Poynting fluxes, field-aligned current densities, and the efficiency of the Io-Jupiter electrodynamic interaction

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Abstract

Juno’s highly inclined orbits provide opportunities to sample high-latitude magnetic field lines connected to the orbit of Io, among the other Galilean satellites. Its payload offers both remote-sensing and in-situ measurements of the Io-Jupiter interaction. These are at discrete points along Io’s footprint tail and at least one event (12th perijove) was confirmed to be on a flux tube directly connecting to Io, allowing for an investigation of how the interaction evolves down-tail. Here we present Alfvén Poynting fluxes and field-aligned current densities along field lines connected to Io and its orbit. We explore their dependence as a function of down-tail distance and show the expected decay as seen in UV brightness and electron energy fluxes. We show that the Alfvén Poynting and electron energy fluxes are highly correlated and related by an efficiency that is fully consistent with acceleration from Alfvén wave filamentation via a turbulent cascade process.

Plain Language Summary

Io and Jupiter are electrodynamically coupled resulting in the Io footprint tail. This is one of the most persistent, stable, and recognizable features of Jupiter's aurora. The Juno spacecraft routinely samples magnetic field lines connected to Io's orbit, allowing for an investigation of this powerful coupling. We use data recorded by Juno to estimate a proxy for the strength of this interaction, i.e. electromagnetic energy, and show its dependence downstream of Io and the interaction decays. We further show that the available electromagnetic energy and electron energy are intimately linked, suggesting a transfer of energy between wave and particles. This is the basis upon which electrons end up precipitating into Jupiter's upper atmosphere and generate some of the brightest auroras.
Key Points:

#1 Alfvénic Poynting fluxes and electron energy fluxes are highly correlated on magnetic field lines connected to Io’s orbit.

#2 The efficiency in the Main Alfvén Wing is ~10%, fully consistent with Alfvén wave filamentation via a turbulent cascade process.

#3 Field-aligned current densities are quantified and exhibit a decay in magnitude down-tail of Io.

1. Introduction

Jupiter’s rotating magnetosphere has an azimuthal velocity, $v_\phi$, that exceeds the orbital velocity, $v_s$, of each of the Galilean satellites. Io’s ionosphere is electrically conducting and large compared with the characteristic thermal plasma length scales, therefore it acts as an obstacle to the rotating magnetospheric plasma. In the rest frame of Io, the magnetosphere sweeps over the satellite from its trailing side at speed $u = v_\phi - v_s$ with an initially unperturbed magnetic field, $B_0$. The flow of plasma around Io produces vorticity in the flow, shearing magnetic field lines thus producing currents. The divergence-free requirement is satisfied by the development of field-aligned currents to and from Jupiter’s ionosphere.

The interaction of the magnetospheric plasma with Io is accompanied by magnetic field disturbances at the fluid scale that correspond to the Alfvén magnetohydrodynamic (MHD) mode, along which energy is carried, and its propagation is strictly parallel or anti-parallel to the magnetic field in the rest frame of the moving plasma. The Alfvénic disturbances are associated with field-aligned currents that extend from Io’s northern and southern hemispheres. These columns, called Alfvén wings, exhibit a bend-back with respect to $B_0$ by an angle $\alpha = \tan^{-1}(u/v_A)$, where $v_A$ is the Alfvén speed, and are the tilted path of the energy transport (Drell et al., 1965; Neubauer, 1980; Saur et al., 2013). The current-carrying magnetic flux tubes connect to Jupiter’s northern and southern ionosphere, thereby establishing a long-range electrodynamic connection.
between Io and Jupiter. Where the Alfvén waves (and field-aligned currents) meet the ionosphere, auroral emissions are observed. Partial reflections of the Alfvén waves permit the interaction to persist down-tail of Io, resulting in secondary auroral spots and extended footprint tails with decaying power (Goertz and Gurnett, 1981; Jacobsen et al., 2010; Bonfond et al., 2017; Schlegel and Saur, 2022; Lysak et al., 2023). A leading hypothesis is that Alfvén waves nonlinearily interact with their reflected counterparts, undergoing a turbulent cascade from larger to smaller scales (Hess et al., 2010; Saur et al., 2002; Janser et al., 2022). At sufficiently small scales, namely, the electron inertial length, Alfvén waves in the inertial limit develop a parallel electric field that can accelerate auroral electrons at Jupiter’s high latitudes (Saur et al., 2018; Damiano et al., 2019; Lysak et al., 2021). Io’s auroral signature is one of the most persistent, stable, and recognizable of Jupiter’s aurora, with a wealth of remote observations made across multiple wavelengths, namely, radio (e.g. Bigg 1964; Queinnec and Zarka 1998) ultraviolet (e.g., Clarke et al., 1996; Prangé et al., 1996; Gérard et al., 2002; Bonfond et al., 2017; Hue et al., 2019), infrared (Connerney et al., 1993; Mura et al., 2018), and visible (e.g. Ingersoll et al., 1998).

More recently, data returned from the Juno spacecraft have provided critical in-situ constraints on the Io-Jupiter interaction, afforded by Juno’s highly inclined orbits that guarantee magnetic field lines mapping to Io’s orbit are sampled near every perijove (PJ) pass. These results have shed light on the various facets of the interaction including electron and proton acceleration (Szalay et al., 2018; 2020a, 2020b), energetic particle dynamics (Paranicas et al., 2019; Clark et al., 2020), magnetic field fluctuations (Gershman et al., 2019), and cross-scale wave-particle interactions (Sulaiman et al., 2020; Janser et al., 2022). Although limited due to the relatively weaker interaction, field and particle observations connected to the orbits of Ganymede and
Europa have also been reported (Allegrini et al., 2020; Szalay et al., 2020c; Hue et al., 2022).

However, a study dedicated to how the Alfvénic Poynting fluxes are related to the electron energy fluxes, as well as estimating the field-aligned current densities of the Io-Jupiter interaction, remain essential pieces of the picture and will be the focus of this letter, where we analyze Io events during Juno’s Prime Mission. Io’s spatially constrained aurora provides a promising opportunity to investigate Jupiter’s underlying auroral processes since the ambiguity of field line mapping is essentially absent (e.g., Allegrini et al., 2020; Mauk et al., 2020, Sulaiman et al., 2022). For this reason, Io’s auroral spot serves as an important fiducial for mapping Jupiter’s magnetic field since the location of Io in its orbit is always known (Connerney et al., 1998; Hess et al., 2011a).

2. Magnetic Field and Electron Observations

Juno crosses magnetic flux tubes connected to Io’s orbit at least twice per perijove pass, in the high latitudes of the northern and the southern hemispheres. The tilt between Jupiter’s dipole and spin axes occasionally allows additional crossings during the same perijove pass. At the time of any given flux tube crossing, there is a longitudinal separation between Juno and Io’s instantaneous location. Measurements of the Io-Jupiter interaction are therefore made along discrete points down-tail of Io’s auroral footprint path.

Four example crossings of flux tubes connected to Io’s orbit at increasing distances down-tail from Io of 2°, 4°, 5°, and 7° during PJ12N, PJ5S, PJ22N, and PJ29N, respectively, are shown in the Supplementary Information (Figure S2). The angular (longitudinal) separation, $\Delta \lambda_{\text{Alfvén}}$, is that between Io and an Alfvén wave trajectory connected to Juno’s footprint (empirically determined by Bonfond et al., 2017), along Io’s orbit. Unlike a simple difference in longitudes or absolute distance down-tail, this parameter was found to be the most robust metric to explain
down-tail changes in electron energy fluxes (Szalay et al., 2020a), revealing an exponentially decaying trend that is consistent with observations and theoretical descriptions of the UV tail emission (e.g., Bonfond et al., 2017).

Figure 1 shows the magnetic field, field-aligned current densities, and electron measurements for these events. Magnetic field measurements, $B_{\text{obs}}$, were acquired by Juno’s fluxgate magnetometer (MAG; Connerney et al., 2017). To assess the field-aligned currents operating on flux tubes connected to Io’s orbit, we analyze the residual magnetic field perturbations, $\delta B$, at the highest available cadence of 64 vectors/s. This is obtained by subtracting the most up-to-date internal magnetic field model (JRM33; Connerney et al., 2021; Wilson et al., 2023) from the measured magnetic field during the intervals of flux tube crossings, i.e., $\delta B = B_{\text{obs}} - B_{\text{JRM33}}$. The external magnetic field contribution from Jupiter’s current sheet is neglected since the measured magnetic field is predominantly of internal origin during the low-altitude, high-latitude passes of Jupiter where Juno crossed the flux tubes connected to an equatorial distance of $\sim$5.9 R$_J$ (1 R$_J = 71,492$ km; Jupiter equatorial radius) where Io’s orbit is located. The relevant coordinate system is the spherical or radial-theta-phi (RTP) which is transformed from relative to Jupiter’s spin axis to the dipole axis (JRM33). The unit vector, $\hat{e}_r$, is in the direction from Jupiter’s center to Juno, $\hat{e}_\theta$ in the direction of increasing magnetic co-latitude, and $\hat{e}_\phi$ in the direction of increasing magnetic east longitude. From Ampère's law, the circulation density of $\delta B$ is directly associated with current densities.

The field-aligned current density, $j_{||}$, is calculated using Ampère’s law and neglecting the displacement current. In the low-altitude, high-latitude region where Juno makes these measurements, the field-aligned vector can be approximated as the radial vector, $\hat{e}_r$. We therefore estimate the field-aligned current as follows:
\[ j_{||} \approx \pm j_r = \frac{\pm 1}{\mu_0 r \sin \theta} \left[ \frac{\partial (B_\varphi \sin \theta)}{\partial \theta} - \frac{\partial B_\theta}{\partial \varphi} \right] \hat{e}_r \]  

(1)

where \( \mu_0 \) is the permeability of free space, \( r \) is the radial distance from Jupiter’s center to Juno, \( \theta \) and \( \varphi \) are the colatitude and east longitude of Juno, respectively, with respect to the JRM33 magnetic dipole axis, and the ± signs correspond to the northern and southern hemispheres, respectively. A caveat with this approach is that the magnetic field fluctuations cannot be uniquely related to currents since single-spacecraft measurements cannot separate temporal and spatial dependences. The underlying assumption is therefore that these fluctuations are primarily spatial, and the gradients are along the spacecraft direction which is reasonable since the angle between the spacecraft velocity vector and \( B_\theta \) is nearly orthogonal.

3. Analysis and Interpretation

The top and middle panels of Figure 1 show that the perturbations, primarily \( \delta B_\varphi \), and their gradients and hence field-aligned current densities generally decrease with \( \Delta \lambda_{\text{Alfvén}} \). This is expected since the strength of the interaction decays down-tail, thus relaxing the requirement to maintain field-aligned currents. Most notably for PJ12N, which is understood to be the Main Alfvén Wing (MAW), the general current structure in the northern hemisphere is such that as Juno travels in the direction of increasing magnetic co-latitude, it measures downward then upward current regions with respect to Jupiter. This translates to an electric current flowing into Io’s northern Alfvén wing on Io’s sub-Jovian hemisphere and away on Io’s anti-Jovian hemisphere. Current substructures are present on top of this general structure. The bottom panels of Figure 1 show the electron differential energy fluxes (DEF), measured by Juno’s Auroral Distributions Experiment (JADE-E; McComas et al., 2017), and ordered by pitch angle at 1s cadence with estimated loss cone angles overlaid (dashed white lines). The loss cone angle is
estimated using the magnetic field model to determine which local pitch angle corresponds to a
mirror point at the 1 bar level. Non-Io fluxes have been subtracted using the same method
described in Szalay et al. (2020a). Despite intermittent “blind spots” in the pitch angle coverage
(gray regions), the loss cone is well resolved for each event revealing field-aligned electron
populations during the flux tube crossings. The events in Figure 1 correspond to the respective
passes in Figure S2 and represent some of the largest field-aligned currents densities and peak
electron energy fluxes (EF) in our sample. It is clear for the PJ12N MAW event that the electron
travel directions are opposite to and therefore consistent with the current directions.

The Poynting flux (PF) was also calculated for each event. Similar to the technique employed by
Gershman et al. (2019), we find the root-mean-square of the magnetic field, $\delta B_{\text{rms}}$, perturbations
within a specified frequency range and calculate the Poynting flux as $\delta B_{\text{rms}}^2 c/\mu_0$. This assumes
that the fluctuations are purely those of electromagnetic waves with an Alfvén speed approximating the speed of light, i.e., $\delta E(f) \sim c\delta B(f)$. One caveat here is that phase mixing from
the superposition of incident and reflected waves can alter $\delta E(f)/\delta B(f)$, however this cannot be
addressed with the absence of a low-frequency vector electric field instrument. Unlike Gershman
et al. (2019), however, rather than calculating $\delta B_{\text{rms}}$ within a fixed frequency range for different
events, we account for the variable altitudes among the sample by selecting a frequency range
between $5 \times 10^{-5}$ and $1 \times 10^{-3}$ times the proton cyclotron frequency, $f_{cH^+}$, well below the theoretical
upper limit of the Alfvén mode. The magnetometer’s Nyquist frequency of 32 Hz for a cadence
of 64 vectors/s, as well as attention to the spectral noise floor, guided the selection of this
frequency range (see Supplementary Information for more details on this technique). The
calculated Poynting flux is therefore underestimated. That said, since most of the power resides
in the lowest frequencies, we conclude that the underestimation is very mild and not dissimilar
from the Poynting flux across the entire frequency range below $f_{cH^+}$, given the power law behavior of the spectral density. Indeed, we will show later a consistency between theoretical and observed powers. The peak electron energy flux (EF) was also calculated by summing the products of DEF and widths of energy bins over JADE-E’s energy steps and accounting for the area-projected weighted size of the loss cone above Jupiter’s atmosphere with a factor of $\pi$ (Szalay et al., 2020a).

Figures 2a and 2b present the calculated Poynting fluxes and the electron energy fluxes as a function of $\Delta \lambda_{\text{Alfvén}}$, respectively, both in mW/m$^2$. For the PF, the number of events that can be analyzed is limited by the signal-to-noise ratio in the magnetometer. Particularly close to Jupiter, identifying small and real perturbations in the magnetic field in the presence of a very strong background magnetic field can be challenging. For this reason, we have a greater proportion of events at low $\Delta \lambda_{\text{Alfvén}}$ where $\delta B$ is larger during these low-altitude passes. Juno’s altitudes during these events are all within 1 R$_J$. PF and EF are highly correlated, both exhibiting decays down-tail and differ consistently with one another by one order of magnitude. The correlation coefficient on the log-log regression yields $r^2 = 0.86$. It is worth noting that an event during PJ18N recorded a very strong interaction, likely on the Main Alfvén Wing, however Juno was at an exceptionally high altitude of 3.33 R$_J$ and closer to Io than Jupiter, with $f_{cH^+}$ an order of magnitude lower than that of the other events, thus preventing a direct comparison of the Poynting flux to be made with the other events. Furthermore, the electron loss cone was not resolved for PJ18N and the energy flux could not be determined (Szalay et al., 2020b). PJ12N is a prime candidate for a Main Alfvén Wing (MAW) crossing as all in-situ instruments measured to date the largest electron and proton energy fluxes, electric and magnetic field spectral densities, and Poynting flux associated with a flux tube connected to Io’s orbit (Gershman et al.,
2019; Clark et al., 2020; Janser et al., 2022; Sulaiman et al., 2020; Szalay et al., 2020b). Here we show that $\delta \mathbf{B}$, the field-aligned current densities, and power are also largest for this event.

Hess et al. (2010) estimated the theoretical efficiencies for three distributions of the power transferred from an Alfvén wave into accelerating electrons at 1 RJ above Jupiter's ionosphere and accounting for the fraction of Alfvén wave power escaping the torus. They compute: (i) a long-scale, unfilamented distribution where the wavelength of the Alfvén wave is large and refraction is high – the efficiency is 0.05%; (ii) filamented waves obtained through a turbulent cascade with a power law spectrum between the injection and dissipation scales – the efficiency is 4-10%; and (iii) secondary short-scale distribution due to the filamentation of the long-scale Alfvén wave by compressional modes – the efficiency is ~100%. In our analysis, Figure 2c shows our efficiencies, $\eta$, calculated as the ratio of EF to PF. PJ12N gives an efficiency of 13%, suggesting that the observations in the MAW are fully consistent with a filamented (power law) distribution. Indeed, using Galileo plasma wave spectra, Chust et al. (2004) postulated that observed high-frequency/small-scale electric field fluctuations in the equatorial region during Io flybys can be interpreted as signatures of strong filamentation of Io’s Alfvén wings before they reflect off the density gradient of the Io torus. We further calculate the efficiencies for events down-tail and find mean and median efficiencies of 7.7% and 5.5%, respectively. We note that these studies by Chust et al. (2004) and Hess et al. (2010) focused on the MAW and not on the emission down-tail as these are complicated by reflected Alfvén waves. A transmission coefficient need not be taken into account for our calculated efficiencies because, at least for the MAW, the local measurements are compared to theoretically computed efficiencies at high latitudes. The efficiencies we derive should be taken as an upper limit, because the Poynting...
fluxes in the Alfvén waves must invariably be larger than what is measured after a fraction of the electromagnetic energy is converted into electron kinetic energy.

The Poynting flux (in mW/m²) in the MAW can be converted to the total power (in W) by multiplying by $\pi \times (1.3R_{Io})^2$ and by a scaling factor of $(B_{Io}/B_{Juno})$, where $B_{Io}$ and $B_{Juno}$ are the magnetic field strengths at Io’s orbit and Juno, respectively, $R_{Io}$ the radius of Io and the factor of 1.3 assumed to accommodate the effective radius due to Io’s ionosphere (Saur et al., 2013). The measured Poynting flux of 4350 mW/m² during PJ12N yields a power of $450 \times 10^9$ W, well within the range of $288 – 1660 \times 10^9$ W theoretically computed by Saur et al. (2013). Again, this should be taken as a lower limit since some fraction of the wave power is transferred to the electrons. The value at the lower end of the range is likely because Io was located at a high (southern) centrifugal latitude, where the interaction is weaker. Io and Juno were also on opposite hemispheres, so the actual power may be up to a factor of 2 greater assuming a 50% transmission coefficient. The power for the down-tail events have also been estimated using this method, similarly exhibiting a decaying trend as shown in Figure 3a.

Figure 3b shows the peak 1s-averaged $|\mathbf{j}_\parallel|$, as a function of $\Delta \lambda_{Alfvén}$ for 10 of the 12 events and scaled to Io’s orbit. The gradients in $\delta \mathbf{B}$ for the two largest $\Delta \lambda_{Alfvén}$ were too small to confidently calculate $\mathbf{j}_\parallel$. Similarly, there is a clear, general trend of decaying $|\mathbf{j}_\parallel|$ as $\Delta \lambda_{Alfvén}$ increases, consistent with the decaying UV brightness with down-tail distance (Bonfond et al., 2017; Gérard et al., 2002; Szalay et al., 2020a). The peak $|\mathbf{j}_\parallel|$, scaled to Io’s orbit, for the MAW was found to be 0.16 $\mu$A/m² (1.0s-averaged) or 0.18 $\mu$A/m² (0.5s-averaged). Considering an area of the interaction region, $\pi \times (1.3R_{Io})^2$, a simple estimate of the current is 2.8 MA or 3.2 MA, respectively. During the Voyager era, Acuña et al. (1981) derived $2.8 \pm 0.1$ MA assuming the currents flow on the periphery of a cylinder of Io’s diameter. In practice, however, the interaction
region is extended beyond Io’s surface owing to its conductive ionosphere. There are differences
that should be considered between the Voyager and Juno events, namely Io’s position with
respect to the centrifugal equator, and possible differences in ionospheric conductivity, as well as
experimental differences in resolution and averaging. A current of ~1 MA is estimated from
theoretical considerations (Hess et al., 2010) and 5 MA from plasma simulation of the Voyager
event (Saur et al., 1999). Although these estimations are broadly consistent with one another, it is
important to note that the current-carrying fluxtube is unlikely to be circular in the orbital plane,
but rather extended along Io’s wake. The structure of the current system is therefore more
complex and needed for accurate conversion between current density and total current.

For each parameter discussed here there is also variability among events of similar Δλ Alfvén. We
explore the possibility of a dependence from Io’s position with respect to the centrifugal equator,
the plane within which plasmas of iogenic origin are confined. This is geometrically defined by
the loci of points where each magnetic field line is at its farthest distance from Jupiter’s spin
axis. The centrifugal plane is tilted from the jovigraphic equator at ~2/3 the dipole tilt and has a
scale height of ~1 R_J (Khurana et al., 2004). As a result, Io is subjected to variability in the local
magnetic field and density at the synodic period as the centrifugal equator sweeps through in its
rest frame (Hess et al., 2010). The centrifugal latitude, θ_c, is solely a function of Jupiter’s
longitude with Io located at the centrifugal equator at ~110° and ~290° System-III west-
longitude, λ_SIII. Figures 3c and 3d show the distributions of θ_c and λ_SIII of Io for each analyzed
event. Strictly, this is Io’s instantaneous position when the initial disturbance was launched
instead of Io’s present position when Juno measured the disturbance down-tail. This therefore
brings the position of Io closer to Juno. Firstly, we magnetically map Juno’s position to Jupiter,
assumed to be instantaneous since the Alfvén speed is nearly the speed of light at the tenuous
high latitudes. The mapped position, considered Io’s footprint on Jupiter, is then used to infer
Io’s initial $\lambda_{SIII}$ position from Bonfond et al. (2017). Finally, Io’s $\lambda_{SIII}$ is converted into $\theta_c$ using an
empirically derived model by Phipps and Bagenal (2020).

It is expected that the interaction is strongest when Io is at the center of the centrifugal equator,
i.e., at the location of maximum density where collisions between the torus ions and Io’s
atmosphere lead to enhanced momentum exchange. However, this does not appear to explain the
differences in Poynting fluxes and current densities among neighbouring events such as PJ5S
and PJ22N for $\Delta\lambda_{Alfvén} \approx 5^\circ$, where one would expect an anti-correlation between the variables
and $|\theta_c|$. PJ29N with a near-equatorial interaction also does not appear to have a markedly greater
power or field-aligned current density. This lack of dependence is likely attributed to the
increasing uncertainty in determining Io’s original position, and thus original $\theta_c$, as the angular
separation between Io and Juno increases. This is due to the variable Alfvén bounce times to
both hemispheres and back to the equator, itself a function of $\lambda_{SIII}$ and ranges between 25 to 30
mins (Hinton et al., 2019).

More importantly, while the average UV brightness of Io’s auroral footprint (connected to the
MAW) was shown to be modulated by Io’s SIII longitude, it displayed significant variability for
any given longitude, with asymmetries between hemispheres also present (Bonfond et al., 2013;
Wannawichian et al., 2013; Hue et al., 2019). Hess et al. (2013) modelled the acceleration
mechanism and Alfvén wave propagation effects showing that the variability could be explained
by a modulation in the efficiency with longitude. There also exists a stark, and yet unexplained,
asymmetry in UV brightness of the Io footprint between $\lambda_{SIII} \sim 110^\circ$ (stronger) and $\sim 290^\circ$
(weaker), both when Io is embedded in the centrifugal equator. The interaction is further
complicated by finer details such as variations in inter-spot distances (Bonfond et al., 2008;
2017; Moirano et al., 2021) and the breaking of the tail symmetry into an alternating Alfvén spot
street (Mura et al., 2018) that was recently explained by Poynting flux morphologies possibly
due to the Hall effect in Io’s ionosphere (Schlegel and Saur, 2022). Future work may attempt to
address these phenomena as Juno progresses into its Extended Mission phase with more
opportunities to sample the Io-Jupiter interaction. Finally, modelling will be required to constrain
the detailed structure of the field-aligned current system between Io and Jupiter (e.g., Kotsiaros
et al., 2022).

4. Conclusions
This letter presents a study on the magnetic field signatures associated with the Io-Jupiter
interaction during Juno’s Prime Mission. We derive Poynting fluxes and field-aligned current
densities and relate these quantities to previously measured electron energy fluxes. Our main
conclusions are as follows:

• The strongest Poynting flux and field-aligned current densities, inferred from the largest
  perturbations in the magnetic field were measured during Juno’s crossing of Io’s Main
  Alfvén Wing during PJ12N. The electromagnetic power has a lower limit of $450 \times 10^9$ W
  and is consistent with theoretical predictions (Saur et al., 2013). Here, Io was south of the
  centrifugal equator, and we therefore anticipate even stronger power and currents when
  Io is embedded in the centrifugal equator.

• The available Poynting flux from the magnetic field fluctuations exhibit a decaying trend
down-tail of Io and are highly correlated with electron energy fluxes ($r^2 = 0.86$). The
  Poynting fluxes are consistently about an order of magnitude greater than the electron
  energy flux indicating an acceleration efficiency of $\sim 10\%$ and fully consistent with
theoretically derived efficiencies from energization of filamented waves obtained through a turbulent cascade (Hess et al., 2010; 2011b).

- The field-aligned current densities exhibit a decaying trend down-tail of Io, consistent with measured UV brightness (Bonfond et al., 2017) and electron energy fluxes (Szalay et al., 2020a).

- It is worth noting, in the interest of comparative planetology, that the Main Alfvén Wing of Enceladus was also sampled by the Cassini spacecraft at Saturn’s high latitudes (Sulaiman et al., 2018). The estimated equatorial field-aligned current is of $\sim 10$ kA, which is $\sim 10^5$ times weaker than the Io-Jupiter interaction. The total generated power is modelled to be $\sim 10^4$ times weaker (Hess et al., 2011; Saur et al., 2013).

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**Open Research**

MAG and JADE data used in this article are at https://doi.org/10.17189/1519711 and https://doi.org/10.17189/1519715, respectively and are publicly accessible through the Planetary Plasma Interactions Node in the Planetary Data System (https://pds-ppi.igpp.ucla.edu/).
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Kotsiaros, S., et al. (2022), Juno probes the electrodynamic interaction between Jupiter and Io, AGU Fall Meeting 2022


Figure 1 – (top panels) Time series of magnetic field perturbations, \( \delta B \), when Juno crossed flux tubes connected to Io’s orbit. All are presented on the same scale. The perturbations were computed by subtracting the JRM33 internal magnetic field model from the measured magnetic field. We further subtract the residuals from the interval average to bring the baseline field close to the zero line. The coordinate system is the radial-theta-phi with respect to Jupiter’s JRM33 dipole axis. Perturbations of \( \delta B_\phi \) are indicative of field-aligned currents with the sign of the gradients related to the current direction, i.e., towards or away from Jupiter. (middle panels) Computed 1s-averaged field-aligned current densities from \( \delta B \) using Equation 1. (bottom panels) Pitch angle spectrograms of background (non-Io) subtracted differential energy flux. Overlaid as white dashed lines are the loss cone angles.
Figure 2 – (a) Poynting fluxes, measured locally, as a function of $\Delta \lambda_{\text{Alfvén}}$. (b) Peak electron energy fluxes, measured locally, as a function of $\Delta \lambda_{\text{Alfvén}}$. (c) Efficiency, or fraction of electron energy to Poynting fluxes, as a function of $\Delta \lambda_{\text{Alfvén}}$. The grey rectangle is the range of efficiencies (4 – 10%) theoretically computed by Hess et al. (2010) for filamented waves obtained through a turbulent cascade. (inset) Illustration of how $\Delta \lambda_{\text{Alfvén}}$ is defined (Szalay et al., 2020a).
Figure 3 – (a) Power as a function of $\Delta \lambda_{\text{Alfvén}}$. The power is calculated by multiplying the local Poynting flux (in mW/m²) by the area of Io using an effective radius of $1.3R_{\text{Io}}$, and scaling to Io’s orbit along the magnetic flux tube as $B_{\text{Io}}/B_{\text{Juno}}$. The blue vertical line on the PJ12N-MAW event represents the range of powers theoretically modelled by Saur et al. (2013). (b) Peak (of the modulus) 1s-averaged field-aligned current densities ($|j_{\parallel}|$), scaled to Io’s orbit, as a function of $\Delta \lambda_{\text{Alfvén}}$. (c) Estimate of Io’s centrifugal latitude at the time when the initial Alfvén wave was launched. (d) Estimate of Io’s System-III west longitude corresponding to its centrifugal altitude in (c).