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Key Points:
- JADE observed 0.1–100 keV electrons, regions void of these electrons, and regions of penetrating radiation in Jupiter's polar aurora region
- The electrons consisted of bidirectional beams with broad energies interspersed between upward beams having narrow energy distributions
- The energy flux of downward electrons shown here ranged from ~0.01 to 5 mW m^{-2}, the upward flux being up to ~100 times larger

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Spatial Distribution and Properties of 0.1–100 keV Electrons in Jupiter's Polar Auroral Region

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Abstract We present observations of 0.1–100 keV electrons from Juno's Jovian Auroral Distributions Experiment Electron instrument over Jupiter's polar auroral region for periods around four Juno perijoves (PJ1, PJ3, PJ4, and PJ5). The observations reveal regions containing magnetic field aligned beams of bidirectional electrons having broad energy distributions interspersed between beams of upward electrons with narrow, peaked energy distributions, regions void of these electrons, and regions dominated by penetrating radiation. The electrons show evidence of acceleration via parallel electric fields (inverted-V structures) and via stochastic processes (bidirectional distributions). The inverted-V structures shown here were observed from ~1.4 to 2.9 R_J and had spatial scales of hundreds to thousands of kilometers along Juno's trajectory. The upward electron energy flux was typically greater than the downward flux, the latter ranging between ~0.01 and 5 mW m^{-2} for two cases shown here which we estimate could produce ~0.1–50 kR of ultraviolet emission.

Plain Language Summary We report on observations of 0.1 - 100 kilo-electron volt electrons from the Jovian Auroral Distributions Experiment Electron instrument (JADE-E) on Juno over the region where Jupiter's ultraviolet (UV) polar aurora is produced. The observations show electrons moving both towards and away from Jupiter. These electrons show both broad and narrow energy distributions, suggesting the presence of at least two different acceleration mechanisms. Regions void of these electrons and regions dominated by penetrating radiation were also identified. The energy flux of the electrons moving towards Jupiter was sufficient to produce the weaker UV polar auroral emissions observed at Jupiter but a different source of electrons, likely with higher energies, is required to account for the brighter emissions.

1. Introduction

Initial observations from Juno have significantly enhanced our understanding of Jupiter's polar magnetosphere and the processes responsible for producing Jupiter's ultraviolet (UV) and infrared (IR) auroral emissions (e.g., Connerney, Adriani, et al., 2017, and references therein). Juno was inserted into a 53 day polar orbit around Jupiter on 5 July 2016. Its first perijove (PJ1) on 27 August 2016 provided the first opportunity to make in situ measurements of the particles and fields in Jupiter's polar magnetosphere while simultaneously observing Jupiter's UV and IR aurora. Results from PJ1 include observations of magnetic field-aligned electron beams at high latitudes that were sometimes bidirectional but mostly upward (Allegrini et al., 2017; Mauk et al., 2017), including a persistent upward energetic (>25 keV) electron beam poleward of the main aurora (Mauk et al., 2017). In this work, "upward" and "downward" will always mean from and toward Jupiter, respectively. The energy spectra of these electrons showed a power law distribution that extended to beyond ~800 keV, suggesting a stochastic acceleration process (Mauk et al., 2017). One interpretation emerging from these observations is that Jupiter's main UV aurora may be produced primarily by diffuse electron precipitation as opposed to electron precipitation driven by large field-aligned potentials (e.g., Allegrini et al., 2017;

Mauk et al., 2017; Szalay et al., 2017). Details on these and other related studies can be found in the "Early Results: Juno at Jupiter" special issue of Geophysical Research Letters.

Here we focus on Jupiter's polar auroral region, the region poleward of the main aurora, which has displayed a host of UV emissions, including active, dark, and swirl regions and nightside and polar dawn spots (see review by Grodent, 2015). It is also where the downward currents (upward electrons) associated with the field-aligned current system coupling Jupiter's magnetosphere-ionosphere-thermosphere are expected to reside (e.g., Cowley & Bunce, 2001; Hill, 1979; Ray et al., 2010). While the highly variable polar UV emissions can contribute up to 30% of Jupiter's UV auroral brightness (Grodent et al., 2003), the origin and acceleration processes for the electrons that produce these emissions are not well established (e.g., Gérard et al., 2016). Results based on UV color ratios from Hubble Space Telescope spectral observations suggest that the electron energies in the polar auroral region can range from several tens to several hundreds of keV (e.g., Gérard et al., 2016, 2014; Gustin et al., 2016). Possible acceleration mechanisms include (i) converging quasi-static, parallel electric fields that produce downward electrons having peaked energy distributions with characteristic inverted-V structures analogous to the upward current regions at Earth (e.g., Evans, 1974; Mozer et al., 1977); (ii) diverging quasi-static, parallel electric fields that produce upward electrons associated with downward current regions (e.g., Carlson et al., 1998; Ergun et al., 1998a); (iii) processes that produce magnetic field aligned electron beams with broad energy distributions via interactions with small-scale electrostatic structures (e.g., Ergun et al., 1998b); or (iv) via the dissipation of energy from magnetic fluctuations driven by Alfvén waves (e.g., Mauk & Saur, 2007; Saur et al., 2003), among others (see review by Mauk & Bagenal, 2012).

In this letter, we present an overview of 0.1–100 keV electron observations over Jupiter's polar auroral region during Juno's northern and southern polar passes bounding PJ1, PJ3 (11 December 2016), PJ4 (2 February 2017), and PJ5 (27 March 2017). We focus on their spatial distribution and their energy and pitch angle distributions, and energy flux and spectra using measurements from Juno's Jovian Auroral Distributions Experiment Electron (JADE-E) sensors (McComas et al., 2013). JADE-E consists of two nearly identical sensors (E060 and E180) designed to measure the energy and pitch angle distribution of ~0.1–100 keV electrons in Jupiter's magnetosphere. A third sensor (E300) was turned off due to a high-voltage power supply failure during Juno's approach to Jupiter. The pitch angle resolution for JADE-E is 7.5°. Due to the E300 sensor being off, JADE-E has full pitch angle coverage only approximately one third of the time. The observations are discussed in terms of their implications for Jupiter's polar auroral region electron environment, the processes that energize these electrons, and their contribution to Jupiter's polar UV emissions.

2. Electron Observations Over Jupiter's Polar Auroral Region

Figure 1 shows samples of 0.1–100 keV electron observations from JADE-E in Jupiter's northern polar auroral region during times when the instrument was operating in high rate science mode (full energy coverage every 1 s). Figures 1a–1e display energy-time differential intensity (or count rate for Figure 1e) spectrograms averaged over all pitch angle directions for selected periods during the early perijoves (no JADE data were obtained near PJ2), highlighting the various electron distributions observed in this region. Included in each figure are the perijove number, year, and day of year (DOY) when the observations were collected, along with Juno's jovicentric distance and magnetic latitude. Juno ranged between ~1.3 and 4.7 R_J from Jupiter and from 59 to 85°N in magnetic latitude (MLAT) for the periods examined here (see Figures 1f and 1g).

The electron distributions in Figures 1a–1c show significant spatial and/or temporal variability, with sharp changes in both intensity and energy occurring on timescales of seconds. Observations in Figure 1a, when Juno ranged from 2.4 to 2.2 R_J and 84 to 85°N MLAT, revealed electrons with energies near and extending above the 100 keV upper energy limit of JADE-E along with electrons with energies below ~10 keV. Electrons at these characteristic energies, along with the rapid transition between these different populations, are common features in Jupiter's polar auroral region. Figure 1b highlights a period when Juno transitioned from magnetic field lines mapping to the poleward edge of the main aurora to field lines mapping to the polar auroral region. This transition was highlighted by the sudden decrease in electron intensity at ~15:07:20 UT on DOY 346 as Juno moved poleward. The observations in Figure 1c contain several intervals of electrons with narrow energy distributions having arc-like features that peak in energy between ~20 and >100 keV (e.g., 8:20:43–8:21:04 UT). These structured electron distributions are interspersed between ~0.1 and 10 keV electrons with broad energy distributions. They resemble the inverted-V electron structures

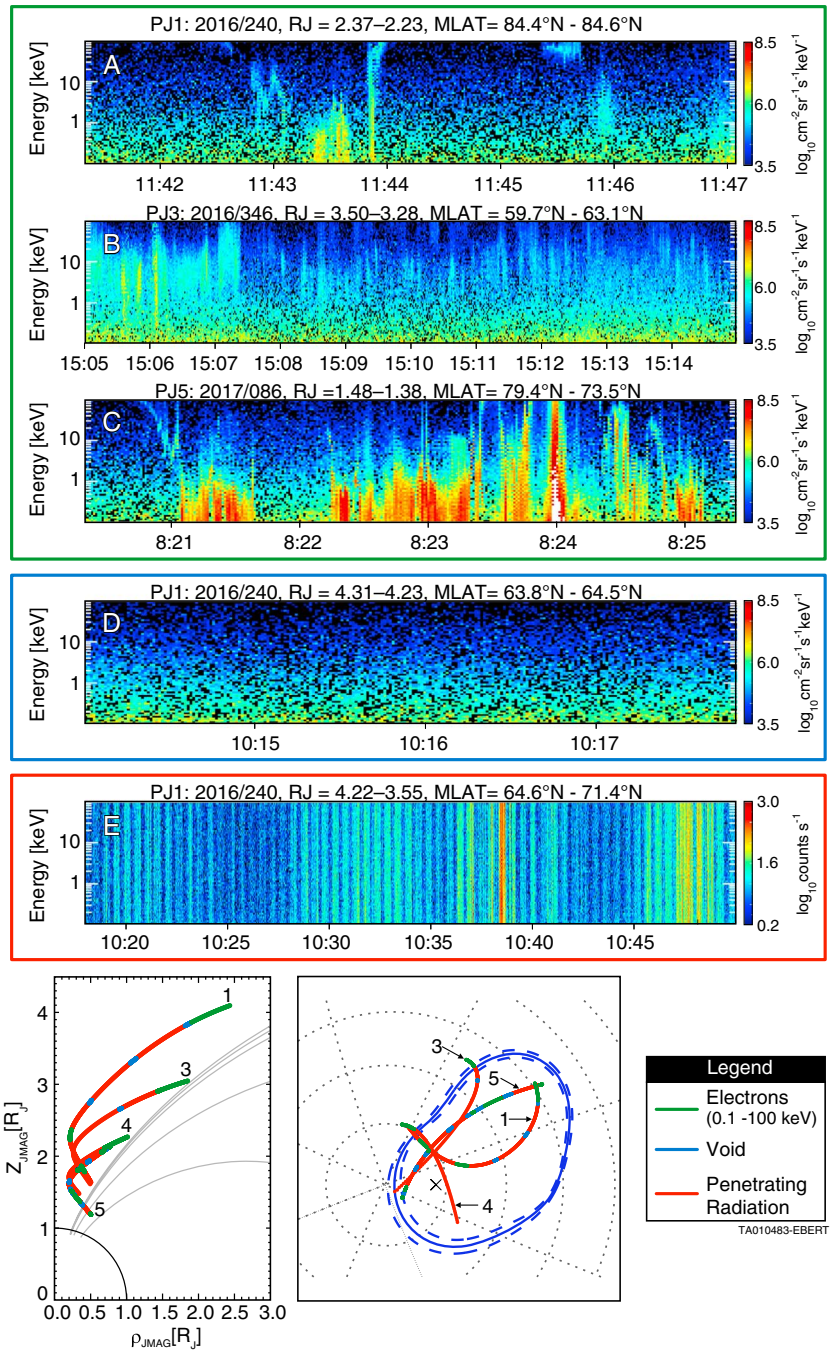


Figure 1. Displayed are representative intervals of (a–c) regions with 0.1–100 keV electrons (green box), (d) regions void of these electrons (blue box), and (e) regions dominated by penetrating radiation (red box) in Jupiter's northern polar auroral region prior to Juno perijoves 1, 3, and 5. (f) Juno's trajectory over Jupiter's northern polar region in a magnetic coordinate system based on the VIP4 + CAN magnetic field model (e.g., Connerney et al., 1981, 1998). Green, blue, and red lines denote periods when JADE-E observed 0.1–100 keV electrons, regions void of these electrons, and penetrating radiation, respectively. Each trajectory is labeled by its associated perijove number. (g) Magnetic projection of Juno's trajectory onto Jupiter's atmosphere and relative to the statistical average position of Jupiter's main aurora as derived from Hubble Space Telescope UV observations (Bonfond et al., 2012). Black dashed circles and lines denote contours of constant jovicentric latitude and system III longitude, respectively. Color-coded JADE-E region identification is the same as Figure 1f.

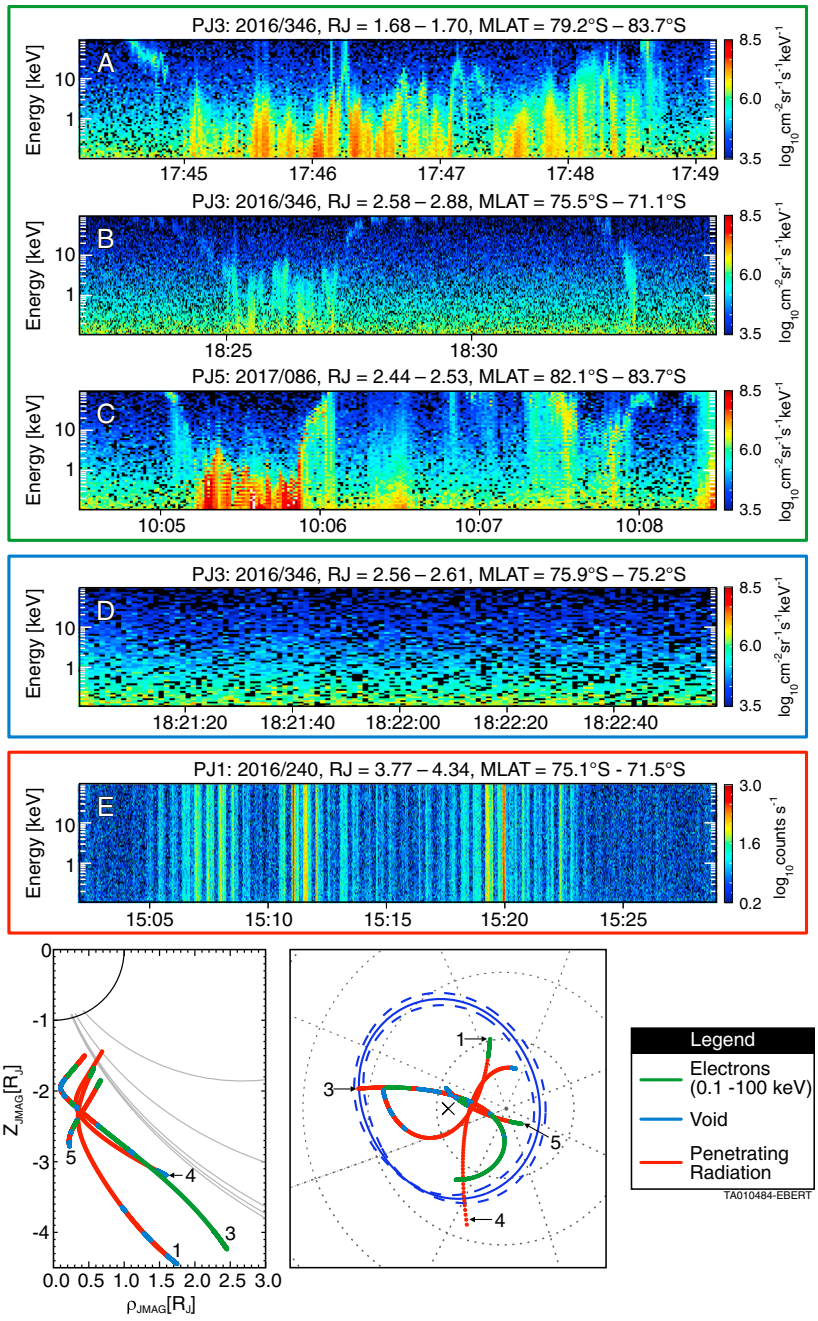


Figure 2. Same format as Figure 1 but for 0.1–100 keV electron observations in Jupiter's southern polar region during the polar passes immediately after Juno perijoves 1 and 3–5.

observed over the Earth's aurora (e.g., Carlson et al., 1998) and, more recently, in possible downward current regions (upward electrons) over Jupiter's polar auroral region at energies up to ~280 keV (Clark et al., 2017). Figure 1d shows a region between 4.31–4.23 R_J and 63.8°–64.5°N MLAT with no identifiable 0.1–100 keV electron distributions or structures. At higher energies, the intensity of downward electrons observed by the Jovian Energetic Particle Detector Instrument (JEDI) (Mauk et al., 2013) was negligible during this period, while the upward electrons showed a persistent, but relatively weak, >1 MeV beam. We refer to these regions as voids throughout the rest of the paper. Figure 1e highlights a period where the signal measured by JADE is dominated by penetrating (background) radiation. The narrow vertical bands of signal across all energy steps indicate that the JADE-E microchannel plate (MCP)

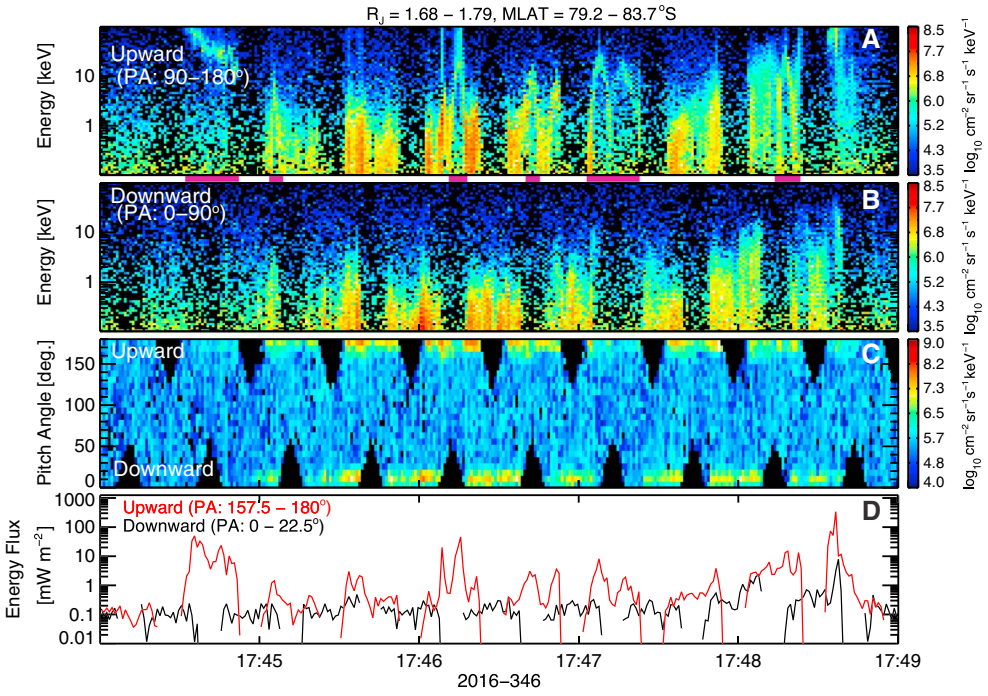


Figure 3. The 0.1–100 keV electron observations over Jupiter's southern pole during PJ3 when Juno ranged between 1.68 and 1.79 R_J in jovicentric distance and 79.2–83.7°S in magnetic latitude. (a and b) Energy-time pitch angle averaged differential intensity spectrograms for electrons with pitch angles between 90° and 180° (upward, Figure 3a) and 0° and 90° (downward, Figure 3b), respectively. Purple horizontal bars identify possible inverted-V structures. Figure 3c displays pitch angle-time spectrograms of electron intensity (summed over energies from ~0.1 to 100 keV). Black triangular regions in the spectrograms reflect pitch angles that were not sampled due to E300 being off. The time series of estimated upward and downward electron energy fluxes within 22.5° of the magnetic field are shown in Figure 3d.

detector is measuring background counts from very energetic charged particles, most likely electrons, that penetrate the instrument shielding as opposed to foreground electrons that enter the detector section through the electrostatic analyzer. We refer to the background counts associated with these very energetic charged particles as penetrating radiation. The MCP detectors in the Juno ultraviolet spectrograph (Gladstone et al., 2014) also measured penetrating radiation during this period. This penetrating radiation could be produced by the >1 MeV upward electrons observed by JEDI (Mauk et al., 2017) and/or the >5 and >10 MeV electrons observed by the Juno Radiation Monitoring Investigation (Becker et al., 2017) over Jupiter's poles.

The spatial distribution of electrons, voids, and penetrating radiation along Juno's trajectory over Jupiter's northern polar auroral region are displayed in Figures 1f and 1g (see legend). The end points of each trajectory reflect the boundary between the main auroral and polar auroral region. These boundaries and the different regions over the polar aurora were identified by eye using the mapping technique described in Szalay et al. (2017) and the JADE-E observations. The boundary between the main and polar auroral regions was typically identified by a decrease (increase) in electron flux as Juno moved poleward (equatorward). While electrons are often observed near these boundaries, intervals of electrons, voids, and penetrating radiation appear at nearly all radial distances and magnetic latitudes studied here. Interestingly, these different features tend not to overlap but instead appear to be mutually exclusive of each other, with penetrating radiation being most common.

Figure 2 shows an example of 0.1–100 keV electron observations from JADE-E in Jupiter's southern polar region using the same format as Figure 1. Juno ranged between ~1.65 and 3.5 R_J from Jupiter and from 67 to 85°S in MLAT for this period. Similar to the north, the observations are characterized by distributions of electrons with narrow (in energy) arc-like structures that peak in energy between 20 and >100 keV (e.g., Figure 2a, 17:47:00–17:47:30 UT) interspersed between ~0.1 and 10 keV electrons with broad energy

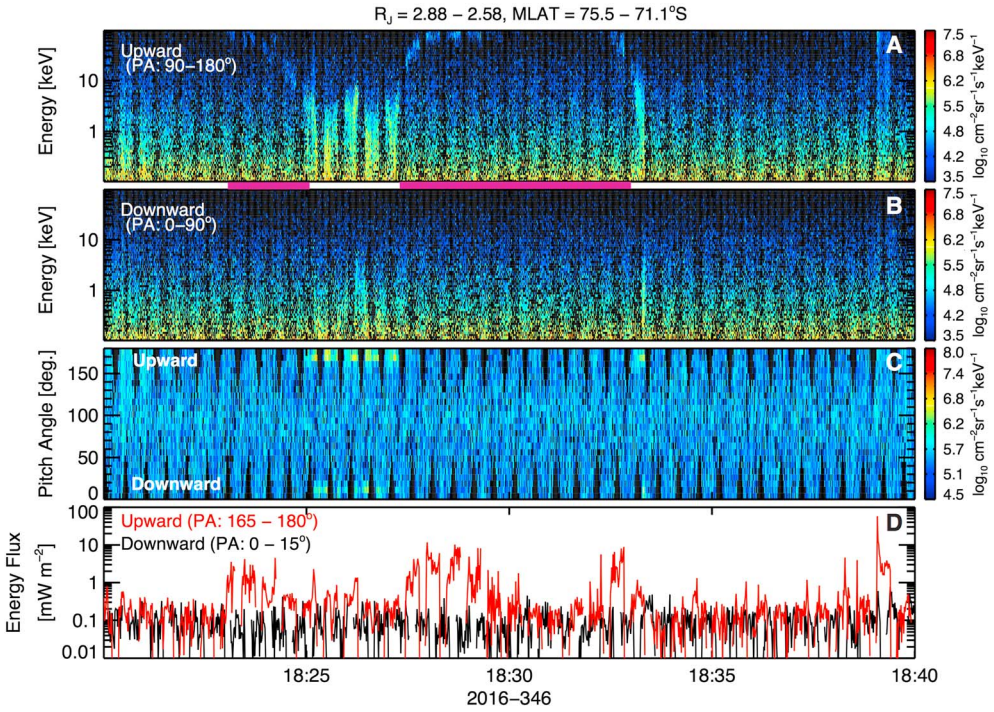


Figure 4. Similar format as Figure 3 but for a period over Jupiter's southern pole during PJ3 when Juno ranged between 2.88 and 2.58 R_J in jovicentric distance and 75.5–71.1°S in magnetic latitude.

distributions, regions void of these electrons, and regions of penetrating radiation, with penetrating radiation being the most common feature.

Figure 3 presents the energy and pitch angle distributions and energy flux of 0.1–100 keV electrons over Jupiter's southern polar auroral region for the interval shown in Figure 2a. Comparing the top two panels, the narrow energy distributions at >10 keV and inverted-V structures are primarily observed in the upward electrons (see Figure 3a). The inverted-V distributions, observed here between 1.7 and 1.8 R_J, have peak energies between ~20 and >100 keV. These structures are estimated to have spatial scales of ~200–500 km along Juno's trajectory based on the product of their time observed (a few to ~10 s) and the spacecraft velocity (~50 km s^{-1}). The electron distributions with energies between 0.1 and 10 keV are bidirectional, having both an upward and downward component, with the intensity of both components being comparable during this interval. The pitch angle distributions in Figure 3c show that both the upward (180°) and downward (0°) electrons are field aligned with their direction of motion being within ~22.5° of Jupiter's magnetic field. The electron energy flux shown in Figure 3d was estimated using the method described in Mauk et al. (2017) and was calculated by $\pi \cdot \Sigma_i$ ($DEF_i \cdot \Delta E_i$) where π is the area-projection-weighted size of the loss cone above Jupiter's atmosphere, i is the JADE-E energy step, DEF_i is the electron differential energy flux of energy step i averaged over pitch angle in units of particles cm^{-2} s^{-1} sr^{-1} keV keV^{-1}, and ΔE_i is the width of the JADE-E energy passband. The energy flux of the downward electrons, those expected to contribute to Jupiter's polar UV emissions, ranged between ~0.01 and 5 mW m^{-2} with a majority of the observations being between ~0.1 and 0.5 mW m^{-2}. Using the model described in Grodent et al. (2001), we estimate the <100 keV downward electrons produce UV auroral emissions of ~0.1–50 kilorayleighs (kR) during this period. The energy flux of the upward electrons was up to 2 orders of magnitude larger, ranging between ~0.1 and >100 mW m^{-2}. The largest energy fluxes were associated with upward electrons having narrow energy distributions at >10 keV and inverted-V structures.

In the same format as Figure 3, Figure 4 examines the interval shown in Figure 2b. These observations are characterized by upward electrons with inverted-V energy distributions from 2.6 to 2.9 R_J that are interspersed between bi-directional electrons with broad energy distributions. Compared to Figure 3, the inverted-V structures have a higher peak energy, extending above the JADE-E upper energy range (see

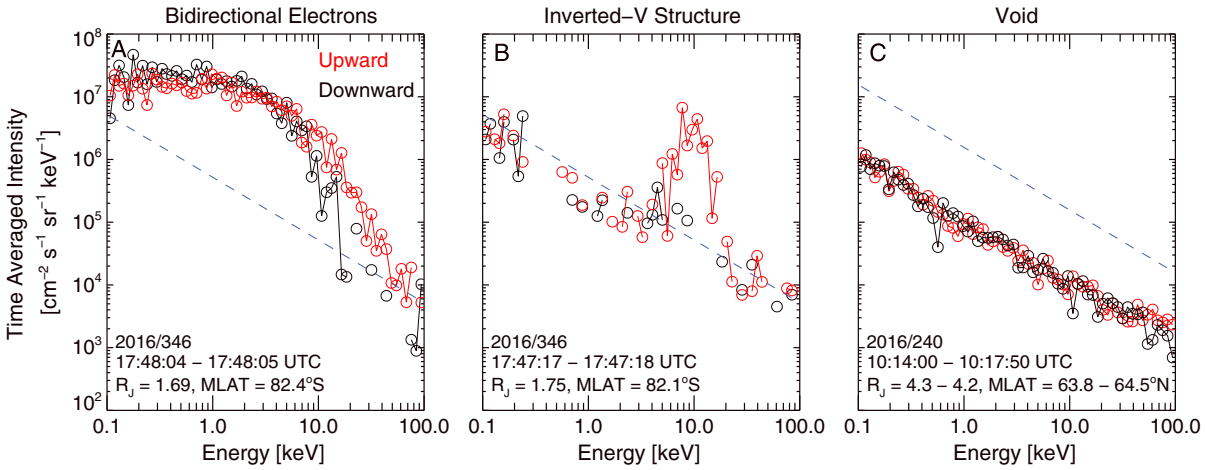


Figure 5. Energy spectra for periods when JADE-E observed (a) bidirectional electrons, upward electrons with an (b) inverted-V energy distribution, and (c) a void. The intensities have been averaged over the number of pitch angle bins used in the calculation and the number of 1 s measurements in the stated time interval. Blue dashed lines denote the JADE-E intensity assuming 1 count per energy step for a 1 s accumulation period divided by the number of pitch angle bins used in each energy spectra calculation.

Clark et al., 2017), and are observed for a much longer duration (up to ~5 min), suggesting that they have spatial scales of up to ~12,500 km along Juno's trajectory. The bidirectional distributions are asymmetric, with the intensity of the upward electrons being larger than the downward electrons. Asymmetric bidirectional distributions have been identified in the >25 keV electron observations over the main auroral and polar auroral region by Mauk et al. (2017). Both the inverted-V structures and bidirectional electrons are field aligned, being within ~22.5° of Jupiter's magnetic field. The energy flux is also asymmetric, with the upward component ranging between ~0.01 and >10 mW m^{-2} and the downward component between ~0.01 and 1 mW m^{-2}. The estimated UV auroral brightness produced by the downward electrons is <10 kR.

Figure 5 compares the time and pitch angle averaged energy spectra for a distribution of bidirectional electrons, an inverted-V distribution of upward electrons, and a void. These represent the characteristic electron distributions in Jupiter's polar auroral region observed by JADE-E. The energy spectra of the bidirectional electrons show symmetric intensities between the upward and downward components (though such symmetry is not always the case) are relatively broad in energy and exhibit a rollover between ~2 and 5 keV and a power law tail (up to 100 keV for the upward electrons). By comparison, the energy spectra of the inverted-V structure are asymmetric, having only an upward component, and peak between ~5 and 20 keV. The differences between these energy spectra likely reflect the different processes accelerating the electrons. The energy spectra for the void have intensities that are well below the estimated 1 count level intensity for JADE-E and show a similar trend with energy. This suggests that the signal measured by JADE-E in this region is very weak and likely originates from penetrating radiation and/or instrument noise.

3. Discussion and Summary

We presented an overview of 0.1–100 keV electron observations over Jupiter's northern and southern polar auroral region when Juno ranged between ~1.3–4.7 R_J and ~60–85° in magnetic latitude. This region has displayed a host of highly variable UV auroral emissions (e.g., Grodent et al., 2003) and is where the downward currents (upward electrons) associated with the system coupling Jupiter's magnetosphere-ionosphere-thermosphere are thought to reside (e.g., Hill, 1979). The observations revealed regions containing magnetic field-aligned beams of bidirectional electrons with broad energy distributions interspersed between beams of upward electrons with narrow energy distributions, some showing characteristic inverted-V signatures, that peak between 20 to >100 keV regions void of these electrons and regions dominated by penetrating radiation were also identified. These different features tended to not overlap nor did they show any apparent spatial organization. Electrons, voids, and penetrating radiation were observed at nearly all radial distances

and latitudes studied here. The penetrating radiation is likely produced by MeV electrons observed over Jupiter's poles (Becker et al., 2017; Mauk et al., 2017) and is the most common feature observed by JADE-E over Jupiter's polar auroral region.

The upward electrons with narrow, peaked energy distributions are consistent with observations from Earth's auroral region of electrons accelerated by parallel electric fields. At Jupiter, the upward electrons with narrow energy distributions have monoenergetic peaks that range from ~20 keV up to at least 280 keV (see Clark et al., 2017). The inverted-V structures were observed between ~1.4 (see Figure 1c) and 2.9 R_J with spatial scales that ranged between ~200 and 500 km (for electrons with relatively small peak energies) up to ~12,500 km (for electrons with large peak energies). The processes that produce the varying spatial scales of these inverted-V structures are an open question.

The bidirectional electrons observed by JADE-E over Jupiter's polar auroral region exhibit signatures for acceleration by stochastic processes (e.g., field-aligned, narrow pitch angles, and broad energy spectra). This process has been invoked to describe the energy distributions of downward electrons that produce Jupiter's main UV emission (e.g., Mauk et al., 2017). Potential mechanisms include acceleration via interactions with small-scale electrostatic structures (e.g., Ergun et al., 1998a, 1998b) or via the dissipation of energy from magnetic fluctuations driven by Alfvén waves (e.g., Saur et al., 2003). Whether these distributions have upward and downward intensities that are symmetric or asymmetric may be a function of whether Juno flew above or below the region where the acceleration was taking place (Mauk et al., 2017). More work is needed to understand the mechanisms energizing these electrons.

The energy flux of downward electrons associated with the bidirectional distributions described above ranged between ~0.01 and 5 mW m^{-2} in two cases shown here, the energy flux of the upward electrons being larger. The auroral brightness produced by these downward electrons was estimated to range between ~0.1 and 50 kR. While these electrons can likely account for the faint emission observed in the dark region ($<$10 kR), and the weaker emissions in the swirl and active regions, another source of electrons is likely needed to account for the bright emissions in the swirl region (up to 200 kR) and the hundreds of kilorayleighs to megarayleighs emissions in the active region associated with polar flares (e.g., Grodent et al., 2003; Waite et al., 2001). This source of electrons may reside in the JEDI energy range.

Finally, we interpret the voids as regions where the aurora may be dark since there was little evidence of downward electrons in either the JADE or JEDI observations during these intervals. Bonfond et al. (2017) identified a region of faint emission in Jupiter's northern swirl region during PJ1 that they interpreted as a possible region of open field lines. Further analysis is needed to identify if these voids map to regions of faint emission and whether they reside on open or closed field lines.

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