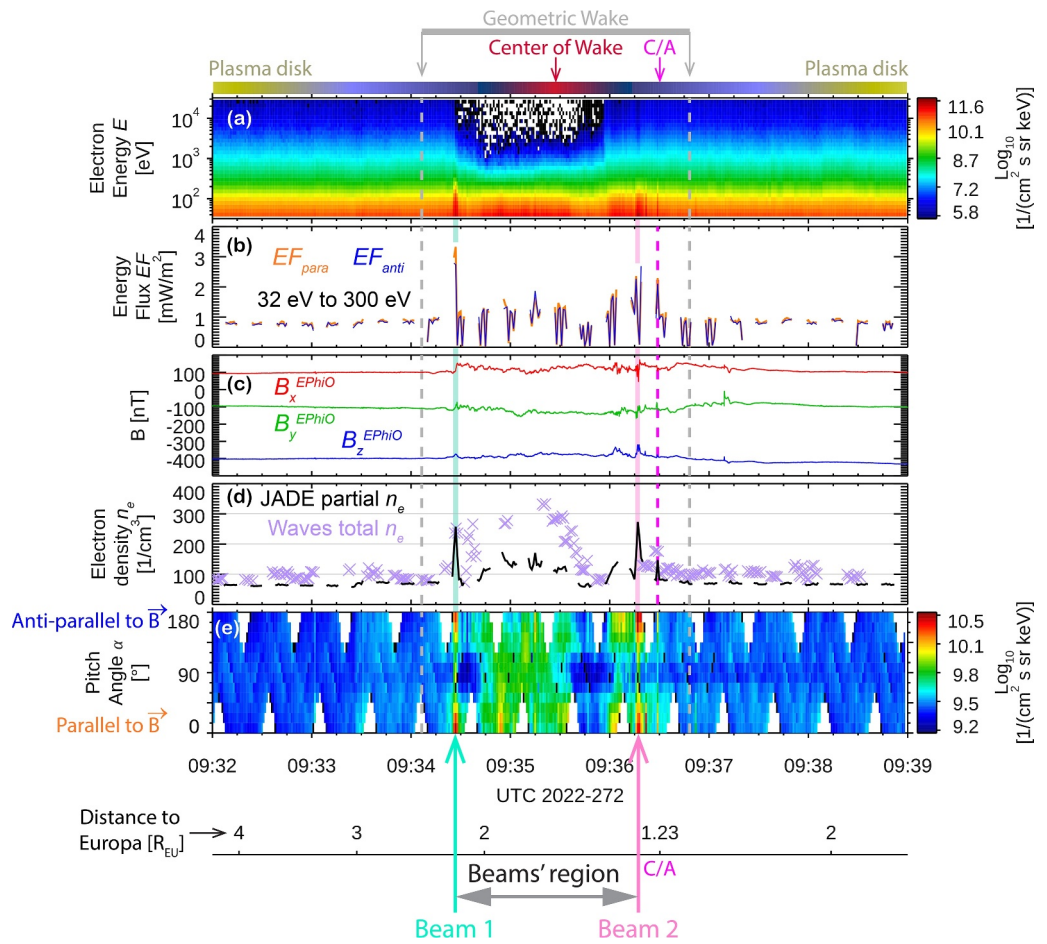
In this letter we present new plasma electron observations from the Juno spacecraft close flyby of Europa. Specifically, these observations reveal bi-directional, magnetic-field-aligned electron beams from a new source.

## 2. Observations of Electron Beams

On 29 September 2022, electron measurements taken with the Jovian Auroral Distributions Experiment (JADE) (McComas et al., 2017) on NASA's Juno mission (Bolton et al., 2017) revealed the presence of magnetically field-aligned electron beams ( $\sim 30$ – $300$  eV) near Europa. The flyby geometry is illustrated in Figure 1. The two inserts plotted along Juno's trajectory show: (a) a metric of how field-aligned the electron distributions are ( $=$  ratio of electron flux parallel to the local magnetic field lines compared to the flux perpendicular to the local magnetic field lines  $= F_{\parallel}/F_{\perp}$ ) and (b) the electron pitch angle spectrogram. The pitch angle is calculated using the magnetic field vector measured by the MAG experiment (Connerney et al., 2017).  $F_{\parallel}$  comprises fluxes within  $45^{\circ}$  of the field-aligned direction and  $F_{\perp}$  the fluxes within  $45^{\circ}$  of the perpendicular direction. Field-aligned electron beams are observed within a region that is slightly smaller than Europa's geometric wake (indicated with dashed gray lines) where the following condition is met  $F_{\parallel}/F_{\perp} > 1 + 5\sigma_{(F_{\parallel}/F_{\perp})}$  (red curve),  $\sigma_{(F_{\parallel}/F_{\perp})}$  being the uncertainty of the ratio from propagated Poisson statistics of counts measured by JADE, a component due to data compression, and a component from background subtraction. If the

ratio  $F_{\parallel}/F_{\perp}$  is at least five times its standard deviation above one, then the distribution is considered field aligned. This condition occurs over nearly the entire region and is referred to as "beams' region" flanked by the two strongest beams highlighted as Beam 1 and Beam 2. Electrostatic solitary waves ( $< 20$  kHz and lower than the upper hybrid band), which are indicative of electron beams, are also observed in the region (Kurth et al., 2023).

Figure 2 shows a timeline of the electron observations and the magnetic field. Panels (a) and (e) show the electron energy and pitch angle spectrograms, respectively. The region of the bi-directional beams, that is, beams parallel and anti-parallel to the direction of the magnetic field (pitch angle near  $0^{\circ}$  and  $180^{\circ}$ ), is delimited by Beam 1 and Beam 2, except for a less intense beam at closest approach (magenta dashed line at UTC 09:36:29). Panel (b) shows the electron partial energy fluxes in the direction parallel (in orange) and anti-parallel (in blue) to the magnetic field. This result only includes electrons with energies that are in the energy range of the JADE instrument and not the entire electron distribution (although the pitch angle coverage is complete). The partial energy flux (EF) is calculated for electron energies between 32 and 300 eV, that is, where the beams are most prominent with respect to ambient electrons (see calculation details in Supporting Information S1). The EF in Beam 1 is a factor of up to 3.3 higher than in Europa's plasma environment prior to and post flyby (average of  $\sim 0.8$  mW/m $^2$ ). There is a slight asymmetry between the parallel and antiparallel fluxes at Beam 1 (Beam 2), where the parallel energy flux is a factor of  $\sim 1.18$  higher ( $\sim 1.13$  lower) than the antiparallel energy flux. In other words, the energy flux for electrons traveling from north to south at Beam 1 (and south to north at Beam 2) is  $\sim 1.18$  higher than that for electrons traveling in the opposite direction. Such asymmetries cause net electric currents and contribute to the currents structuring the magnetic field. The sign of the electric current of Beam 1 derived from the magnetic field (Figure 2c) is not consistent with larger parallel fluxes for Beam 1 suggesting the missing current is carried by electrons below 30 eV. Overall, the possible role of the beams in carrying electric



**Figure 2.** Electron beams spectrograms and derived energy flux and densities as a function of time and distance from Europa. (a) Electron intensity spectrogram, (b) electron partial energy flux in the range from 32 to 300 eV, (c) magnetic field components in the EPhiO reference frame (see Figure 1), (d) electron partial density (black) from JADE and total density (violet) from Waves (Kurth et al., 2023), and (e) electron pitch angle spectrogram. Beams 1 and 2 have more than 3.3 times the energy flux and 2.6 times the density than the electrons in the surrounding plasma environment.

current and whether the associated current contributes to closure of currents within Europa's atmosphere/ionosphere or the role in current continuation within the Alfvén wings are issues that deserve further attention but are beyond the scope of this observational report.

Perturbations in the magnetic field components (Figure 2c) are observed throughout the beams' region, suggesting that the electron beams are contributing to those perturbations. Two of the largest perturbations are observed with Beam 1 and Beam 2. Coincident with Beam 1, a jump in the  $B_x$  component of  $\sim 50$  nT occurs (Figure 2c). The increase stretches over approximately 1 second when Juno is traveling in the  $y$ -direction (corresponding to a width of  $\sim 20$  km). From Ampere's law, this jump represents a current density of  $\sim 2 \cdot 10^{-6}$  A/m<sup>2</sup> assuming that the current density is uniformly distributed in a sheet along magnetic flux tubes advecting with the flow; larger current densities would be required if the current was not uniform. Such large current densities are about a factor of 10 larger than field aligned currents predicted from modeling of Europa's interaction (Blöcker et al., 2016; Saur et al., 1998). An imbalance between the observed northward and southward going electron beams at Beam 1 in the JADE data (Figure 2b) corresponds to a net electric current as high as  $\sim 5 \cdot 10^{-6}$  A/m<sup>2</sup>. This implies that the observed electron beams might contribute to the electric current system connecting Europa's ionospheric currents to its Alfvén wing system. As pointed earlier, an unmeasured amount of current might still be carried by electrons below 30 eV, which are not resolved by the JADE instrument, and thus these observations represent a lower bound. The magnetic field measurements obtained during the Juno flyby have been modeled with a hybrid model by Addison et al. (2024). That study ascribed the primary drivers of the observed magnetic field structure to an

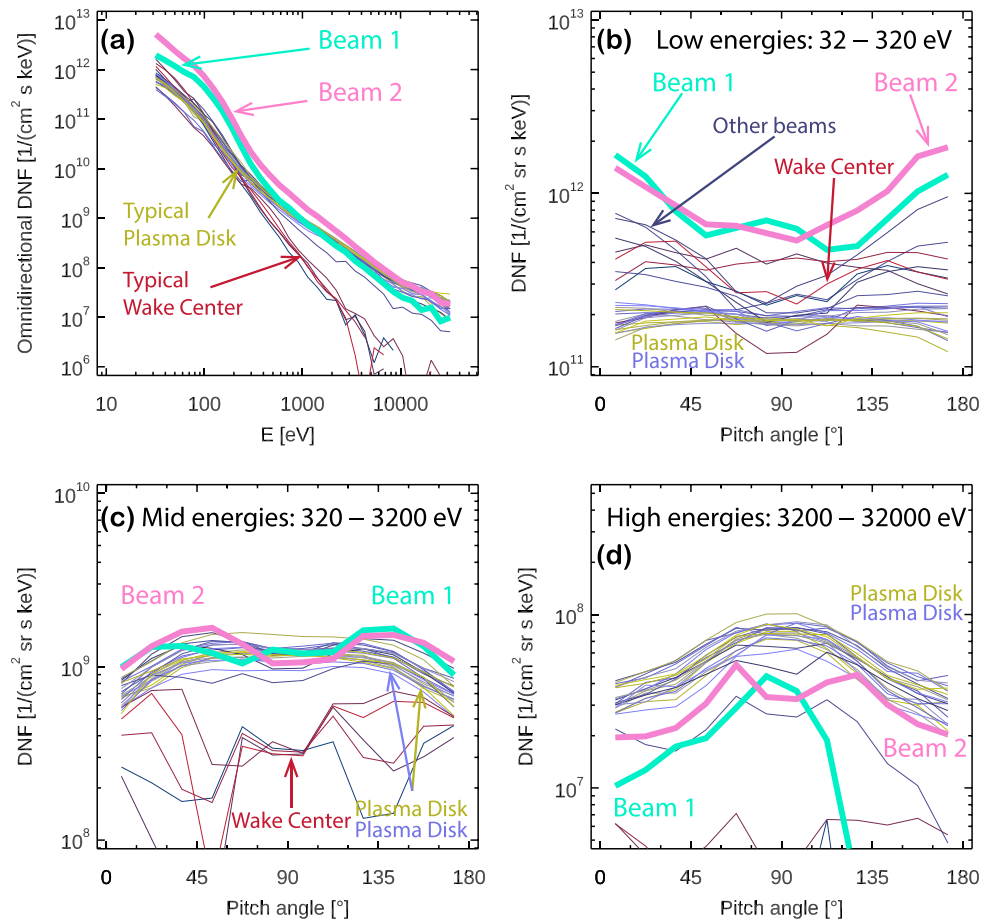
asymmetry in Europa's atmosphere (by more than five orders of magnitude) and deviation of the magnetospheric upstream plasma flow from the corotational direction.

The electron density in the beams' region is higher than in Europa's plasma disk environment, implying that the potential for ionization of the beams in Europa's atmosphere is stronger than that from the electron distributions in the nearby environment (e.g., before ~09:33). Figure 2d shows the electron partial density from JADE (in black) and the total electron density (in violet) derived by the Waves investigations (Kurth et al., 2017, 2023). Details of the calculation of the partial electron density with JADE are given in Allegrini et al. (2021) and in Supporting Information S1. The electron distributions prior to and after the flyby (i.e., ~09:32 and ~09:38) are representative of Europa's plasma disk environment with total electron densities of  $\sim 92 \text{ cm}^{-3}$  and  $\sim 104 \text{ cm}^{-3}$ , respectively. There is a clear change in the beams' region where the peak partial electron densities are  $\sim 258 \text{ cm}^{-3}$  (Beam 1) and  $\sim 274 \text{ cm}^{-3}$  (Beam 2), which are more than 2.6 times the ambient electron densities in the nearby space environment of Europa at the time of the flyby. The JADE's partial electron density agrees with Waves's total electron density at Beam 1 ( $\sim 236 \text{ cm}^{-3}$ ) but is higher by a factor of  $\sim 2$  at Beam 2 ( $\sim 130 \text{ cm}^{-3}$ ). Kurth et al. (2023) caution that the upper hybrid emissions used to derive the Wave's electron density appear sporadically during the flyby, possibly due to variations in the electron distributions and polarization that may make them less visible depending on the spin phase of the electric antenna. That could explain the difference in Beam 2.

The electron beams are energetically important as a source for Europa's ionosphere because electron impact is the dominant ionization mechanism for creating Europa's ionosphere (Hall et al., 1995; Roth et al., 2014) and the observed beam energies where the ionization cross sections are most efficient ( $\sim 25\text{--}300 \text{ eV}$  for  $\text{H}_2$ ,  $\sim 35\text{--}650 \text{ eV}$  for  $\text{O}_2$ , e.g., Straub et al., 1996). In Figure 3a we show the total differential number flux (DNF or intensity; calculation shown in Supporting Information S1) as a function of energy. The color coding of the different curves corresponds to the horizontal color bar on top Figure 2a, where yellow and light blue are in the plasma disk (Europa's environment at the time of the flyby), while dark blue and red are close to the center of Europa's geometrical wake ( $\sim$ beams' region). The two bi-directional beams are in turquoise (Beam 1) and pink (Beam 2) as in Figures 1 and 2. Beams 1 and 2 spectra have intensities about a factor of three to eight higher than the plasma disk from  $\sim 30$  to  $270 \text{ eV}$ . Hence, compared to the electrons in Europa's plasma disk environment, the electron beams will ionize three to eight times more atoms and molecules in Europa's atmosphere. The other beams (dark blue and red colors) are also enhanced at low energies but reduce below plasma disk intensities above  $\sim 300 \text{ eV}$ . These beams are energetically different than the beams at Io that were observed at higher energies from  $\sim 100 \text{ eV}$  to  $\sim 30 \text{ keV}$  (Frank & Paterson, 1999; Williams et al., 1996). They are also energetically different from the electron beams (that peak around  $2\text{--}3 \text{ keV}$ ) that cause the Europa footprint aurora in Jupiter's atmosphere (Allegrini, Gladstone, et al., 2020; Rabia et al., 2023).

The beams are observed along the Juno trajectory in a spatial region within the two strongest beams 1 and 2. We however expect the beams to be also present upstream and downstream of the Juno trajectory. The electron beams are ducted along the magnetic field. Thus, the electrons are advected downstream along with the rotating magnetic field of Jupiter. This results in "sheets of beamed electrons." A schematic visualization of the sheets associated with the two strongest beams is presented in Figure 4. The extent of these sheets is unconstrained from these observations until the source and acceleration mechanism is better understood. Future flybys, for example, on the upstream side of the trajectory, are required for further characterization. The magnetic field measurements (Figure 2c) support the idea of sheets of beamed electrons. A localized wire-like beam carrying an electric current would not lead to large discontinuities in the  $X_{\text{EPhIO}}$  component of the magnetic field, but rather to magnetic field perturbations falling off with the inverse of the distance from the beam.

We use the pitch angle distribution to constrain the likely origin of the beams. Figures 3b–3d show the intensity as a function of pitch angle for the low- ( $\sim 32\text{--}320 \text{ eV}$ ), mid- ( $\sim 320\text{--}3,200 \text{ eV}$ ), and high-energies ( $\sim 3,200\text{--}32,000 \text{ eV}$ ). At energies below  $320 \text{ eV}$  (Figure 3b), the intensity in the pitch angle bin closest to the field-aligned direction ( $0\text{--}15^\circ$  and  $165^\circ\text{--}180^\circ$ ) compared to that perpendicular to the field ( $75^\circ\text{--}105^\circ$ ) is a factor of  $\sim 2.2$  (Beam 1) and  $\sim 4.4$  (Beam 2) higher. The beams' distributions appear up to about  $50^\circ$  away from the field aligned direction. If we approximate the magnetic field using JRM33 (Connerney et al., 2022) with a plasma disk model (Connerney et al., 2020) and use the conservation of the first adiabatic invariant, then the electrons with a pitch angle of  $50^\circ$  at Europa will have a pitch angle of  $90^\circ$  at the mirroring point at about  $2.3 R_J$  from the magnetic equator (where  $1 R_J = 71,492 \text{ km}$  is the equatorial radius of Jupiter). The mirroring point distance along the field line is  $1.9 R_J = 87 R_{\text{Eu}}$  from Europa in the north and  $3.6 R_J = 165 R_{\text{Eu}}$  in the south. This estimate is inconsistent



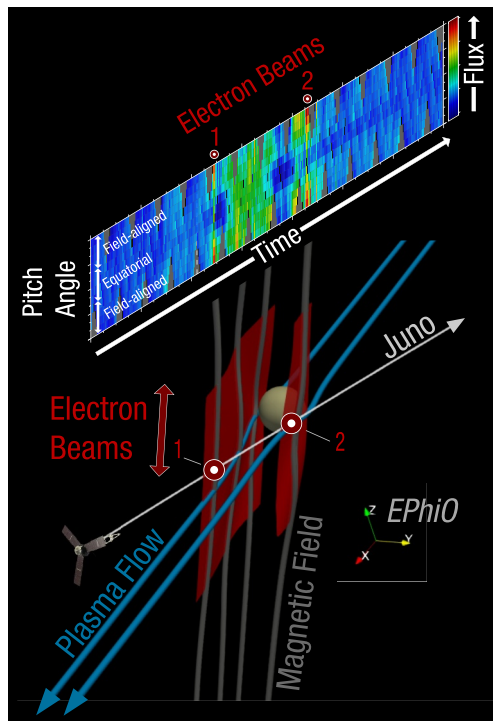
**Figure 3.** The field aligned electron beams have higher intensities than Jupiter's plasma disk in the near vicinity of Europa and the angular width of the beams is about  $50^\circ$ . (a) 15-s averages of the omni-directional differential number flux (or intensity). The color coding of the spectra is according to the distance from the center of the geometrical wake (scale on top of Figure 2a). Dark red and dark blue are roughly within the geometrical wake and light blue and yellow are outside the geometrical wake. (b–d) electron pitch angle distributions for low (32–320 eV), medium (320–3,200 eV), and high (3,200–32,000 eV) energy electrons. The two strong electron beams have intensities three to eight times higher than the electrons in the nearby environment of Europa for energies up to  $\sim 300$  eV.

with an origin close to Jupiter and thus makes the electron beams detected near Europa distinct from the electron beams observed near Io, which originate close to Jupiter. The plasma disk scale height at the orbit of Europa are likely time and local time dependent, but estimates range from  $H = 0.9 R_J$  (Roth et al., 2014) to  $1.7 R_J$  (Bagenal & Delamere, 2011). Therefore, the acceleration of these beams could take place within or near the plasma disk.

### 3. Discussion and Conclusion

Figures 2a and 3a show that  $>300$  eV electrons are suppressed (by a factor of up to  $\sim 10$  at 30 keV) in the beams' region, while lower energy electrons (excluding the strong beams) are still at comparable intensities to the plasma disk region. In Jupiter's magnetosphere, the electrons are trapped in a bounce motion back and forth between Jupiter's north and south hemisphere. If the half-bounce time (the time it takes for electrons to travel from the magnetic equator, i.e. roughly Europa's location, to Jupiter and back) is shorter than the time it takes the plasma flow to pass Europa (the convection time), then the intensity at these energies is reduced because these electrons impact the moon. This condition is observed here with field-aligned electrons above  $\sim 300$  eV.

JADE observed electron beams at Europa that were not detected by Galileo. These beams were not expected close to Europa but rather further downstream due to the faster (factor of  $\sim 5$ ) convection speed at Europa relative to Io. A possible explanation is that the beam's origin is closer than anticipated. For example, assuming an origin of the



**Figure 4.** Visualization of the expected structure of the electron beams. The electron beams travel along the magnetic field lines and interact with Europa's atmosphere.

beams at  $\sim 1.9 R_J$  from Europa along the M-shell (i.e., at the mirroring point in the north of electrons that have a  $50^\circ$  pitch angle at Europa), the Alfvén travel time from Europa to this distance is  $\sim 267$  s, while electrons with 100 eV only need about 23 s to return back to Europa (total of  $267 + 23 = 290$  s). Similar travel times are found for the mirroring point in the south (277 and 43 s, respectively). For these estimates, we assumed that the ion density is equal to the electron density (see Figure 2d), the scale height is given by Bagenal and Delamere (2011), and the magnetic field magnitude is calculated from JRM33 and CON2020. Assuming an interaction strength of  $0.55 =$  ratio of the maximum change of the total flow speed to the unperturbed flow speed, see Szalay et al. (2024), “PUI advection model” section and Saur et al. (1999, 2013), leads to a plasma travel time of  $\sim 340$  s over Europa's interaction region of  $3 R_{Eu}$  including its atmosphere. Thus, under those assumptions the downstream (wake) side of Europa transited by Juno could be populated with electron beams. A closer beam location compared to the  $1.9 R_J$  estimate from the previous section, would imply a source pitch angle distribution smaller than  $50^\circ$  suggesting that electrons are partially energized parallel to the magnetic field. Further studies on the source of the electron beams are required. Overall, the proximity of the beams to Europa is an indication that the acceleration of these electrons takes place much closer to Europa than anticipated. This acceleration process is thus distinct from the acceleration processes in the moons' Alfvén wings occurring close to Jupiter such as for Io's electron beams. The latter accelerate electrons to much higher energies and cause the moons' footprints in Jupiter's atmosphere (Bonfond et al., 2017; Clarke et al., 2002; Hess et al., 2011) and observed energetic electrons within the wings and close to the moons for nearly standing flows (Allegrini, Gladstone, et al., 2020; Krupp et al., 2023; Mauk & Saur, 2007; Rabia et al., 2023; Williams et al., 1996). The observations of the electron beams reported here therefore reveal a new and previously unknown mechanism of sub-Alfvénic moon magnetosphere interaction.

Europa's global atmospheric density and its plumes have primarily been derived from electron impact excited ultraviolet (UV) emission (Hall et al., 1995; Roth, 2021; Roth et al., 2014) and imprints in the magnetic field (Arnold et al., 2019; Jia et al., 2018). Large electron fluxes such as those in the beams observed by JADE affect the interpretation of the UV emission. It will reduce the required neutral density globally and locally by nearly the same factor if they go through the dense part of the atmosphere. The distribution of the electron beams away from the Juno trajectory is uncertain; however, beams closer to Europa's surface passing through denser parts of its atmosphere will have a significant influence on the emission, for example, they can possibly enhance the emission up to a factor of 3.3 based on the fluxes of Beam 1.

Electron impact is the dominant process ionizing Europa's atmosphere (Saur et al., 1998) and producing its ionosphere. The electron beam intensities are highest in the low part of the energy range, from  $\sim 30$  to  $\sim 300$  eV, where the electron impact excitation and ionization cross sections are largest. Therefore, these electron beams contribute to ionizing the neutral gas along their path. Ionization near Europa contributes to its atmospheric loss which results in plasma mass loading (pick-up ions) to Jupiter's magnetosphere (Szalay et al., 2024). The wake region sampled by Juno is filled with electrons (Figures 2d and 2e), contrary to predictions from several numerical simulations without electron beams (e.g., Blöcker et al., 2016; Saur et al., 1998; Schilling et al., 2008) that typically show an empty or partially empty wake. This suggests that, similarly to Io, the electron beams at Europa play a key role in filling the wake with newly ionized plasma.

Ionization near Europa also contributes to producing its tenuous ionosphere, modifying the electric current system and the magnetic field environment. In particular, the presence of electron beams will affect plasma conditions that are used to infer the extent of a subsurface ocean via the induction signal (Khurana et al., 1998; Zimmer et al., 2000). The spatial structure of the beams is likely time-variable. Induction signals from Europa's conductive ocean on close flybys by Galileo are on the order of 50–100 nT (e.g., Khurana et al., 1998; Kivelson & Southwood, 2003; Schilling et al., 2007; Zimmer et al., 2000). The magnetic field perturbations at the strong beams from this flyby are of similar amplitudes as the induction signals. The spatial distribution of both magnetic field

perturbations are different and the reported electron beams do not call into question the principal conclusion on the existence of induced magnetic fields in Galileo spacecraft measurements. However, the electron beams clearly affect the magnetic field environment and need to be accounted for in further precise magnetic sounding studies of Europa's subsurface ocean.

The electron beams have more than three times the energy flux, more than two-and-a-half times the density, three to eight times the intensity of the ambient electrons near Europa's orbit, and they are associated with large variations in the magnetic field. These beams thus significantly shape Europa's space plasma environment through emissions, ionization, and electric currents. All these resulting effects need to be anticipated and understood thoroughly for the data analysis of future missions such as ESA's (European Space Agency) JUICE (Jupiter Icy Moons Explorer) and NASA's (National Aeronautics and Space Administration) Europa Clipper mission.

### Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

### Data Availability Statement

The data presented here resides at NASA's Planetary Data System. The Juno data is available in Allegrini, Wilson, et al. (2020), Connerney (2020), and Kurth and Piker (2022). Text files associated with the figures presented in this paper is accessible at Zenodo <https://doi.org/10.5281/zenodo.10974579>.

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### References

- Addison, P., Haynes, C. M., Stahl, A. M., Liuzzo, L., & Simon, S. (2024). Magnetic signatures of the interaction between Europa and Jupiter's magnetosphere during the Juno flyby. *Geophysical Research Letters*, *51*(2), e2023GL106810. <https://doi.org/10.1029/2023GL106810>
- Allegrini, F., Gladstone, G. R., Hue, V., Clark, G., Szalay, J. R., Kurth, W. S., et al. (2020). First report of electron measurements during a Europa footprint tail crossing by Juno. *Geophysical Research Letters*, *47*(18), e2020GL089732. <https://doi.org/10.1029/2020GL089732>
- Allegrini, F., Kurth, W. S., Elliott, S. S., Saur, J., Livadiotis, G., Nicolaou, G., et al. (2021). Electron partial density and temperature over Jupiter's main auroral emission using Juno observations. *Journal of Geophysical Research*, *126*(9), e2021JA029426. <https://doi.org/10.1029/2021JA029426>
- Allegrini, F., Wilson, R. J., Ebert, R. W., & Loeffler, C. (2020). Juno J/SW JOVIAN AURORAL DISTRIBUTION CALIBRATED V1.0. JNO-J/SW-JAD-3-CALIBRATED-V1.0 [Dataset]. *NASA Planetary Data System*. <https://doi.org/10.17189/1519715>
- Arnold, H., Liuzzo, L., & Simon, S. (2019). Magnetic signatures of a plume at Europa during the Galileo E26 flyby. *Geophysical Research Letters*, *46*(3), 1149–1157. <https://doi.org/10.1029/2018GL081544>
- Bagenal, F., & Delamere, P. A. (2011). Flow of mass and energy in the magnetospheres of Jupiter and Saturn. *Journal of Geophysical Research*, *116*(A5), A05209. <https://doi.org/10.1029/2010JA016294>
- Blöcker, A., Saur, J., & Roth, L. (2016). Europa's plasma interaction with an inhomogeneous atmosphere: Development of Alfvén winglets within the Alfvén wings. *Journal of Geophysical Research*, *121*(10), 9794–9828. <https://doi.org/10.1002/2016JA022479>
- Bolton, S. J., Lunine, J., Stevenson, D., Connerney, J. E. P., Levin, S., Owen, T. C., et al. (2017). The Juno mission. *Space Science Reviews*, *213*(1–4), 5–37. <https://doi.org/10.1007/s11214-017-0429-6>
- Bonfond, B., Saur, J., Grodent, D., Badman, S. V., Bisikalo, D., Shematovich, V., et al. (2017). The tails of the satellite auroral footprints at Jupiter. *Journal of Geophysical Research*, *122*(8), 7985–7996. <https://doi.org/10.1002/2017JA024370>
- Clarke, J., Ajello, J., Ballester, G., Ben Jaffel, L., Connerney, J., Gérard, J.-C., et al. (2002). Ultraviolet emissions from the magnetic footprints of Io, Ganymede and Europa on Jupiter. *Nature*, *415*(6875), 997–1000. <https://doi.org/10.1038/415997a>
- Connerney, J. E. P. (2020). Juno MAG CALIBRATED DATA J V1.0, JNO-J-3-FGM-CAL-V1.0 [Dataset]. *NASA Planetary Data System*. <https://doi.org/10.17189/1519711>
- Connerney, J. E. P., Baron, R., Satoh, T., & Owen, T. (1993). Images of excited H<sub>3</sub><sup>+</sup> at the foot of the Io flux tube in Jupiter's atmosphere. *Science*, *262*(Issue 5136), 1035–1038. <https://doi.org/10.1126/science.262.5136.1035>
- Connerney, J. E. P., Benn, M., Bjarno, J. B., Denver, T., Easley, J., Jorgensen, J. L., et al. (2017). The Juno magnetic field investigation. *Space Science Reviews*, *213*(1–4), 39–138. <https://doi.org/10.1007/s11214-017-0334-z>
- Connerney, J. E. P., Timmins, S., Herceg, M., & Joergensen, J. L. (2020). A Jovian magnetodisc model for the Juno era. *Journal of Geophysical Research: Space Physics*, *125*(10), e2020JA028138. <https://doi.org/10.1029/2020JA028138>
- Connerney, J. E. P., Timmins, S., Oliverson, R. J., Easley, J. R., Joergensen, J. L., Kotsiaros, S., et al. (2022). A new model of Jupiter's magnetic field at the completion of Juno's Prime Mission. *Journal of Geophysical Research: Planets*, *127*(2), e2021JE007055. <https://doi.org/10.1029/2021JE007055>
- Dols, V., Delamere, P. A., & F. Bagenal, F. (2008). A multispecies chemistry model of Io's local interaction with the Plasma Torus. *Journal of Geophysical Research*, *113*(A9), A09208. <https://doi.org/10.1029/2007JA012805>
- Frank, L. A., & Paterson, W. R. (1999). Intense electron beams observed at Io with the Galileo spacecraft. *Journal of Geophysical Research*, *104*(A12), 28657–28669. <https://doi.org/10.1029/1999JA900402>
- Hall, D. T., Strobel, D. F., Feldman, P. D., McGrath, M. A., & Weaver, H. A. (1995). Detection of an oxygen atmosphere on Jupiter's moon Europa. *Nature*, *373*(6516), 677–679. <https://doi.org/10.1038/373677a0>
- Hess, S. G. P., Delamere, P. A., Dols, V., & Ray, L. C. (2011). Comparative study of the power transferred from satellite-magnetosphere interactions to auroral emissions. *Journal of Geophysical Research*, *116*(A1), A01202. <https://doi.org/10.1029/2010JA015807>



- Jacobsen, S., Saur, J., Neubauer, F. M., Bonfond, B., Gérard, J.-C., & Grodent, D. (2010). Location and spatial shape of electron beams in Io's wake. *Journal of Geophysical Research*, *115*(A4), A04205. <https://doi.org/10.1029/2009JA014753>
- Jia, X., Kivelson, M. G., Khurana, K. K., & Kurth, W. S. (2018). Evidence of a plume on Europa from Galileo magnetic and plasma wave signatures. *Nature Astronomy*, *2*(6), 459–464. <https://doi.org/10.1038/s41550-018-0450-z>
- Khurana, K. K., Kivelson, M. G., Stevenson, D. J., Schubert, G., Russell, C. T., Walker, R. J., & Polansky, C. (1998). Induced magnetic fields as evidence for subsurface oceans in Europa and Callisto. *Nature*, *395*(6704), 777–780. <https://doi.org/10.1038/27394>
- Kivelson, M. G., & Southwood, D. J. (2003). First evidence of IMF control of Jovian magnetospheric boundary locations: Cassini and Galileo magnetic field measurements compared. *Planetary and Space Science*, *51*(13), 891–898. [https://doi.org/10.1016/S0032-0633\(03\)00075-8](https://doi.org/10.1016/S0032-0633(03)00075-8)
- Krupp, N., Roussos, E., Fränz, M., Kollmann, P., Paranicas, C., Clark, G., et al. (2023). Pitch angle distributions of energetic particles near Callisto. *Journal of Geophysical Research*, *128*(10), e2023JA031794. <https://doi.org/10.1029/2023JA031794>
- Kurth, W. S., Hospodarsky, G. B., Kirchner, D. L., Mokryzcki, B. T., Averkamp, T. F., Robison, W. T., et al. (2017). The Juno waves investigation. *Space Science Reviews*, *213*(1), 347–392. <https://doi.org/10.1007/s11214-017-0396-y>
- Kurth, W. S., & Piker, C. W. (2022). Juno E/J/SS waves CALIBRATED SURVEY FULL RESOLUTION V2.0, JNO-E/J/SS-WAV-3-CDR-SRVFULL-V2.0 [Dataset]. *NASA Planetary Data System*. <https://doi.org/10.17189/1520498>
- Kurth, W. S., Wilkinson, D. R., Hospodarsky, G. B., Averkamp, T. F., Santolik, O., Sulaiman, A. H., et al. (2023). Juno plasma wave observations at Europa. *Geophysical Research Letters*, *50*(24), e2023GL105775. <https://doi.org/10.1029/2023GL105775>
- Mauk, B. H., & Saur, J. (2007). Equatorial electron beams and auroral structuring at Jupiter. *Journal of Geophysical Research*, *112*(A10), A10221. <https://doi.org/10.1029/2007JA012370>
- McComas, D. J., Alexander, N., Allegrini, F., Bagenal, F., Beebe, C., Clark, G., et al. (2017). The Jovian auroral distributions experiment (JADE) on the Juno mission to Jupiter. *Space Science Reviews*, *213*(1–4), 547–643. <https://doi.org/10.1007/s11214-013-9990-9>
- Rabia, J., Hue, V., Szalay, J. R., André, N., Nénon, Q., Blanc, M., et al. (2023). Evidence for non-monotonic and broadband electron distributions in the Europa footprint tail revealed by Juno in-situ measurements. *Geophysical Research Letters*, *50*(12), e2023GL103131. <https://doi.org/10.1029/2023GL103131>
- Roth, L. (2021). A stable H<sub>2</sub>O atmosphere on Europa's trailing hemisphere from HST images. *Geophysical Research Letters*, *48*(20), e2021GL094289. <https://doi.org/10.1029/2021GL094289>
- Roth, L., Saur, J., Retherford, K. D., Strobel, D. F., Feldman, P. D., McGrath, M. A., & Nimmo, F. (2014). Transient water vapor at Europa's South Pole. *Science*, *343*(6167), 171–174. <https://doi.org/10.1126/science.1247051>
- Saur, J., Grambusch, T., Duling, S., Neubauer, F. M., & Simon, S. (2013). Magnetic energy fluxes in sub-Alfvénic planet star and moon planet interactions. *Astronomy & Astrophysics*, *552*, A119. <https://doi.org/10.1051/0004-6361/201118179>
- Saur, J., Neubauer, F. M., Strobel, D. F., & Summers, M. E. (1999). Three-dimensional plasma simulation of Io's interaction with the Io plasma torus: Asymmetric plasma flow. *Journal of Geophysical Research*, *104*(A11), 25105–25126. <https://doi.org/10.1029/1999JA900304>
- Saur, J., Neubauer, F. M., Strobel, D. F., & Summers, M. E. (2002). Interpretation of Galileo's Io plasma and field observations: I0, I24, and I27 flybys and close polar passes. *Journal of Geophysical Research*, *107*(A12), 1422. <https://doi.org/10.1029/2001JA005067>
- Saur, J., Strobel, D. F., & Neubauer, F. M. (1998). Interaction of the Jovian magnetosphere with Europa: Constraints on the neutral atmosphere. *Journal of Geophysical Research*, *103*(E9), 19947–19962. <https://doi.org/10.1029/97JE03556>
- Schilling, N., Neubauer, F. M., & Saur, J. (2007). Time-varying interaction of Europa with the Jovian magnetosphere: Constraints on the conductivity of Europa's subsurface ocean. *Icarus*, *192*(1), 41–55. <https://doi.org/10.1016/j.icarus.2007.06.024>
- Schilling, N., Neubauer, F. M., & Saur, J. (2008). Influence of the internally induced magnetic field on the plasma interaction of Europa. *Journal of Geophysical Research*, *113*(A3), A03203. <https://doi.org/10.1029/2007JA012842>
- Straub, H. C., Renault, P., Lindsay, B. G., Smith, K. A., & Stebbings, R. F. (1996). Absolute partial cross sections for electron-impact ionization of H<sub>2</sub>, N<sub>2</sub>, and O<sub>2</sub> from threshold to 1000 eV. *Physical Review*, *54*(3), 2146–2153. <https://doi.org/10.1103/physrev.54.2146>
- Szalay, J. R., Allegrini, F., Ebert, R. W., Bagenal, F., Bolton, S. J., Fatemi, S., et al. (2024). Oxygen production from dissociation of Europa's water ice surface. *Nature Astronomy*. <https://doi.org/10.1038/s41550-024-02206-x>
- Szalay, J. R., Bonfond, B., Allegrini, F., Bagenal, F., Bolton, S., Clark, G., et al. (2018). In situ observations connected to the Io footprint tail aurora. *Journal of Geophysical Research: Planets*, *123*(11), 3061–3077. <https://doi.org/10.1029/2018JE005752>
- Williams, D. J., Mauk, B. H., McEntire, R. E., Roelof, E. C., Armstrong, T. P., Wilken, B., et al. (1996). Electron beams and ion composition measured at Io and in its torus. *Science*, *274*(5286), 401–403. <https://doi.org/10.1126/science.274.5286.401>
- Williams, D. J., McEntire, R. W., Jaskulek, S., & Wilken, B. (1992). The Galileo energetic particles detector. *Space Science Reviews*, *60*(1–4), 385–412. <https://doi.org/10.1007/BF00216863>
- Zimmer, C., Khurana, K. K., & Kivelson, M. G. (2000). Subsurface Oceans on Europa and Callisto: Constraints from Galileo magnetometer observations. *Icarus*, *147*(2), 329–347. <https://doi.org/10.1006/icar.2000.6456>

## References From the Supporting Information

- Allegrini, F., Bagenal, F., Ebert, R. W., Louarn, P., McComas, D. J., Szalay, J. R., et al. (2022). Plasma observations during the 7 June 2021 Ganymede flyby from the Jovian Auroral Distributions Experiment (JADE) on Juno. *Geophysical Research Letters*, *49*(23), e2022GL098682. <https://doi.org/10.1029/2022GL098682>
- Kurth, W. S., Sulaiman, A. H., Hospodarsky, G. B., Menietti, J. D., Mauk, B. H., Clark, G., et al. (2022). Juno plasma wave observations at Ganymede. *Geophysical Research Letters*, *49*(23), e2022GL098591. <https://doi.org/10.1029/2022GL098591>