Juno observations of energetic charged particles over Jupiter’s polar regions: Analysis of monodirectional and bidirectional electron beams


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Abstract: Juno obtained unique low-altitude space environment measurements over Jupiter’s poles on 27 August 2016. Here Jupiter Energetic-particle Detector Instrument observations are presented for electrons (25–800 keV) and protons (10–1500 keV). We analyze magnetic field-aligned electron angular beams over expected auroral regions that were sometimes symmetric (bidirectional) but more often strongly asymmetric. Included are variable but surprisingly persistent upward, monodirectional electron angular beams emerging from what we term the “polar cap,” poleward of the nominal auroral ovals. The energy spectra of all beams were monotonic and hard (not structured in energy), showing power law-like distributions often extending high as 280 mW/m², we suggest that mechanisms generating these beams are among the primary processes generating Jupiter’s uniquely intense auroral emissions, distinct from what is typically observed at Earth.

1. Introduction

NASA’s Juno Jupiter polar orbiting spacecraft targets multiple disciplines including understanding Jupiter’s polar space environment and its powerful aurora [Bolton and Juno Science Team, 2010; Bagenal et al., 2014]. This goal was dramatically advanced by the 27 August 2016 low-altitude Juno passage over the northern and southern poles, while instruments measured magnetic fields (Juno Magnetic Field Investigation (MAG)), plasma waves (Juno Waves Investigation (WAVES)) [see Kurth et al., 2017], plasmas (Jovian Auroral Distributions Experiment (JADE)) [McComas et al., 2013], energetic particles (Jupiter Energetic-particle Detector Instrument (JEDI)) [Mauk et al., 2013], ultraviolet auroral emissions (Ultraviolet Spectrograph (UVS)) [Gladstone et al., 2014], and infrared auroral emission (Jovian Infrared Auroral Mapper (JIRAM)) [Adriani et al., 2014]. A preliminary overview of measurements from all of these instruments has been prepared by Connerney et al. [2017b], including high-level discussions of the particle beaming phenomena analyzed here.

Here we provide a detailed examination of some measurements obtained by the Jupiter Energetic-particle Detector Instrument (JEDI) measuring energy, angular, and compositional distributions of electrons (~25 to >800 keV) and ions (protons: ~10 keV to >1.5 MeV; oxygen and sulfur to >10 MeV). JEDI uses solid-state detectors (SSDs), thin foils, and microchannel plate (MCP) detectors to measure electron SSD single rates (SSDs shielded by 2 μ Al), time-of-flight by energy (TOFxE) for higher energy ions, and time of flight by MCP pulse height (TOFxPH) for lower energy ions [Mauk et al., 2013].

We focus on electron distributions, particularly magnetic field-aligned electron angular beams. These distributions are collimated in angle but have decreasing monotonic (not structured) energy distributions. They are presentations of earlier observations of magnetic field-aligned electron angular beams observed in the more distant regions of Jupiter’s magnetosphere (reviewed by Mauk and Saur [2007] and Mauk and Bagenal [2012]) and other magnetospheres [Saur et al., 2006; Mitchell et al., 2009]. They have been interpreted
based on Earth-auroral observations of similar beams within the downward electric current (upward electrons) regions of Earth’s auroral current system [Carlson et al., 1998]. At Earth the strong discrete auroral emissions occur elsewhere, specifically in the upward electric current regions where downward electron distributions are generally strongly peaked in energy. The observations reported here provide an indication that processes that generate the energy-monotonic electron angular beams represent at least one of the primary auroral acceleration processes generating Jupiter’s powerful auroral emissions. Electrons with energies below those measured by JEDI, and measured by the JADE instrument, surely contribute as well, and future studies will combine the measurements for both sensors and with Juno auroral emission measurements (UVS and JIRAM). Those data are not yet available in the needed form for this letter.

2. Encounter With Jupiter’s Poles

Figure 1 shows the geometry of the encounter. Figure 1a shows the Juno trajectory in a cylindrical coordinate system with z = dipole magnetic pole derived from the VIP4 magnetic field model. (b and c) Magnetic projections onto Jupiter by using the same model. See text for additional information.

Figure 1. Trajectory of Juno with respect to Jupiter on 27 August (day 240) 2016. (a) A cylindrical coordinate system with z = dipole magnetic pole derived from the VIP4 magnetic field model. (b and c) Magnetic projections onto Jupiter by using the same model. See text for additional information.
3. JEDI Observations

Figures 2 and 3 show JEDI summary plots for the northern polar pass (Figure 2) and for near-planet region bracketing portions of the northern and southern polar regions (Figure 3). The panels are (a) JEDI-270 electrons, channel-averaged over 30 s, and organized according to the azimuth angle (Figure 1d definition); (b) the same data organized according to the pitch angle (PA) relative to the local magnetic field (from MAG), where PA = 0 corresponds to particles with velocity parallel to the magnetic field (note that panels (a) and (b) show downward pitch angles are near 180° for the inbound (before 12:45) and near 0° for the outbound. The occasional horizontal enhancements near ~150 keV in Figures 2c and 2d represent foreground electrons with energies high enough (>800 keV) to penetrate the detector and leave a “minimum ionizing” signature. The blue bar just above the top plot represents the predicted (from Figure 1) location of the region poleward of the main aurora, called here the “polar cap (PC).”

**Figure 2.** Selected data from JEDI sensors during the northern polar pass of Jupiter. (a–e) Aspects of electron measurements. (f and g) Aspects of proton measurements. See text for additional descriptions of the plots. The inserts “acc” (accidentals) and “pen” (penetrators) represent regions contaminated by penetrating radiation.

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(b) are mostly redundant, but they make the character of the beams a little easier to see; (c) an electron energy-time spectrogram with measurements centered between 165° and 180° pitch angles (30 s averaging); (d) a similar plot for electrons with measurements centered between 0° and 15° pitch angles; (e) summed count rates (1/s) for each of the six electron telescopes comprising JEDI-90 (0.5 s); (f) JEDI-90 and JEDI-270 TOFxE protons, channel-averaged over 30 s, organized according to the particle pitch angle; and (g) a 15 s cadence summation of all JEDI-90 ion valid events for TOFxE (blue curve representing $E > 50 \text{ keV}$ ions) and, separately, TOFxPH ion events (red curve representing $E > 10 \text{ keV}$ ions). The letters “acc” in the two bottom plots are where the sensors are overwhelmed by particle radiation, causing false signals called “accidentals.” The letters “pen” in the electron plots show measurements that are substantially contaminated by radiation penetrating detector shielding. The time axis is labeled with hours of the day.

Figure 3. Same as Figure 2 but for times that bracket the northern and southern polar passes.
magnetic latitude, and dipole L from the VIP4 dipole model and radial position. The tick marks, labeled at the very top, identify times of particular interest. These times correspond to the red stars in Figure 1.

Near the position marked “E1” in Figure 2 (~0835 UT), as the spacecraft exits a high radiation region, the electrons and ions show sharp intensifications near the mapped position of the statistical UV auroral oval (Figure 1b) at \( R \sim 6.2 \) RJ. The angular distributions for electrons show striking, roughly symmetric bidirectional angular beaming (Figure 4-E1 shows a snapshot). The ions are much closer to being isotropic; the subtle bidirectionality of the ion distributions is only barely discernible in Figure 2f.

Within the regions polarward of the main auroral oval (Figure 1b), designated here the “polar cap” (“PC”; a consensus on terminology has not been achieved), we see a variable but surprisingly persistent upward directed, monodirectional angular electron beam (Figure 4-E2 shows a snapshot for position E2). The same phenomenon, and just as persistent, is observed within the southern “polar cap” (Figure 4-E7 shows a snapshot from position E7). The beams are very energetic. Specifically, Figure 2d shows the dynamic energy spectra of the upward-going beams. The horizontal region of enhancement running left and right at a constant energy centered near 150 keV represents foreground electrons that come through the nominal collimator openings with

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**Figure 4.** Selected pitch angle distributions of energy-channel-averaged intensities for (E1–E7) JEDI-measured electrons and (P1 and P2) protons. Sample positions are shown in Figures 1–3. The arrows labeled “Jupiter” show downward directions with respect to Jupiter. LC (loss cone) is estimated by using the expression provided in the text.
energies high enough (>~700–800 keV) to penetrate the SSD sensors and leave behind what is termed a “minimum ionizing” energy deposition that is less than the energy of the electron itself. This feature is much less distinct in the downward-going electron distributions, indicative of softer high-energy tails (section 4).

As Juno lowers its radial position approaching the main auroral oval in Figures 2 and 3 (refer to Figure 1), the monodirectional electron beams start to show bidirectionality, but with the upward-going beams typically more intense than the downward-going beams in both hemispheres. A snapshot is shown in Figure 4-E3. The E3 position represents the most intense northern hemisphere beaming that occurs in the vicinity of the statistical auroral oval. Overlapping in time with the region of asymmetric electron bidirectionality (~1100 to ~1200) is a weak asymmetric bidirectionality in the proton distributions (Figures 2f and 3f). The asymmetry is reversed there with the downward ion intensities (precipitating) more intense than the upward intensities.

The degree to which JEDI resolves the loss cones (LCs) is best discerned in the ion pitch angle distributions (Figure 3f), where sharp edges are best seen near 0° for the inbound (upward-going loss cone) and near 180° for the outbound (except where contamination exists, labeled “acc”). These edges are very roughly (within 30%) consistent with an estimate using LC angle ~ Sin^{-1}(1/R^3)^{1/2} derived assuming magnetic moment conservation and that magnetic field strength B ~ 1/R^3. This LC estimate is provided in the panels of Figure 4. At positions E4 and E5, sampled nominally equatorward of the statistical auroral oval, we see electron distributions with quasi-trapped pitch angle distributions but with substantial asymmetries in the intensities that reside within the loss cones (snapshots in Figures 4-E4 and 4-E5). The downward loss cones are roughly full, but the upward loss cones are depleted. We interpret this finding as representing a traditional Earth-like diffuse auroral precipitation process.

Positions E6 and E7 in the southern regions represent roughly a repetition of the behaviors seen at positions E3 and E2 in the northern regions. However, the E6 distributions are substantially more intense than those observed at E3 and are where we see (section 4) the maximum energy fluxes heading toward the atmosphere within the geometric magnetic loss cone.

Protons, more occasionally than electrons, also show monodirectional beaming characteristics (see Figure 4-P1). Trapped proton distribution with empty upward loss cones and full downward loss cones are also observed, slightly poleward of where that behavior is seen in the electrons (Figure 4-P2). Several other obvious features of interest in Figures 3 and 4 are discussed in other JEDI-focused studies.

4. JEDI Electron Energetics

Figure 5a1 shows a measurement spectrum (blue diamonds) for an input spectrum with a relatively soft high-energy tail (E6: near field aligned and downward). The JEDI efficiency falls off both below 30 keV (not yet modeled) and above 700–800 keV. When the high-energy tail is relatively hard with substantial penetrating electrons, an additional “minimum ionizing” feature appears that peaks near 150 keV (Figure 5a2; E6: near field-aligned and upward). The red (input spectra) lines in Figure 5a, resulting in the blue response lines, represent our present best attempts to unfold the detector response characteristics. Our procedures for performing these inversions are still in their infancies. Figure 5b shows our best reconstructions of the spectra for some of the events presented in this report. All of these spectra fall monotonically with energy, and many of them are very spectrally hard, clearly extending in energy to well above the JEDI energy limit.

Figure 5c shows a minimum estimate of the downward (toward Jupiter) energy fluxes of ~30–1000 keV electrons. These numbers are derived by filtering the data for measurements having pitch angles centered within 15° of the downward magnetic field direction (15° is chosen to assure complete parallel sampling at all times; the results are insensitive to this choice). We then perform the sum: \( \pi \cdot \Sigma_{n} (I_{n} \cdot E_{n} \cdot \Delta E_{n}) \) over all “n,” where “n” represents the JEDI energy channels, \( I_{n} \) is the particle intensity from each channel, \( E_{n} \) is the central energy, and \( \Delta E_{n} \) is the energy band pass of each channel. The \( \pi \) is the area-projection-weighted size of the loss cone just above the atmosphere utilized under the rough estimation from the observations that the downward loss cone is fully populated. It must be recognized that the loss cone is cleanly resolved only within the region in Figure 5c that is marked with the thick horizontal green bar. To turn these fluxes into auroral emissions, we must assume, unproven, that there is no retarding electron potential comparable to the energies involved.

Energy fluxes observed in the vicinity of the nominal auroral oval have peaking values that range from about 8–10 mW/m^2 (E1 and E3) to over 280 mW/m^2 (E6). Features more equatorward, apparently representing
diffuse precipitation processes (E4 and E5), have values between 60 and 80 mW/m². Modeled scalings in Gustin et al. [2016] yield emission intensities of about 80 kilorayleigh (kR; for 9 mW/m²), 2500 kR (for 280 mW/m²), and 600 kR (for 70 mW/m²). These energy fluxes and auroral intensity numbers are

Figure 5. Selected analyses of JEDI-measured electron energetics over Jupiter’s poles. (a) Details of the energy-spectra derivation process. (b) Selected derived energy spectra. (c) Estimates of the downward energy deposition of electrons into Jupiter’s poles for 30–1000 keV electrons (see text). (d) A comparison between those same downward fluxes and the corresponding upward fluxes.
comparable to published auroral emission intensities for nominal auroral conditions [e.g. Gérard et al., 2014; Gustin et al., 2016].

Figure 5d shows a repeat of Figure 5c, but added to it are the corresponding energy fluxes for the upward-going intensities, calculated in the same way. This figure demonstrates dramatically how large the up/down asymmetries are for the electron beams in the polar caps and near the main auroral oval. It shows that, while the electron beams over polar caps are quite variable and even spiky, the asymmetric beams never really disappear (on a 30 s basis) between the spikes over a broad radial distant range (0.5 to > 4 \(R_J\) altitudes), as demonstrated by the clean separation between the upward and downward fluxes.

5. Discussion

Remote multispectral (color ratio) observations of Jupiter’s aurora by using the Hubble Space Telescope, and now Hisaki, have been used to estimate characteristic energies for the electrons that cause Jupiter’s aurora. These characteristic energies often range from tens of keV (~50 keV) to hundreds of keV (265–500 keV) [Gérard et al., 2014; Gustin et al., 2016; Tao et al., 2016], a range that is contained within JEDI’s energy range. And JEDI observes precipitation energy fluxes within the geometric loss cones at altitudes between 0.5 and 1.0 \(R_J\), sufficient to explain nominal auroral intensities. And yet no peaked energy distributions were observed of the sort often observed over discrete auroral features at Earth, suggestive of downward acceleration by coherent magnetic field-aligned electric fields [e.g. Carlson et al., 1998]. The primary downward acceleration regions could, of course, reside below the altitudes reached by the Juno spacecraft at the relevant times (<0.5 \(R_J\) altitude). But adding to the mystery is the fact that no localized magnetic field-aligned electron current signatures were identified as Juno passed over expected auroral structures as expected from pre-encounter estimates [Connerney et al., 2017b]. Given those mysteries, we pursue here the idea that the mechanisms that generate the asymmetric, bidirectional electron beams are among the prime mechanism for generating Jupiter’s uniquely intense auroral emissions, contrary to expectations from Earth [Carlson et al., 1998]. This process would be in addition to the clear diffuse auroral precipitation that is evident in the JEDI data in somewhat more equatorward regions.

The broad monotonic energy distribution shapes of the angular beams are suggestive of a stochastic acceleration process, just as inferred as an addition to the apparent coherent upward electrostatic acceleration at Earth within the downward electric current regions [Carlson et al., 1998]. The stochastic process in that case is thought to be random electron encounters with small-scale solitary electrostatic structures [Ergun et al., 1998]. An alternative possible source of stochastic acceleration is that proposed by Saur et al. [2003] involving the dissipation of turbulent Alfvénic fluctuations. The diversity of asymmetry is interesting. One possibility is that the beams are generated bidirectionally within an extended slab above the auroral ionosphere. If the spacecraft flies above that slab, then it sees primarily upward-directed electron beams, unless those upward beams return to the local position after reflecting off of the converging field lines at the opposite hemisphere. That bouncing process is presumably how the electron distributions at position E1 became bidirectional. Within the polar cap, the field lines connect to vastly more distant regions of the magnetosphere (if not open) and the electrons may have much more difficulty in finding their way back. The qualitative north-south symmetry in the observed phenomenology makes it unlikely that the cause is asymmetry in relative field strengths in the north and south. In order to see locally accelerated downward electron beams according to our hypothesis, one would need to penetrate deeply enough into the slab where the electrons are being accelerated. The source of the electrons that are accelerated into the beams is unknown, but one possibility is the process of upward acceleration (to perhaps 10 keV) of ionospheric electrons proposed by Ozak et al. [2013]. Irrespective of all of the uncertainties, we suggest that the hypothesized stochastic acceleration process generating the electron angular beams is at least one of the primary auroral acceleration processes at Jupiter generating the most intense auroral emissions.

Asymmetric angular electron beams carry electric currents that certainly may be dramatically modified by lower energy particles. Current density onto Jupiter’s ionosphere is estimated here by using the up-down integrated intensity differences, assuming the size of the pitch angle cone that is participating, and projecting the answer to just above the ionosphere by using an estimate of the field strength variation. The beam in Figure 4-E2 has \(\mathcal{J}_{\text{up}} \sim -0.13\) and \(-0.11 \mu\text{A/m}^2\) (minus for downward) for two different assumptions: the cone of participation is equal to an arbitrary 10°, and then is equal to the geometric loss cone. The structured
currents get larger as the statistical auroral ovals are approached. The peak estimated currents, observed in the southern hemisphere where the downward energy flux is greatest (Figure 4-E6), are $-1.2 \mu \text{A/m}^2$ and $-7 \mu \text{A/m}^2$ for our two assumptions. These currents are downward even where the downward electron energy flux is maximum. While downward currents in the polar cap (presumably away from strong emission features) are consistent with prevailing thoughts on Jupiter’s auroral configuration [Cowley and Bunce, 2001; Hill, 2001], it remains a mystery how the currents observed elsewhere fit into that picture and with the absence of magnetic signatures of localized Jupiter auroral currents [Connerney et al., 2017b]. JADE electron measurements (~0.1–100 keV) will certainly be required to fully understand the electron current structure and the total particle energetics of the auroral processes [Allegrini et al., 2017].

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References
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