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Key Points:

- Juno's likely crossing of Io's Main Alfvén Wing (MAW) during PJ12 reveals evidence of transverse ion acceleration
- Observations suggest wave-particle interactions with ion cyclotron waves as the favored acceleration mechanism; however, Alfvén acceleration was not ruled out
- Ion conics generated in Io's footprint tail or near the MAW are more intense and energetic than observed in other auroral regions

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Energetic Proton Acceleration Associated With Io's Footprint Tail

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Abstract Observations of energetic charged particles associated with Io's footprint (IFP) tail, and likely within or very near the Main Alfvén Wing, during Juno's 12th perijove (PJ) crossing show evidence of intense proton acceleration by wave-particle heating. Measurements made by Juno/JEDI reveal proton characteristics that include pitch angle distributions concentrated along the upward loss cone, broad energy distributions that span ~50 keV to 1 MeV, highly structured temporal/spatial variations in the particle intensities, and energy fluxes as high as ~100 mW/m². Simultaneous measurements of the plasma waves and magnetic field suggest the presence of ion cyclotron waves and transverse Alfvénic fluctuations. We interpret the proton observations as upgoing conics likely accelerated via resonant interactions with ion cyclotron waves. These observations represent the first measurements of ion conics associated with moon-magnetosphere interactions, suggesting energetic ion acceleration plays a more important role in the IFP tail region than previously considered.

Plain Language Summary NASA's Juno spacecraft orbits Jupiter's polar region and makes direct measurements of the fields and particles that are responsible for creating Jupiter's powerful auroras. In this article, we present new observations that show intense proton acceleration occurring at altitudes near the auroral emissions created by the interaction between Jupiter's moon Io and the surrounding plasma and magnetic field environment. These unique observations provide clues on how particles are being accelerated and will help constrain particle acceleration theories.

1. Introduction

Juno's exploration of Jupiter's polar magnetosphere (Bagenal et al., 2017; Connerney, Adriani, et al., 2017) has given prominence to the "far-field" region of the Io-Jupiter interaction with new in situ measurements of Io's footprint (IFP) tail auroral emissions. The far-field interaction specifically refers to the electromagnetic coupling between Io and Jupiter's ionosphere. Decades of remote observations have established that Io generates steady auroral emissions in the radio (Bigg, 1964; Queinnee & Zarka, 1998; Zarka, 2000), infrared (Connerney et al., 1993), and ultraviolet wavelengths (Clarke et al., 1996; Prangé et al., 1996). Furthermore, more recent HST observations and analyses have characterized its auroral structuring (Bonfond et al., 2008) and correlated brightness changes with Io's centrifugal latitude and system III longitude (Bonfond et al., 2013; Gerard et al., 2006; Hue et al., 2019). Previous flybys of Io from the Voyager and Galileo missions mapped out the local Io-plasma interaction. Plasma and energetic particle (e.g., Belcher et al., 1981; Frank et al., 1996; Gurnett et al., 1996; Williams et al., 1996) and magnetic field (e.g., Acuña et al., 1981; Kivelson et al., 1996) perturbations were not only observed and consistent with theories of Alfvén wing model but also have been discussed in the context of a unipolar inductor model (e.g., Bagenal, 1983; Crary & Bagenal, 1997;

Goertz, 1980; Goldreich & Lynden-Bell, 1969; Gurnett & Goertz, 1981; Neubauer, 1980; Saur, 2004). Since the Galileo epoch, HST observations (Bonfond et al., 2008, 2009) and modeling efforts (Hess et al., 2010, 2013; Jones & Su, 2008; Saur et al., 2013) have propelled our understanding of electron acceleration mechanisms generating the Io footprint, for example, highlighting the importance of inertial Alfvén waves. In situ measurements from the Juno mission are revealing new aspects of Io's auroral interaction, which will help further ideas surrounding how particles are accelerated in this region.

Recent analyses of the Juno magnetic field (Gershman et al., 2019), plasma wave (Sulaiman et al., 2020) and the low-energy charged particle data (Szalay et al., 2018; Szalay, Allegrini, et al., 2020; Szalay, Bagenal, et al., 2020) almost universally depict Alfvénic acceleration as a notable, if not dominant, electron acceleration mechanism (Damiano et al., 2019) associated with the IFP tail. More specifically, Gershman et al. (2019) found evidence of transverse magnetic field fluctuations consistent with strong magnetohydrodynamic (MHD) turbulence that can supply $\sim 3,000 \text{ mW/m}^2$ of Alfvénic Poynting flux near Io's Main Alfvén Wing (MAW). Similarly, plasma wave observations presented by Sulaiman et al. (2020) show evidence of inertial Alfvén waves, intense ion cyclotron waves, and whistler-mode auroral hiss radiation. Field-aligned low-energy (100 eV/Q to 100 keV/Q) electron beams with broadband energy distributions further support the existence of whistler-mode hiss and the imprints of stochastic particle acceleration via Alfvén waves (Szalay et al., 2018). Finally, a detailed look at the low-energy (10 eV/Q to 46 keV/Q) ion population suggests there is also a significant amount of proton acceleration occurring both at the high latitudes (in similar locations to the electrons) and near the Io torus “boundary”—leading Szalay, Bagenal, et al. (2020) to hypothesize that Alfvén waves generated near Io may be an important acceleration mechanism for the protons as well.

In this work, we are motivated by the aforementioned studies (e.g., Gershman et al., 2019; Sulaiman et al., 2020; Szalay, Allegrini, et al., 2020; Szalay, Bagenal, et al., 2020) to present the higher-energy charged particle observations with a particular focus on the proton data obtained during Juno's 12th perijove (PJ) crossing of the IFP tail in the northern hemisphere. We focus on the proton measurements because the Jupiter Energetic particle Detector Instrument (JEDI) (Mauk, Haggerty, Jaskulek, et al., 2017) observed the most significant ion acceleration event to date, strongly suggesting that the electromagnetic coupling between Io and Jupiter is responsible for energizing protons up to $\sim 1 \text{ MeV}$ away from the planet. We compare these data to the magnetic field (Gershman et al., 2019) and plasma wave (Sulaiman et al., 2020) data from the same PJ12 IFP tail crossing near the MAW to better understand the underlying physics governing this unusually intense and unexpected event.

2. Observations

2.1. Juno's Crossing of the IFP Tail

The data presented here were collected on the inbound leg of PJ12 as Juno crossed the IFP tail in the northern hemisphere between $\sim 09:20:35$ and $09:20:55 \text{ UT}$ on 2018-091 (1 April 2018). Figure 1 is a trajectory schematic comprised of three different representations. Figure 1a illustrates Juno's intersection of a field line that maps to 5.9 R_J (where $1 \text{ R}_J = 71,492 \text{ km}$), that is, Io's orbital position, in a cylindrical magnetic dipole coordinate system. Figure 1b is a northern polar projection of Jupiter's auroral regions in system III coordinates that encompasses the Io footprint tail (purple curve), Juno's magnetic footprint (orange curve)—calculated using the JRM09 model (Connerney et al., 2018), and the statistical position of the main auroral oval (black trace) derived from Hubble Space Telescope (HST) observations (e.g., Grodent et al., 2003). Juno crossed the IFP tail at an altitude of 0.39 R_J and with a longitudinal separation of approximately 1.7° from Io's MAW spot (e.g., Bonfond et al., 2009) when accounting for the Alfvén wave trajectory bendback between Io and Jupiter's ionosphere. This remains Juno's closest approach to the MAW and potentially a direct crossing (Szalay, Allegrini, et al., 2020). Figure 1c shows Juno ultraviolet spectrometer (UVS) (Gladstone et al., 2017) observations of Jupiter's main auroral oval and the IFP tail approximately 6 min prior to Juno crossing IFP tail. The UVS data are presented in a system III coordinate system with the red trace representing Juno's magnetic footprint.

2.2. Brief Description of Juno/JEDI

We focus on observations made by Juno's JEDI. JEDI comprises three sensors (J90, J180, and J270) which measure the energy, angular, and compositional distributions of $>25\text{-keV}$ electrons and $>10\text{-keV}$ ions

Figure 1. Io footprint tail crossing geometry. (a) Juno's trajectory in cylindrical magnetic coordinates with Io's M-Shell overlaid. (b) Magnetic footprints of Juno (orange curve), Io (purple), and the statistical location of Jupiter's main emission depicted by the bounding black curves. (c) Similar representation as panel (b) but illustrates the ultraviolet footprint overlaid for reference (red curve). Juno/UVS observations occurred approximately 6 min before Juno crossed the IFP.

(Mauk, Haggerty, Jaskulek, et al., 2017). During this event, the J90 and J270 sensors operated in a high rate mode, thus accumulating time-of-flight by energy rates for 0.25 s at a cadence of 0.5 s, with no sector averaging. Pitch angle distributions were obtained by combining the JEDI measurements with the measured local magnetic field from Juno/MAG (Connerney, Benn, et al., 2017). The geometric loss cone size at this time is 40° based on the dipole field approximation and 51° based on the JRM09 magnetic field model (Connerney et al., 2018). Both methods agree well with the measured loss cone distributions in the ion data. Each solid-state telescope has a full width at half maximum field-of-view (FoV) that is approximately $\sim 17^\circ \times 9^\circ$ and therefore can resolve the loss cone in this region. The duration of the

footprint tail crossing is ~ 20 s, which is shorter than it takes Juno to complete one revolution (Juno spins at approximately two revolutions per minute). This is important because instantaneous look directions and pitch angle averaging between the two sensors can average out fine structure in the IFP tail region. Therefore, we choose to perform all integral moment calculations, that is, characteristic energies and energy fluxes, using a 1-s sampling window over a pitch angle range that contains just the upward moving protons (between 40° and 90°). The integral moment equations are outlined in Mauk et al. (2004) and Clark et al. (2018).

2.3. Energetic Charged Particle Observations

Figure 2 presents an overview of the energetic charged particles (Figures 2a–2d) as well as the plasma wave electric field spectral densities (Figure 2e) from Sulaiman et al. (2020) and the transverse magnetic field fluctuations (Figure 2f) from Gershman et al. (2019). Plasma wave and magnetic field measurements were obtained from Juno's Waves (Kurth et al., 2017) and magnetic field (Connerney, Benn, et al., 2017) investigations, respectively. The most prominent feature observed by JEDI is the dramatic proton intensity and pitch angle enhancements (Figures 2c and 2d) corresponding to the IFP tail. In Figure 2d, protons in the IFP tail are shown to be concentrated along the loss cone (horizontal dashed lines) in the upward direction. There is also evidence of ions streaming upward along the local magnetic field line, but that feature only persists for ~ 1 s. We do not discuss it further here. The energy-time distribution of the protons (Figure 2c) reveal broad energization ranging from ~ 50 keV to upward of ~ 1 MeV. During the same time interval, the energetic electrons only show a modest response associated with the IFP tail. Figures 2a and 2b show a slight enhancement in low-energy (< 60 keV) electrons and a slight decrease in the very energetic electron environment (> 1 MeV), which leaves a signature indicated by the characteristic penetrating charged particle band—a range of residual energies generated by electrons fully penetrating the SSDs—near 160 keV (Mauk et al., 2018). While ions show significant intensities in the upward loss cone, electrons mostly populate the downward loss cone.

Figure 3 shows proton energy spectra and pitch angle distributions for various times associated with IFP tail crossing. The energy distribution of the protons resemble a power law—monotonically decreasing intensities toward increasing particle energy (see Figure 3, left panel). There is no clear evidence of peaked or accelerated Maxwellian-like energy distributions, representative of quasi-static magnetic field-aligned electric fields (Clark, Mauk, Paranicas, et al., 2017; Mauk, Haggerty, Paranicas, et al., 2017; Mauk et al., 2018). In Figure 3, the energy spectra from published Juno/JEDI proton observations are compared (Clark, Mauk, Haggerty, et al., 2017; Mauk et al., 2018). The observations made in the footprint tail suggest that the protons are more efficiently accelerated than in the other auroral regions, which can be seen by the power law curves representing $E^{-2.5}$ and $E^{-3.5}$. Pitch angle distributions for two different times show clear peaks with centroids near 53° and a full width at the 10% level of $\sim 30^\circ$. Error bars in Figure 3 are determined by estimating the counting uncertainties associated with a Poisson distribution.

In Figure 4, we provide a closer inspection of the energy-time structuring and show the integral moments calculated using a 1-s sampling window over a pitch angle range that contains just the upward moving protons (between 40° and 90°). The energy-time spectrogram in Figure 4a shows discrete stripes that occur somewhat regularly throughout the ~ 20 -s IFP tail crossing. Similarly, in Figure 4b, the 100-keV proton intensities are chosen to highlight the variations, which fluctuate by factors of 3–10 on intervals as short as 1 s. Juno provides just a single point measurement and cannot disentangle the temporal/spatial ambiguity; therefore, the 2- to 3-s variations may also be associated with fine spatial structures in the auroral region. It is possible that the variations are a measurement artifact due to the finite angular resolution of JEDI. A crude analysis suggests that a collimated beam of particles can produce an ~ 2 -s variation in JEDI as a result of Juno's $12^\circ/\text{s}$ rotation rate combined with the $\sim 27^\circ$ separation between the JEDI telescopes. This sort of temporal variation is observed in the polar cap where electron beams are often narrower than JEDI can resolve (Mauk, Haggerty, Jaskulek, et al., 2017; Paranicas et al., 2018). In this particular event, the variation is likely not an artifact because the measured width of the proton pitch angle distribution is relatively broad, that is, $\sim 30^\circ$ (see Figure 3), compared to a single telescope FoV.

The integral moments associated with the IFP tail crossing show energetic protons characteristic energies varying between ~ 80 and 400 keV (with a mean ~ 200 keV) (Figure 4c) and likewise the proton energy fluxes (Figure 4d, averaged over pitch angles 40° to 90° from ~ 50 keV to 1 MeV) to vary between ~ 10 and

Figure 2. Particles and fields overview of the Juno PJ12 IFP tail crossing. (a–d) The Juno/JEDI observations of the energetic electrons and protons. (a and b) Energetic electron energy-time and pitch angle-time spectrograms, respectively. (c and d) Energetic proton energy-time and pitch angle-time spectrograms, respectively. (e) Electric field frequency-time spectrogram and (f) magnetic field frequency-time spectrogram. The black dashed lines in (c) and (d) represent the size of the loss cone in degrees using the dipole field approximation. The black solid curve in (e) represents the proton cyclotron frequency derived by Juno/MAG (Sulaiman et al., 2020).

Figure 3. Measured energy spectra (left panel) and pitch angle distributions (right panel). For comparison purposes, energy spectra of proton conic distributions observed during PJ1 (Clark, Mauk, Paranicas, et al., 2017) and PJ7 (Mauk et al., 2018) are also shown as well as power law curves illustrating the different spectral slopes.

Figure 4. (a) JEDI J90 and J270 combined proton energy-time spectrogram filtered on pitch angles 40° to 90°; (b) 100-keV proton intensities; (c) >50-keV proton characteristic energies; (d) J90 (black diamonds), J270 (gray triangles) energetic proton energy flux versus JADE-E (blue circles) energy fluxes of plasma electrons < 40 keV.

~ 100 mW/m² for the J90 sensor and ~ 1 and ~ 30 mW/m² for the J270 sensor. Note that instantaneous pitch angle coverage is attributed to these differences. For comparison, we show the plasma electron (100 eV to 40 keV) precipitating energy fluxes (Szalay, Allegrini, et al., 2020) measured by Juno/JADE-E (McComas et al., 2017). JADE-E energy fluxes vary between ~ 3 and 600 mW/m².

3. Discussion and Conclusions

The angular distribution of energetic protons along the upward loss cone reveal strong evidence for energetic ion conic acceleration associated with IFP tail and probably the MAW. Ion conics are the result of thermal ionospheric ions heated perpendicular to the magnetic field via wave-particle interactions and then accelerated upward due to gradients in the magnetic field and/or field-aligned electric fields (e.g., Carlson et al., 1998; Chang, 1993; Gorney et al., 1985; Klumpar, 1979; Lynch et al., 2002; Retterer et al., 1994). Wave heating alone does not produce the most energetic ions; therefore, it is thought that electrostatic confinement via magnetic field-aligned potentials is required to trap the ions and further accelerate in the wave-heating region. This is referred to as the so-called “pressure cooker” mechanism (e.g., Gorney et al., 1985). Observations from Parker Solar Probe close to the Sun (Mitchell et al., 2020), Cassini at Saturn (Mitchell et al., 2009), and Juno at Jupiter (Clark, Mauk, Paranicas, et al., 2017) have confirmed their existence elsewhere in the solar system but have not been directly observed as a result of planet-moon interactions. Below, we discuss possible proton acceleration mechanisms associated with the IFP tail.

The first mechanism we consider is a cyclotron resonant heating mechanism. Sulaiman et al. (2020) analyzed the Juno/Waves measurements during the PJ12 IFP tail crossing and found evidence of upward-propagating, left-hand polarized ion cyclotron waves with large spectral densities (maximum of $\sim 10^5$ V²/m²/Hz) near and at the proton cyclotron frequency. Using the theoretical energy transfer relationship from Chang et al. (1986), Sulaiman et al. (2020) estimated the ion heating rate, denoted as $dW_{\perp}/dt$, to have an upper limit of ~ 500 eV/s. To estimate the proton energies achievable from this heating rate, we need to know the time-of-flight of the ions between their source region and the spacecraft. First, the altitude of the source region can be estimated from the measured pitch angle distributions, shown in Figure 3, and by assuming the first adiabatic invariant is conserved as the protons are transported along the magnetic field. We also assume the protons are heated purely perpendicular to the local magnetic field, that is, pitch angles of 90°, in the source region (see similar method outlined in Clark, Mauk, Paranicas, et al., 2017 and references therein) and neglect changes in an ion's pitch angle as it is transported along the field line. The measured local magnetic field during the IFP tail crossing is $\sim 3 \times 10^5$ nT and the centroid of the proton pitch angle distributions vary between $\sim 50^\circ$ and 60° . Combining this information together and using the latest magnetic field model (JRM09; Connerney et al., 2018), we find the source location to be $\sim 11,000$ km or $0.16 R_J$ above Jupiter's 1-bar oblate surface. The last piece of information required is the bulk velocity of ions in Jupiter's ionosphere. The only published ion bulk flow measurements in this region to date are from a study of low-energy ions in Jupiter's topside ionosphere using the JADE-Ion sensor (Valek et al., 2020). The authors performed a numerical integration of the plasma proton distributions and derived an outflow speed, v_{bulk} , of 20 km/s. Here, we assume this to be the outflow speed of the protons in the region connected to the IFP tail, and thus, the time-of-flight of the protons is estimated to be approximately $t \approx 900$ s where, $t = d/v_{bulk}$, where $d = 18,500$ km is the integrated length along the field between Juno at $0.33 R_J$ and the source region at $0.16 R_J$. Multiplying the proton's time-of-flight with the heating rate derived by Sulaiman et al. (2020) suggests ion cyclotron heating may be able to produce conic energies as large as 450 keV. This number is commensurate with the characteristic energies of the proton observations in the IFP tail (see Figure 4c). Major limitations of this crude estimate include the assumption that the wave heating is constant along the flux tube between the source region and the spacecraft and the bulk ion speed remains the same. While the wave-heating assumption appears to be reasonable in Earth's auroral region (e.g., Lynch et al., 2002), it is uncertain if the same holds true for Jupiter. Next, we consider the role of Alfvén waves as a possible energization mechanism.

The second mechanism we consider is Alfvénic acceleration. One striking observation can be found in Figure 4d that shows the energetic ion energy flux as being comparable to the 0.1- to 40-keV electron energy flux, suggesting the energy partitioning between the two charged particle populations is similar. To estimate a power conversion efficiency, we use observations from magnetic field data. Gershman et al. (2019) analyzed the magnetic field fluctuations in Jupiter's polar magnetosphere and found direct evidence of strong

transverse perturbations associated with the IFP tail. The perturbations were identified as Alfvénic (between 0.2 and 5 Hz) and the Alfvén Poynting flux was calculated to be as high as $\sim 3,000 \text{ mW/m}^2$ during the likely PJ12 crossing of Io's MAW. Sulaiman et al. (2020) used Juno/Waves data to demonstrate that Alfvénic fluctuations, first observed by MAG, extend into the higher frequencies spanning a range from ~ 50 to 800 Hz . Clearly, Alfvén waves are present and carry a significant source of energy in the IFP tail and near the MAW. Therefore, if the energy reservoir is the same for the two populations, then the observations presented here suggests that energy conversion efficiencies between Alfvén waves and ions ($\sim 3\text{--}5\%$) are comparable to the lower-energy electrons except for brief moments where the electron energy flux peaks as high as 580 mW/m^2 . This is surprising because previous works, for example, Hess et al. (2010), demonstrate that most of the Alfvénic Poynting flux is converted to electrons. We note that numerous studies have investigated ion acceleration in Earth's aurorae and the role of Alfvén waves (e.g., Chaston et al., 2004, 2015; Johnson & Cheng, 2001; Knudsen & Wahlund, 1998; Li & Temerin, 1993; White et al., 2002). However, in the absence of wave-particle interaction models for the Io fluxtube and its tail, which consider the ion response specifically, we turn to comparisons with models at larger L-shells. Saur et al. (2018) find that on L-shells between 10 and $40 R_J$, at high latitudes, ion-Landau damping is effectively not taking place, while electron Landau damping of inertial Alfvén waves is a highly effective acceleration mechanism in accordance with previous modeling and existing observations of energetic electrons (e.g., Bonfond et al., 2017; Clark et al., 2018; Hess et al., 2010, 2013; Saur et al., 2018; Szalay, Allegrini, et al., 2020). If the temporal scales of the waves become extremely small, then ion cyclotron damping becomes more prominent (e.g., Sulaiman et al., 2020). Of the two resonant mechanisms discussed, that is, Landau and cyclotron damping, non-resonant mechanisms (e.g., Lu & Li, 2007) of ion acceleration through Alfvén waves have not been studied for the Jupiter system and their effectiveness is thus difficult to assess without detailed studies.

The Juno/JEDI data presented in this study represent the first measurements of energetic proton conics associated with IFP tail near the MAW. This discovery showcases the diversity of planetary systems and interactions present where ion conics exist, for example, Earth, Saturn, and Jupiter's auroral regions and now as a result of moon-magnetospheric interactions. Our primary conclusions in this study are the following:

1. Energetic proton acceleration associated with the IFP tail appears significant and perhaps the most intense ion event recorded by Juno/JEDI to date.
2. The angular distributions of the protons suggest these are the ion conic distributions and are likely accelerated by ion cyclotron waves via a resonant interaction; however, Alfvénic turbulence was not ruled out and may play a role.
3. Proton acceleration associated with IFP tail is more intense than compared to the main auroral (Mauk et al., 2018) or polar cap regions (Clark, Mauk, Paranicas, et al., 2017), thus highlighting the unique and strong electromagnetic interaction between Jupiter and Io.

Data Availability Statement

All Juno data presented here are publicly available from NASA's Planetary Data System as part of the JNO-J-JED-3_CDR-V1.0 data set for the Juno/JEDI instrument and The JNO-J/SW-JAD-3-CALIBRATED-V2.0 and JNO-J/SW-JAD-2-UNCALIBRATED-V1.0 for the Juno/JADE instrument.

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