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Key Points:

- Three distinct heavy ion populations observed in Jupiter's plasma sheet: Io-genic plasma, Europa-genic plasma, and Io-genic energetic particles
- The mixture of Io-genic and Europa-genic plasma varies greatly throughout the Europa-Ganymede region
- We find evidence Europa's oxygen neutral toroidal clouds are more localized than its hydrogen cloud

Supporting Information:

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

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Europa Modifies Jupiter's Plasma Sheet

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Abstract Jupiter's plasma sheet has been understood to be primarily composed of Io-genic sulfur and oxygen, along with protons at lower mass density. These ions move radially away from Jupiter, filling its magnetosphere. The material in the plasma sheet interacts with Europa, which is also a source of magnetospheric pickup ions, primarily hydrogen and oxygen. Juno's thermal plasma instrument JADE, the Jovian Auroral Distributions Experiment, has provided comprehensive in situ observations of the composition of Jupiter's plasma sheet ions with its Time-of-Flight mass-spectrometry capabilities. Here, we present observations of the magnetospheric composition in the Europa-Ganymede region of Jupiter's magnetosphere. We find material from Europa is intermittently present at comparable densities to Io-genic plasma. The intermittency of Europa-genic signatures suggests Europa's neutral oxygen toroidal cloud is more localized to Europa's vicinity than its hydrogen cloud. These observations reveal a more complex and compositionally diverse magnetosphere than previously thought.

Plain Language Summary Jupiter's charged particle environment is overwhelmingly driven by material lost from Io. This material interacts with the icy moon Europa, which can also inject charged particles into the environment. We find that Europa appreciably contributes to and modifies its local charged particle environment, revealing a more complex and compositionally diverse magnetosphere than previously thought.

1. Introduction

Jupiter's magnetospheric plasma is dominantly populated by pickup ions from the inner-most Galilean moon Io, which inputs $\sim 10^2$–10^3 kg s^{-1} of plasma (Bagenal & Delamere, 2011). This plasma is radially transported outward and encounters the icy moons Europa, Ganymede, and Callisto. Previous observations from Voyager, Galileo, and Juno found the plasma composition to be dominated by AMU/q = 16 (O^+/S^{2+}) ions (Bagenal, 1994; Bagenal & Dols, 2020; Bagenal et al., 2016; Kim et al., 2020a, 2020b). Europa (Smyth & Marconi, 2006), Ganymede (Marconi, 2007), and Callisto (Carberry Mogan et al., 2021) are expected to provide an additional source of plasma, mainly hydrogen and oxygen in atomic and molecular forms. While measurements during Pioneer 10's flyby of Jupiter were consistent with plasma injection into the Jovian plasma sheet from Europa (Intriligator & Miller, 1982), the extent to which these icy moons contribute to and modify their magnetospheric environment has not been well-constrained.

Europa's atmospheric mass loss is expected to be primarily O_2 (Dols et al., 2016; Saur et al., 1998), with a comparable number loss of H_2 (e.g., Vorburger & Wurz, 2018). These neutrals can then orbit Jupiter in a neutral toroidal cloud (Smith et al., 2019; Smyth & Marconi, 2006) and are most readily lost as ions due to electron impact ionization, where they subsequently become pickup ions (PUIs) incorporated into the Jovian magnetospheric plasma (Smith et al., 2019). Neutrals also charge exchange with plasma (Lagg et al., 2003; Nénon & André, 2019) to produce energetic neutral atoms (Mauk et al., 2003). Juno plasma composition observations in the Europa-Ganymede region showed a persistent population of H_2^+ to be present, originally lost from Europa (Szalay, Smith, et al., 2022). Additionally, significant fluxes of hydrogen and oxygen PUIs were observed in the immediate vicinity of Europa during Juno's flyby of the moon (Szalay et al., 2024).

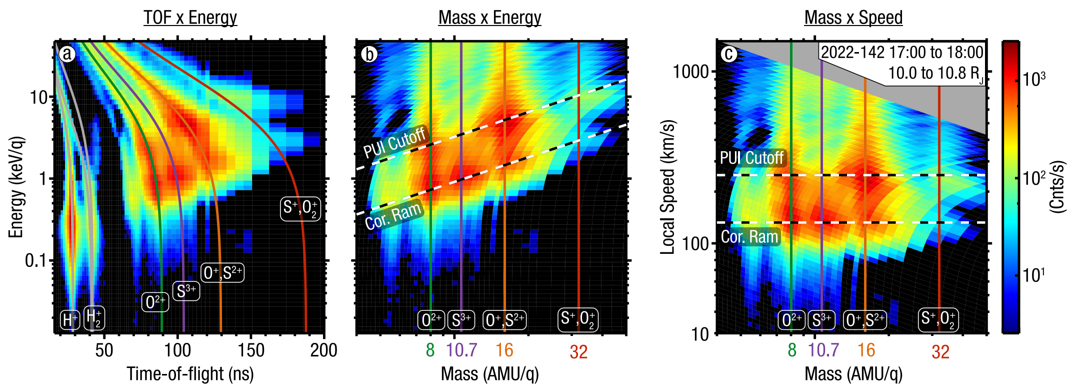

Figure 1. Time-of-flight (TOF) data from 2022-142 17:00 to 18:00, all three panels show the same data focusing on the TOF range covering heavy ions (oxygen and sulfur). Panel (a): count rates in TOF × Energy per charge. Panel (b): mass per charge on the *x*-axis. Panel (c): local speed on the *y*-axis. The two dashed lines show where rigidly corotating plasma would appear (lower) and the cutoff energy for locally picked up ions (upper).

While the Juno H_2^+ observations provided important observational constraints on Europa's icy surface evolution, such ions do not appreciably contribute to the number density and internal pressure of Jupiter's magnetospheric plasma. Europa's input of heavy ion PUIs to the magnetosphere has been suggested to be responsible for modifying the ion temperatures, however, Europa was not expected to significantly alter the composition of the plasma sheet (Delamere et al., 2005). Ultraviolet observations (Hansen et al., 2005) provided upper limit estimates of total neutral content of Europa's neutral clouds, indicating they would likely not contribute appreciable oxygen to the plasma sheet (Shemansky et al., 2014). Additionally, the equatorial plasma pressure is expected to transition from a magnetic pressure-dominated state inside ∼15 R_J (1 $R_J \equiv$ 71,492 km) to a particle pressure-dominated state outside ∼15 R_J (Mauk et al., 2004). However, there is uncertainty in the relative contributions of pressure from "cold" plasma (<50 keV), "hot" plasma (>50 keV), and the magnetic pressure, particularly since the ion composition of cold plasma was never directly measured in situ before Juno. Therefore, the contribution from Europa-genic heavy ions could play a role in the plasma sheet composition and pressure of Jovian magnetospheric plasma. Juno has the mass-resolved plasma observations to assess this. Additionally, with the exception of H_2^+ (Szalay et al., 2024), the relative contributions of direct PUIs from Europa's atmosphere versus subsequent pickup from Europa's neutral toroidal cloud are not well-constrained.

The Juno mission has been in a polar orbit about Jupiter since July 2016 (Bolton et al., 2017). It is equipped with the Jovian Auroral Distributions Experiment (JADE) (McComas, Alexander, et al., 2017), which includes a time-of-flight (TOF) mass spectrometry subsystem to measure ions from 13 eV/q to 46 keV/q. Its ion TOF data revealed many new findings about the composition in the Jovian plasma environment, including the prevalence of light ions in the outer magnetosphere (McComas, Szalay, et al., 2017), topologically closed fields in Jupiter's polar-most regions (Szalay, Clark, et al., 2022), and the discovery of significant quantities of H_3^+ along with ion outflow constraints at Ganymede (Allegrini, Bagenal, et al., 2022; Allegrini, Wilson, et al., 2022; Valek et al., 2022). JADE has also provided a comprehensive compositional inventory of the magnetosphere (Kim et al., 2020a, 2020b).

In this study, we use JADE's ion composition measurements to reveal Europa's imprint on Jupiter's plasma sheet. In Section 2, we highlight the composition measurements obtained by Juno, providing specific examples of the diverse composition in the plasma sheet in Section 3. We conclude with a discussion in Section 4 of implications for our evolving understanding of Jupiter's magnetospheric plasma.

2. Time-Of-Flight Plasma Measurements

All JADE data discussed in this study are from its ion TOF data product, which integrates over all look directions. Throughout the study we analyze and display the JADE TOF data in count rates as we forward model various species' distributions to cross-compare their effects in the TOF count rate data. Figure 1a shows an example of count rates as a function of TOF and energy per charge, on 2022-142 17:00 to 18:00. The colored lines on this spectrogram show where peak count rates from different species occur (Kim et al., 2020a). While Figure 1a

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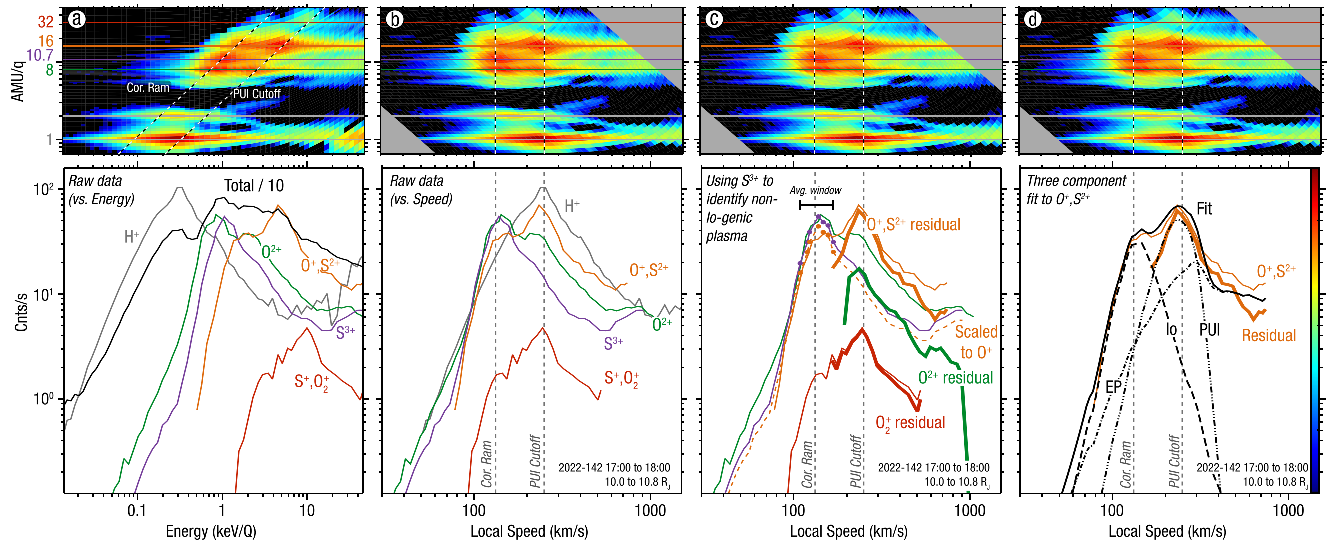

Figure 2. Time-of-flight (TOF) data from 2022-142 17:00 to 18:00 along with average rates for H^+, O^{2+}, O^+/S^{2+}, S^{3+}, and S^+/O_2^+. Panel (a): rates as a function of energy with the total rate across all TOF values (black) divided by 10. Panel (b): converts the energy on the *x*-axis to local speed. The two dashed lines show where rigidly corotating plasma would appear (left) and the cutoff energy for locally picked up ions (right). Panel (c): data-driven S_3^+ subtraction method to isolate non-Io-genic material. Panel (d): fit method with three populations: Io-genic, Pickup Ion-PUI, Energetic Particle-EP. Data points within the "Avg. window" in (c) show where the average value for each spectrum is calculated to rescale S^{3+}. The colorbar has the same scale as the *y*-axis.

displays the data as collected, it is often more meaningful to display this data as a function of mass per charge instead of TOF, as shown in Figure 1b where we limit the mass range to heavy ions with AMU/q > 4. This display involves "unfolding" the data such that features of constant AMU/q are vertical features. We can subsequently transform the TOF data such that instead of energy per charge on the *y*-axis, we show local speed (Figure 1c). This representation is particularly useful to compare species measured at the same speed, such as a corotating plasma. Overlaid on Figures 1b and 1c are two relevant plasma speeds in the local spacecraft frame (Text S1 in Supporting Information S1).

Figure 2a shows the same data as Figure 1 with rate spectra shown in the bottom of each panel. Species-dependent rates were calculated by averaging over masses within 10% of each AMU/q value. We omit showing an H_2^+ profile as this feature requires additional complex analysis due to the overlap of proton count rates with the AMU/q = 2 line from instrumental effects (Szalay, Smith, et al., 2022). The spectrograms have inverted axes from Figure 1, where the mass dependence is on the *y*-axis to align features in energy/speed with the spectra below. The total rate over all TOFs is shown with the black line, divided by a factor of 10. As shown in this panel, the total rate is a sum of many complex species-dependent spectra. Previous analyses of Jovian plasma data without TOF composition relied on multi-species fits to estimate species-dependent rate spectra (e.g., Bagenal, 1994). Each species exhibits a peak at a different energy per charge and has different overall structure, where none of the observed species are Maxwellian. Hence, inverting rate spectra as a function of energy using simple fits is problematic.

Figure 2b shows the same data with (local) speed on the *x*-axis. These spectra are significantly more ordered in speed than as a function of E/q. While both Io and Europa produce various charge states of oxygen, only Io can produce sulfur. S^{3+} serves as an important diagnostic of Io-genic material and does not overlap with any other major ion in Jupiter's plasma in AMU/q space. As shown in Figure 2b, S^{3+} exhibits a peak rate near corotation ram, consistent with a plasma population injected at smaller inner radial distances and transported out to 10–11 R_J observed here. In this example, AMU/q = 8 (O^{2+}) also exhibits a peak at corotation ram, with a second peak near the PUI cutoff, suggestive of multiple populations. AMU/q = 16 (O^+/S^{2+}) shows a strong peak near the PUI cutoff and AMU/q = 32 (S^+/O_2^+) exhibits a monotonically increasing rate profile until the PUI cutoff.

To diagnose the extent to which non-Io-genic PUIs are present, we use two methods. The first, shown in Figure 2c, uses a solely data-driven technique. In this method, we subtract the spectra of Io-genic S^{3+} from other species' spectra. To do so, we: (a) find the speed where the S^{3+} spectrum peaks; (b) determine the average count

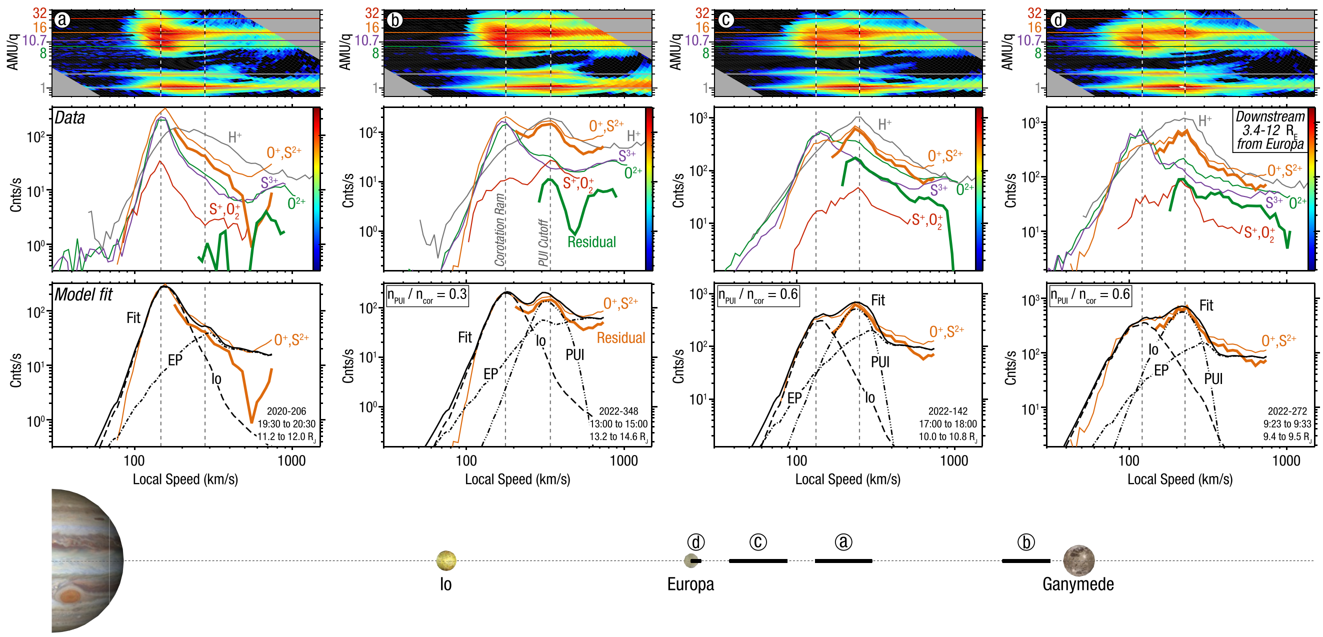

Figure 3. Four example plasma composition observations showing a diverse set of plasmas within the Europa-Ganymede region of the Jovian plasma sheet. The top two rows of panels show the same information as Figure 2. The third row shows three-component fits and data-driven residuals (thick lines) to the AMU/q = 16 spectra only, as this species presented the highest partial density and most distinct populations. The schematic at the very bottom indicates the radial distance range within the plasma sheet for each of the four observation periods.

rate within ±3 energy steps of this peak for the S^{3+} and AMU/q = 8, 16, and 32 spectra; and (c) scale the S^{3+} spectrum to that of the other species and subtract. Figure 2c shows an S^{3+} spectrum scaled to the AMU/q = 16 spectrum with the dashed orange line. These scaled spectra (including that scaled to AMU/q = 8 and 32), which approximates the speed distributions from a purely Io-genic plasma species, are subtracted from the other species' spectra to yield the residual thick line spectra in Figure 2c. These residual spectra should then be dominated by non-Io-genic material, presumably oxygen from Europa, as any material picked up in the vicinity of Io's orbit would have lower injection speeds compared to Europa's orbital location. As shown in this figure, all residual spectra peaks occur very near the PUI cutoff speed, providing strong evidence these populations are recently picked-up Europa-genic oxygen ions.

The second method involves forward-modeling with an empirical three kappa-distribution plasma (Livadiotis & McComas, 2013) corresponding to (a) Io-genic plasma, (b) recently picked up ions, and (c) energetic particles (EPs) (Text S2 in Supporting Information S1). While the EPs are understood to be also from Io, they are treated as a separate population as they have likely undergone significant transport through the middle/outer magnetosphere in contrast to the low-energy plasma from Io (e.g., Bagenal & Delamere, 2011; Ng et al., 2018; Saur, 2004).

Figure 2d shows the results of this three-component χ^2 minimization fit to the observed rates for AMU/q = 16. The fit well-reproduces the total rates and remarkably, the PUI component follows very closely to the core of the residual, determined via the first method, with both peaking near the PUI cutoff. Hence both the S^{3+} data-driven subtraction method and the three-component forward-model fit independently identify a distinct population peaking around the local PUI cutoff speed. While we use rates here, the peak location will shift slightly downward in speed for phase space density. Fresh PUIs observed before additional heating or cooling occurs exhibit a sharp peak at these speeds (e.g., McComas et al., 2021; Zirnstein et al., 2022). Thus, the observed broadness could indicate the PUIs are heated after being incorporated into the plasma.

3. Diverse Composition Observed in the Plasma Sheet

Having developed two independent techniques to estimate the relative amount of non-Io-genic plasma, we investigate four distinct periods in Figure 3 that exhibit different relative abundances of Io-genic versus non-Io-genic plasma. The bottom portion of this figure shows the radial distances within the plasma sheet for each

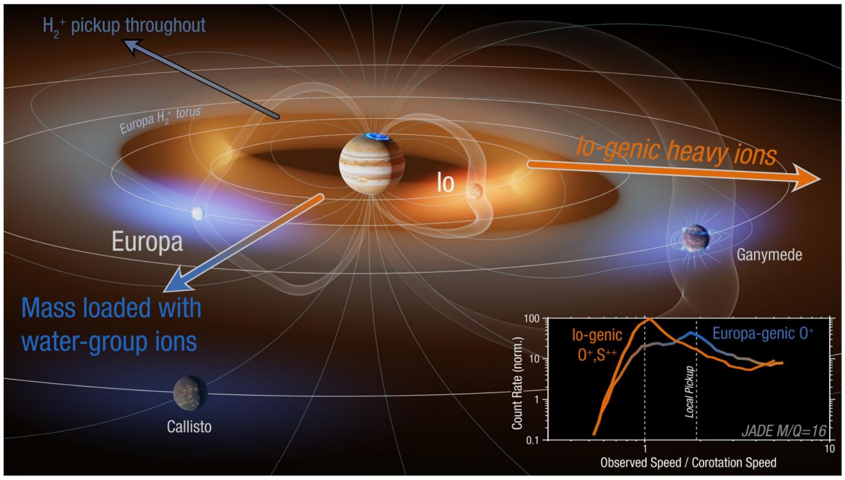

Figure 4. Schematic showing Europa-genic mass loading for plasma that is radially transported in the vicinity of Europa's neutral oxygen. The bottom right inset shows the two AMU/q = 16 spectra from Figures 3a and 3c. While Europa-genic O^+ is sporadically observed due to a more confined neutral O population in the vicinity of Europa, H_2^+ pickup occurs more consistently throughout all longitudes as the H_2 neutral toroidal cloud is likely not as confined to Europa's immediate vicinity. Adapted from Szalay, Smith, et al. (2022).

observation. Figure 3a shows an example where no discernible population near the local PUI cutoff is observed. Here, all species peak strongly at corotation ram, and the residuals do not show evidence for a recently picked up population. Omitting the PUI component of the fit for this period, we can reproduce the count rate spectrum with just a corotating plasma and energetic particle set of populations. Figure 3b shows an example with two peaks in the AMU/q = 16 count rates at comparable magnitudes. The inset labels in panels b–d show the numerical partial density ratio between the PUI and Io (corotational) populations for the empirical kappa fits (2nd method). For the period shown in Figure 3b, $n_{PUI}/n_{cor} = 0.3$. The residuals exhibit a strong peak near the PUI cutoff speed, as does the AMU/q = 32 spectrum. The fits also show a significant population near the PUI cutoff. This all indicates the plasma in this region is likely composed of O^+, O^{2+} and O_2^+ PUIs from Europa which, interestingly, is much farther from Europa than the case shown in Figure 3a.

Figure 3c shows the same period from Figures 1 and 2, where $n_{PUI}/n_{cor} = 0.6$. An interesting comparison can be made between these observations and those shown in Figure 3d taken 3.4–12 R_E (1 $R_E \equiv$ 1,560.8 km) immediately downstream from Europa right before Juno's close flyby of the moon. The plasma encountered downstream from Europa on 2022-272 9:23 to 9:33 was heavily loaded with oxygen PUIs (Szalay et al., 2024). This was to be expected given Europa's oxygen-dominated atmosphere and the subsequent ionization and pickup of these neutrals as freshly picked up ions (Dols et al., 2016; Saur et al., 1998; Smith et al., 2019; Smyth & Marconi, 2006). However, the plasma observed approximately from 10 to 10.8 R_J shown in Figure 3c exhibits a nearly identical plasma and composition distribution, while also being ~180° in longitude away from Europa. This could indicate the plasma observed and shown in Figure 3c was originally in the very near vicinity of Europa, which injected significant quantities of Europa-genic oxygen PUIs, then was radially transported outward where Juno encountered it. While directly attributing the origin of plasma modification from a different radial distance is challenging as it is sensitive to the radial speed profile, composition analysis can provide an additional avenue to understand the radial transport and evolution of magnetospheric plasma.

4. Discussion and Conclusions

From in situ plasma time-of-flight mass spectrometry observations, we found the plasma composition within the Europa-Ganymede region is highly diverse and notably can contain significant quantities of Europa-genic oxygen ions. We identified three periods in the Europa-Ganymede region (from 9 to 15 R_J) far from Europa that range from exhibiting no signature of Europa-genic plasma, to having Europa-genic abundances comparable to those from Io. Europa-genic plasma was identified via two independent methods: (a) taking the residual AMU/q = 16 spectra after subtracting scaled spectra from AMU/q = 10.7 (S^{3+}) and (b) fitting an empirical three-component plasma distribution to the observed species-dependent count rate profiles for AMU/q = 16. All periods investigated here exhibit a core thermal Io-genic population and an energetic particle high-energy tail.

While Io produces $\sim 10^2$–10^3 kg s^{-1} plasma, orders of magnitude more than Europa, we find Europa's contribution to local plasma regions can still be significant. As the plasma is radially transported outward, it fills a larger volume and the number density decreases as a function of radial distance. Between Io's and Europa's orbital distance, the plasma density decreases by a factor of $\sim 10^2$ and the radial transport speed increases by ∼10–20x (Bagenal & Delamere, 2011). Therefore, Io-genic plasma at Europa's orbit would be perturbed by 10–100's kg s^{-1} of pickup ions if those ions are evenly spread throughout Europa's orbit. If pickup ions are not uniformly injected throughout Europa's orbit, but instead preferentially injected in the vicinity of Europa, it would require even less mass input to perturb the plasma distribution, but would result in “patchy” PUI injection. These observations suggest such a patchy injection method occurs.

Neutral oxygen loss rates have been estimated to be ∼5–1,100 kg s^{-1} (e.g., Addison et al., 2022; Dols et al., 2016; Harris et al., 2022; Johnson et al., 2019; Plainaki et al., 2018; Saur et al., 1998), with a sizable portion of those neutrals to be incorporated into the Jovian magnetosphere as PUIs. Juno's Europa flyby revealed 12 ± 6 kg s^{-1} of O_2 is produced at Europa from dissociation of its icy surface (Szalay et al., 2024), where the fraction of this oxygen to eventually become PUIs remains to be determined. Local injection of Europa-genic PUIs could very well be comparable to the lower end of the 10–100's kg s^{-1} estimate discussed above and therefore appreciably contribute to plasma that encounters Europa's neutrals, particularly if the injection is more localized to Europa. We therefore attribute the broad compositional diversity in the Europa-Ganymede region to plasma that encountered Europa and/or its extended neutral toroidal cloud, versus plasma that did not encounter appreciable neutrals and subsequent pickup (Figure 4). The variability of electron impact ionization, along with other ionization pathways, in producing PUIs from Europa's neutrals may also play a role in this variability.

We do not produce a statistical assessment on the occurrence rate of plasma regions loaded with Europa-genic oxygen, however, the diversity in Europa-genic oxygen content highlighted here suggests that some plasma encountered significant pickup, while others were not exposed to an additional source of oxygen as the plasma was transported radially past Europa's orbit. In contrast, H_2^+ PUIs are consistently observed throughout the Europa-Ganymede region (Szalay, Smith, et al., 2022). A likely explanation for why H_2^+ is consistently observed while Europa-genic O^+, O^{2+}, and O_2^+ PUIs are intermittently observed is that oxygen ion injection is a process much more local to Europa's vicinity, such that most plasma transported past Europa's orbit (but far from Europa itself) would not encounter appreciable Europa-genic oxygen pickup ions. Such a comparison provides evidence that Europa's oxygen neutral toroidal clouds are more limited in size compared to its molecular hydrogen cloud, consistent with previous modeling (Smith et al., 2019). Similar to the H_2^+ observations, we do not find evidence for any appreciable contribution from Ganymede to the heavy ion composition, however, future statistical analyses could quantitatively constrain this.

While not analyzed in detail here, the proton rates in Figure 3 also peak at the local PUI cutoff for all examples where Europa-genic oxygen is found. Given the similarity between the proton and AMU/q = 16 spectra, we suggest the protons in Figures 3b–3d are in part Europa-genic. Interpreting proton energy distributions can be challenging as proton transport is different from that of the heavy ions (Sarkango et al., 2023).They may also be susceptible to acceleration from resonant plasma interactions in the vicinity of each moon's orbit, further modifying their energy distribution (Sarkango et al., 2024). Protons in Jupiter's magnetosphere can originate from a combination of three different sources: Jupiter's ionosphere, the moons, and the solar wind. Protons are estimated to be replenished in Jupiter's inner magnetosphere at a rate of 2.5–13 kg s^{-1} (Bodisch et al., 2017). Polar observations from Juno revealed that 1–5 kg s^{-1} of protons are accelerated away from the planet in the vicinity of Jupiter's main auroral emissions (Szalay et al., 2021) and incorporated into the magnetospheric plasma, suggesting the ionosphere is likely the dominant source. For the moons, ∼0.05 kg s^{-1} of H has been estimated to be lost from Io (Frank & Paterson, 1999), with a fraction injected as PUIs, and ∼0.1 kg s^{-1} of H^+ has been estimated to be produced as PUIs from Europa (Szalay, Smith, et al., 2022). Hence both moons are insufficient to account for the total magnetospheric proton population. However, just as with the heavy ions, we suggest Europa can be the locally dominant source of protons for plasma that experiences significant hydrogen pickup in the vicinity of Europa. Far in the deep magnetotail, proton-dominated plasma was consistently observed by New Horizons (McComas et al., 2007), with the strongest periodicity in the plasma matching Europa's orbital period (McComas, Allegrini, et al., 2017). In light of these observations from Juno, it is possible New Horizons observed the imprint of Europa's intermittent pickup ion injection process over a thousand Jovian radii down-tail.

When fitting AMU/q = 16 rate spectra (O^+/S^{2+}), we were unable to meaningfully reproduce the observations with a single kappa distribution given the large observed fluxes at energies above a few keV/q. The high energy tails are likely due to a distinct separate population from the Io-genic core thermal plasma. Interpretations of Voyager plasma observations also found the need for a "hot" oxygen population in addition to the thermal oxygen population to reproduce the Faraday cup measurements up to 6 keV (Dougherty et al., 2017). Such a higher energy population could be due to the inward radial transport of energetic particles and outward radial transport of thermal plasma (e.g., Bagenal & Delamere, 2011; Ng et al., 2018; Saur, 2004). Given that these populations are distinct, and possibly even being transported in opposite radial directions, they must be considered separately for any analysis of Jovian charged particle data. The plasma pressure is expected to be dominated by >50 keV heavy ions (Mauk et al., 2004)—the higher energy extension of these populations—and the magnetic pressure is still expected to dominate in this region. While we do not calculate partial pressures here, Europa-genic plasma of comparable density and higher average energy than Io-genic plasma is observed. Hence, Europa-genic PUIs are anticipated to provide a comparable, if not intermittently dominant, contribution to the partial internal plasma pressure for particles below 50 keV. Future analyses could statistically and quantifiably constrain the relative contributions to the plasma pressure between Io-genic corotating plasma, Europa-genic PUIs, and energetic particles.

In conclusion, we find Europa intermittently modifies Jupiter's plasma sheet composition and internal pressure. The extent to which Europa's imprint is observed is highly variable and likely driven by the spatially confined region near Europa where heavy ion pickup is most intense (Figure 4). H_2^+ is much more uniformly observed past Europa and likely picked up throughout all longitudes near Europa's orbital distance. Hence, we find Europa has a more profound effect on Jupiter's magnetosphere than previously understood.

Data Availability Statement

The JADE data used was the version 04 data from the Planetary Data System (PDS) data set JNO-J/SW-JAD-3-CALIBRATED-V1.0 (Allegrini, Bagenal, et al., 2022; Allegrini, Wilson, et al., 2022).

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