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Key Points:
- We surveyed the Jovian Auroral Distribution Experiment electron data for science orbits 01, 03-30 and found upward, downward, and bidirectional electron conics 2.5% of the time.
- We observed all electron conics to occur most often at altitudes of 0.3–0.4 R_J and local times of 15–16 hr.
- We observed all electron conic types to have energies greater than 0.7 keV below an altitude of 0.5 R_J and over the main auroral region.

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Abstract

We present a survey of electron conics over Jupiter's high latitude regions utilizing 22.6 hr of data from the Jovian Auroral Distribution Experiment electron instrument aboard NASA's Juno spacecraft during science orbits 01 and 03-30. We observed electron conics for about 2.5% of this time and characterized them into three types based on their direction of motion along Jupiter's magnetic field lines: upward, downward, and bidirectional. We observed the upward electron conics most often and at energies of 0.057–80.1 keV, while we observed the downward electron conics least often and at energies of 0.073–1.2 keV. We observed bidirectional electron conics mostly around the same times and places as the upward electron conics having energies of 0.081–49.6 keV. We observed all electron conic types to occur mostly at altitudes 0.3–0.4 R_J and local times 15–16 hr. Furthermore, we observed all electron conic types to have energies greater than 0.7 keV below an altitude of 0.5 R_J and over the main auroral region.

1. Introduction

Electron conics were first discovered at Earth using the High Altitude Plasma Instrument (HAPI) aboard the Dynamics Explorer 1 (DE-1) spacecraft (Menietti & Burch, 1985). Menietti and Burch (1985) reported upward going electron distributions that peak at angles oblique to the local magnetic field, specifically, the electron conic pitch angle is just a little closer to 90° than the loss cone. For instance, if the loss cone has a pitch angle of 155°, then the electron conic will peak at a pitch angle less than 155°. Menietti and Burch (1985) observed electron conics within a pitch angle range of 150° and 170°. Two examples in that study showed data from the nightside main auroral region, and one example showed data from the polar cap. The electron conics in the nightside main auroral region appeared within the energy range of 2–5 keV, while those observed in the polar cap had energies on the order of 0.05–4 keV (Menietti & Burch, 1985). Electron conics of this nature are referred to as Type 1 electron conics by Morgan et al. (2000). Subsequent studies reported Type 1 electron conics from Viking (Hultqvist et al., 1988; Lundin et al., 1987), S3-3 (Swift & Gorney, 1989), and FAST (Chaston et al., 2002; Su et al., 2008) data. Surveys of both DE-1 and Viking data were performed to identify the spatial distribution of electron conics (Eliasson et al., 1996; Menietti et al., 1994). Eliasson et al. (1996) found that electron conics were generally observed mostly in the altitude range of 1.41–3.30 R_E (1 R_E = 6371 km), and invariant latitudes between 75° and 79°, where a satellite's invariant latitude is just its magnetic latitude on a planet's surface. One finds the invariant latitude by tracing along the magnetic field line. They also observed electron conics mostly at local times between 12 and 16 hr. In most cases, electron conics were observed in conjunction with upward ion beams whose energies were greater than or equal to the upward electron conics. Bidirectional electron conics appeared inside the Earth's auroral acceleration region, a range of altitudes within which there is a quasi-static electric potential accelerating particles (Burch et al., 1990). The electrons are caught between the electrostatic potential and the magnetic mirror point, producing the bidirectional conic distribution. Electron conics observed in Earth's main auroral region typically have energies on the order of 1–10 keV, while it seems there is a dependence on altitude as well, since DE-2 reported conics with only a few hundred eV (Burch, 1995).

Besides Earth, electron conics have been discovered at Jupiter (Louarn et al., 2018). Here we focus on electron conics at Jupiter and compare them with conics at Earth. While Jupiter and Earth both have magnetospheres encompassing the whole planet, they differ in many ways. Jupiter's magnetic moment is roughly 18,000 times that...
of Earth's, and its magnetosphere is bigger too, with the magnetotail stretching as far as Saturn's orbit (Bagenal et al., 2014). Furthermore, Jupiter has an internal source of magnetospheric plasma from its volcanic moon Io, and an internal energy source from Jupiter's fast rotation (Bagenal et al., 2014). Earth on the other hand gets most of its magnetospheric energy from the solar wind (Bagenal et al., 2014).

Section 2 below describes the data used and the selection process. Section 3 describes the electron conic types. Section 4 describes where we see each conic type and at what energies we observe them. Section 5 gives a preliminary comparison between the electron conics we observe at Jupiter and what Earth-based studies reported. Section 6 concludes the paper and offers some topics for future studies.

2. Data Selection

For this study, we used mainly electron data from the Jovian Auroral Distributions Experiment electron (JADE-E) instrument, taken with its highest time resolution of 1 s, along with some of the JADE ion (JADE-I) instrument data taken at its highest time resolution of 2 s (McComas et al., 2017). While both JADE-E and JADE-I are electrostatic analyzers, and thus measure energy per unit charge, I refer only to an electron's or proton's energy throughout this paper because electrons and protons both have a charge with an absolute value of 1. We utilized magnetometer (MAG) data (Connerney et al., 2017) at a resolution of 1 s to calculate the electron pitch angles, as well as the model loss cone pitch angle. We used a two-step process to select the JADE data from science orbits 01 and 03–30 (JADE-E was off during the second science orbit pass due to a spacecraft issue). In step 1, we identified time intervals where Juno's altitude was below 3.7 Jovian radii (1 R_J = 71,492 km). We chose this maximum altitude because the model loss cone pitch angle at greater altitudes became significantly less than the pitch angle resolution of the JADE-E instrument of 7.5°. Juno's invariant latitude was between 60° and 90°, the JADE-E count signal-to-noise ratio (SNR) was greater than 2 after summing over all look directions, and there was full pitch angle coverage in either the upward or downward model loss cone. For this study, we used a 7.5° pitch angle bin width. We found the SNR by dividing the electron intensity by the background intensity. Each JADE-E sensor has a background anode separated from the imaging anodes by a mask that ensures only penetrating radiation and other background sources reach it (Allegrini et al., 2021 S1; McComas et al., 2017).

To find invariant latitude, we used the JRM09 (Connerney et al., 2018) magnetic field model, along with the CAN (Connerney et al., 1981) current sheet model. We warn the reader that the JRM09 magnetic field model is accurate only to about 30 R_J, and that the CAN current sheet model only to about 50 R_J (Salveter et al., 2022). These models will be referred to collectively as the JRM09+CAN model from here on out. Changing the SNR criterion from greater than 2 to greater than 5 resulted in about an 8% reduction in the data we selected and did not change the main conclusions of this study. Using these criteria, we selected a total of 22.6 hr of observations in Jupiter's auroral region.

Using conservation of the first adiabatic invariant, we derive Equation 1 below to calculate the model loss cone. B_{JRM09+CAN} represents the model magnetic field at the UV altitude, defined as the altitude at which the UV aurora peaks in intensity, found to be 400 km above Jupiter's 1-bar pressure level (Clarke et al., 1998). We found this value by mathematically tracing the field lines from the spacecraft to Jupiter using Euler's method. We had to use the model magnetic field at the UV altitude because we currently do not have in situ measurements of the magnetic field in that region. B_{Juno} represents the magnetic field strength at Juno's location measured by the MAG instrument (Connerney et al., 2017) aboard Juno, and \( \alpha_{Juno} \) represents the loss cone pitch angle at Juno's location. We assumed that electrons mirroring away from Jupiter and back to Juno do so at a 90° pitch angle.

\[ \alpha_{Juno} = \sin^{-1} \left( \frac{B_{Juno}}{B_{JRM09+CAN}} \right) \]  

In step 2, we searched the 22.6 hr of JADE-E data from step 1 for electron conics. We imposed the following criteria for an electron conic: the electron phase space density (PSD) peaks away from the field-aligned direction by at least a single pitch angle bin, the electron PSD peaks by at least a factor of 2 greater than the intensity in adjacent pitch angle bins if it lasts more than 1 s, and the electron PSD peaks by an order of magnitude if it only lasts for 1 s. The first two criteria are consistent with the Earth-based studies, however, we did not impose the criterion that the electron distribution peak outside of the model loss cone as was done at Earth (Menietti & Burch, 1985) because we observed only 4 of 204 electron conics where the peak pitch angle was outside the loss cone at all
Figure 1. A flowchart of the data selection steps. Step 1 is boxed in teal on the left. In this step, we selected Jovian Auroral Distribution Experiment electron (JADE-E) measurements when Juno was in a certain location with respect to Jupiter, as well as good signal and pitch angle coverage. Step 2 is boxed in yellow on the right. In this step, we searched the JADE-E data from Step 1 to identify the electron conics according to certain criteria highlighted in yellow. Boxes highlighted in green show where we chose an electron conic, while the box highlighted in red shows where we did not choose an electron conic due to failing the criteria. Phase space density is abbreviated as phase space density, loss cone as LC, and signal-to-noise ratio as signal-to-noise ratio. The extra criterion regarding the magnetic field elevation angle is not shown here (see text for more details).

Figure 2 shows an interval when we observe upward electron conics. The data in this interval were taken on 2017 days of year (DOY) 086 from 08:29:40 to 08:31:30 UTC in the northern hemisphere. Conics separated by as little as one second are counted as multiple conics. Thus, Figure 2 contains nine conics, some of which last only one second, others a few seconds. Panel 2a shows the energy versus time spectrogram, with differential energy flux summed over all pitch angles. Panel 2b shows a pitch angle versus time spectrogram with PSD summed over the electron conic energies from ~0.1 to ~4.3 keV.

The electron conic from 08:29:44–46 occurs in the presence of a downward beam. There appear to be two distinct electron populations, one at energies between 30 and 100 keV and another between 0.1 and 1.3 keV, which is the energy range for this electron conic. While not shown here, electrons with energies greater than this electron conic appear as a faint bidirectional beam. The conic from 08:30:16–16 extends up to 3.1 keV, while the electron conic from 08:30:29–33 extends up to 4.3 keV, both occurring concurrently with a downward beam, as well as an upward electron beam at energies beyond 4.3 keV. The electron conics from 08:30:44–49, 51–55, and 08:30:56–08:31:00 all occurred in the presence of a clear upward beam at higher energies. Finally, electron conics from 08:31:16–18, 22–23, and 27–29 occurred in the presence of downward beams within the electron conic energies. The black triangles result from JADE-E300 being turned off due to a high voltage failure.

Figure 3 shows a pitch angle versus energy spectrogram with. The dashed black lines going horizontally across are the model loss cone pitch angles just as in Figure 2. The time interval is 08:30:29–33 from Figure 2. The fact that there is a downward beam observed with the electron conic suggests JADE-E observed this electron conic below Jupiter’s auroral acceleration region.

Figure 4 is in the same format as Figure 2, with the exception that the pitch angle versus time data have been summed over the energies from 0.04 to 0.08 keV on 2018-250 while Juno traveled over the southern hemisphere. Figure 4 shows a downward electron conic occurring from 01:56:07–17. Interestingly, the electron population again seems to be split into two distinct groups similar to what was shown in Figure 2. There were no upward going electrons at the conic energies shown here. Notably, the pitch angle coverage is not as complete, with the
diagonal black pixels showing that Juno’s orbital geometry with respect to Jupiter did not allow electrons near 90° to be measured. Again, the black triangles result from JADE-E300 being turned off.

Figure 5 is in the same format as Figure 3. This time, we show a downward conic taken during 01:56:07–17 from Figure 4. The downward electron conic is easily visible for the lowest energies, while there are no upward going electrons observed at any energy. This downward conic is narrow in pitch angle compared to that shown in Figures 2 and 3, and it occurs inside the loss cone.

Figure 6 is in the same format as Figure 2, but this time the pitch angle versus time spectrogram is summed over the electron conic energies from 15 to 50 keV, the energy range of the bidirectional electron conic from 15:11:53–59. Preceding this bidirectional conic is an upward conic from 15:11:30–40 which ranges in energy from 5 to 44 keV. Were it not for the missing pitch angle coverage, it is possible the whole time interval would show a bidirectional conic. We only observed the electrons at the same energies as the conics for the whole interval of 2020-101 from 15:11:30 to 15:12:12.

Figure 7 shows the bidirectional conic occurring from 15:11:57–59 from Figure 6. We observed the electron conic in Figure 7 at the same energies, pitch angles, and phase space densities in both directions up to the point where we lost pitch angle coverage close to 50 keV.
4. Spatial Distribution of Electron Conics

Figure 8 shows the spatial distribution of upward electron conics represented as green circles. Each green circle represents 1s of data during which we saw an upward electron conic. Panel 8a shows a magnetic coordinate system using the dipole moments of the JRM09 + CAN model. The solid black curves show Juno’s full trajectory for science orbits 01, 03–30, while the black circle represents Jupiter. The axes z and ρ show that this is a cylindrical coordinate system. We observe upward electron conics in the north all close to each other as represented in this magnetic coordinate system close to the planet. Meanwhile, in the south, we see a bit more of a range of distances from Jupiter for these upward electron conics. Panel 8b shows the upward electron conics projected to Juno’s magnetic footprint at the time of observation at the UV altitude in System III coordinates. The blue curves represent the main auroral region as observed by the Hubble Space Telescope measurements (Bonfond et al., 2012). The two solid blue curves are the outer and inner values, while the dashed blue curve represents the average position. Interestingly, we observe upward electron conics at latitudes above 70° and between longitudes 220°–280° right around the main auroral region. Next, we observe most of the upward electron conics below latitudes of 70° and between longitudes of 160°–200° poleward of the main auroral region. Finally, we observe upward electron conics between longitudes of 120°–140° equatorward of the main auroral region. Panel 8c has the same format as 8b, but this time for the south. We observe upward electron conics in the south at a wide range
of longitudes, almost all occurring on the main auroral region. Of the 204 electron conics, 156 occurred upward, 125 in the north, and 31 in the south.

Figure 9 shows downward electron conics represented as orange circles. All panels in Figure 9 have the same format as the respective panels in Figure 8. The most obvious feature is how few downward electron conics are compared to upward electron conics. Of the 204 electron conics, 10 occurred downward, 8 in the north, and 2 in the south. We observe them along the main auroral region in both the north and south.

Figure 10 has the same format as Figures 8 and 9. We represent bidirectional electron conics as red circles. The bidirectional electron conics appear in mostly the same places with respect to Jupiter and the main auroral region as the upward electron conics, within 0–2 min in fact. Of the 204 electron conics, 38 occurred bidirectional, 20 in the north, and 18 in the south.

Figure 11 shows the energy and spatial distributions of all three types of electron conics. Energy is in units of keV for the vertical axis of all panels. The horizontal axis of panels a–c is Juno’s west longitude at the UV altitude footprint location. Panels a–c show upward, downward, and bidirectional electron conics respectively, where the different colors are the same as Figures 8–10. Each colored circle represents one of the 204 electron conics used in this study. We found the maximum electron conic energy by looking at pitch angle versus energy plots such as shown in Figures 3, 5 and 7 and choosing the maximum energy that satisfied the criteria outlined in Figure 1 and Section 2. The spatial parameter is the average Juno position for that electron conic time interval.

Figure 5. Showing the downward electron conic in Figure 4 from 01:56:07 to 01:56:17 in the same format as Figure 3.

Figure 6. Same format as Figure 2 but for 2020-101 during a southern auroral crossing from 15:11:20 to 15:12:20. Shown here are two bidirectional electron conics highlighted by red, horizontal lines on both the top and bottom of panel 6b.
Panel 11a shows that we observe upward electron conics to have energies between 0.057 and 80.1 keV. Upward conics having energies below 1 keV are observed at all west longitudes, while those above 1 keV are mostly restricted to longitudes between 170° and 245°. Panel 11d shows most of the electron conics above 1 keV are restricted to the northern hemisphere within latitudes of 54°–78°. Panel 11g shows a clear trend in higher energy upward electron conics observed closer to the planet, save for an outlier at about 1.7 R\textsubscript{J} and an energy of about 80 keV.

Panel 11b shows that we observe downward electron conics to have energies between 0.073 and 1.2 keV. We observe downward electron conics mostly at longitudes between 141°–190°. Only 1 occurred beyond 1 keV. Panel 11e shows that downward electron conics occur almost exclusively in the northern hemisphere, as mentioned before. It seems higher energetic downward electron conics occur close to latitudes of about 60°. Panel 11h shows again a clear trend of higher energetic downward electron conics closer to Jupiter.

Panel 11c shows that we observe bidirectional electron conics to have energies between 0.081 and 49.6 keV. There does not seem to be a longitudinal trend for the bidirectional electron conics. Aside from a few outliers between longitudes of 144°–153°, bidirectional electron conics occurred below 1 keV at all longitudes. We also observed a similar number of them in both hemispheres as shown in panel 11f. Finally, panel 11i shows bidirectional electron conics occurring at higher energies closer to Jupiter, except for a few outliers between 1.7 and 1.8 R\textsubscript{J}.

We caution the reader regarding the results shown in Figures 8–11. Juno is but one spacecraft, and it is possible the spatial distribution of electron conics are biased according to Juno’s orbital geometry. For instance, the maximum number of JADE-E measurements we used for this study based on our selection criteria occurred while Juno was below an altitude of 1 R\textsubscript{J}, so it is not surprising that the maximum number of observed electron conics occurred below an altitude of 1 R\textsubscript{J}. Likewise, any pattern for the spatial distribution and energy range of electron conics in latitude and longitude may be due to Juno being close to Jupiter during that time. This is further exacerbated because successive Juno orbits process such that periapsis occurs at higher planetocentric latitudes in the northern hemisphere. Indeed, if we limited the data points in Figure 11 to those wherein Juno’s altitude was below 0.5 R\textsubscript{J}, we would not see any electron conic types in the south, and we would observe all electron conic types within a narrower longitude range from 117° to 270°. By contrast, the total number of all electron conic types with energies greater than 0.7 keV is reduced by less than 10%, suggesting that at least altitude appears to be important for electron conic energy. To fully deconvolute the spatial distribution results would require at least two spacecraft in a geometrical configuration such as that in the study by Burch (1995) at Earth.

5. Comparison With Earth-Based Studies

Before concluding, it is worthwhile to give a brief, preliminary comparison of electron conics observed at Jupiter and Earth. As shown in panels 11g-i, we observed all electron conic types to increase in energy the closer we observed to Jupiter, with the exception of a few outliers. This differs from Earth-based studies showing a maximum energy for bidirectional and upward electron conics from a few keV and even up to 40 keV peaking at altitudes corresponding to the auroral acceleration region, with those below...
the acceleration having energies only on the order of several hundred eV (Burch, 1995; Eliasson et al., 1996; Lundin et al., 1987; Menietti et al., 1994).

Looking at Figures 8–11 together would suggest that electron conics at Jupiter have greater energies on auroral field lines compared to those on field lines poleward or equatorward similar to the Earth-based studies (Eliasson et al., 1996; Menietti & Burch, 1985; Peterson et al., 2015). No Earth-based study to date has reported downward electron conics.

Figure 12 shows the maximum proton energy on the vertical axis versus maximum electron conic energy on the horizontal axis. The data points are represented as purple circles, and almost all of them appear above the diagonal black line representing the point where the maximum energies would be equal. All but 11 of these points show the proton energy is greater than the electron conic energy. The four rightmost ones beyond 40 keV can be explained by the fact that JADE-I only measures to 46 keV. André and Eliasson (1992) showed a similar trend in their Figure 3 for Viking orbits 343 and 418. Indeed, Earth-based electron conics papers using the Viking data report ion beams having comparable or greater energies than the corresponding electron conics. This is also mostly true for the HAPI/DE-1 studies.

There are important limitations to keep in mind regarding Figure 12. First, we used a different method for the maximum energies of protons compared to the electron conics. We used the same maximum electron conic energies as Figure 11. For the ions, JADE-I only measures the full ion pitch angle range (0°–180°) once every Juno spin (∼30s), which is not fast enough for these electron conics occurring on the order of one second to a few seconds in most cases. Furthermore, due to instrument placement on Juno and Juno’s orbital geometry over the high latitude regions, JADE-I measures mostly ions around pitch angles of 90°, making the analysis of upward ion beams difficult. These difficulties necessitated our calculating the maximum energy by calculating the characteristic energy according to equations 1 and 2 of Clark et al. (2018) during each of the 204 electron conic time intervals used and taking the maximum characteristic energy. We calculated this maximum characteristic energy over all JADE-I energies and pitch angles.

Figure 13 shows histogram plots comparing the results from this study to those in Eliasson et al. (1996). The JADE-E data are shown in red, while the V3 plasma experiment aboard the Swedish Viking satellite data are shown in black. Panel 13a shows number of electron conic events on the vertical axis and altitude in planetary radii on the horizontal axis. To get the altitude for JADE-E, the altitudes for a particular electron conic event were averaged just as in Figure 11. Thus, summing over all the red histogram bins would result in 204 total electron conic events. Both JADE-E and V3 show a maximum at some altitude, while before and after there are few to no electron conics observed. Although, the maximum occurs much closer to Jupiter than at Earth normalizing to planetary radii; 0.3–0.4 R_J compared to 2.05–2.15 R_E. Panel 13b shows the total number of measurements made in a particular altitude bin, so that summing over all the JADE-E measurements results in the 23 hr used for this study. Panel 13c shows the normalized distribution of electron conics. We normalized the electron conics in the same manner as Eliasson et al. (1996). We divided the number of events in one bin by the total number of measurements in that same bin, then multiplied by 1000. Thus, the first altitude bin had 3 electron conics in it and 346 total JADE-E measurements. (3/346) * 1000 = 8.67, and this is plotted in panel 13c. This shows a peak between 0.3 and 0.4 R_J compared to the 1.6–1.7 R_E.

Panel 13d shows number of electron conic events versus local time. Both JADE-E and V3 show a similar distribution, even though JADE-E took the
majority of its measurements at local times between 0 and 6 hr. Panel 13f shows again a similar distribution in both data sets, with the maximum occurring between 15 and 16 hr for JADE-E and 14–15 hr for V3. The outlier for V3 between 1 and 2 hr is perhaps not as robust as one might think since only 1 event occurred here, it is not statistically significant.

Figure 11. This figure shows the maximum electron conic energy (see text for more details) versus certain orbital parameters for all three electron conic types. The top panels all show upward electron conics, middle panels all show downward electron conics, and bottom panels all show bidirectional electron conics. The vertical axis for all panels shows energy in units of keV. The horizontal axis shows Juno’s footpoint at the UV altitude in west longitude in degrees for panels (a–c), Juno’s footpoint at the UV altitude in latitude in degrees for panels (d–f), and Juno’s altitude above Jupiter’s 1-bar pressure level in units of Jovian radii for panels (g–i). As before, green circles represent upward electron conics, orange circles downward electron conics, and red circles bidirectional electron conics.
Panel 13g shows electron conics distributed over invariant latitude. Panel 13h shows the total measurements, and finally, panel 13i shows the normalized electron conics. Panel 13i shows no clear trend in invariant latitude for the electron conics observe by JADE-E.

We next consider a few generation mechanisms of electron conics at Jupiter and compare them to what has been hypothesized at Earth. Figure 2 shows a downward electron beam observed with the electron conic, suggesting JADE-E observed this electron conic below Jupiter’s auroral acceleration region. The upward electron conic extends to higher energies and phase space densities, not unlike the upward electron conics reported at Earth. Taken together, this suggests either perpendicular heating via wave-particle interaction (Menietti & Burch, 1985; Wong et al., 1988), or else a resonance with the time-varying portion of a quasi-static potential structure (André & Eliasson, 1995).

At Earth, bidirectional electron conics appear inside the Earth’s auroral acceleration region, caught between the electrostatic potential and the magnetic mirror point (Burch et al., 1990). This suggests the same mechanism generates the electron conic in both directions, with the downward conics coming from the northern hemisphere. Figure 7 shows a bidirectional electron conic with similar phase space densities and energies in both directions, suggesting that Alfvén waves (Louarn et al., 2018) could be generating these conics, or else electrons caught between an electric potential and the mirroring point as at Earth.

We leave the reader with a note of caution concerning this preliminary comparison between electron conics at Jupiter and Earth. First, we draw attention to the fact that Eliasson et al. (1996) used over 600 Viking orbits for their study compared to just 29 Juno orbits for our study. Second, invariant latitude does not have as much effect at Jupiter than at Earth. At Earth, invariant latitude is used because Earth’s magnetic field is close to dipolar. Meanwhile at Jupiter, the magnetic field is not dipolar. As shown by Figures 8–10, Jupiter’s main auroral region in the northern hemisphere is neither oval nor circular in shape compared to Jupiter’s southern hemisphere, or either hemisphere at Earth. Thus, any invariant latitude could be inside, equatorward, or poleward of the main auroral oval, and it does not help to use invariant latitude at Jupiter. The deviation of a dipole field applies also to magnetic longitude, and thus to local time. The comparable local times wherein we observe electron conics at both planets does not necessarily translate directly to similar points along the respective planets’ main auroral regions.

6. Conclusion

We surveyed 22.6 hr of Juno data from science orbits 01, 03–30 and observed electron conics for about 2.5% of this time. We further characterized these electron conics into three types based on their direction of motion along Jupiter’s magnetic field lines: upward, downward, and bidirectional. We observed the upward electron conics most often and at the highest energies, while we observed the downward electron conics least often and at the lowest energies. We observed bidirectional electron conics mostly around the same times and places as the upward electron conics having mostly similar energies as the downward electron conics. Furthermore, we observed all electron conic types to have energies greater than 0.7 below altitudes of 0.5 RJ and over the main auroral region.

We have briefly compared the electron conics at Jupiter and Earth. We observe downward electron conics at Jupiter, while no downward electron conics have been yet reported at Earth. We observed electron conics of all types at Jupiter at higher energies closer to Jupiter as opposed to the most energetic electron conics at Earth being observed inside the main auroral acceleration region. The histograms of normalized electron conics versus altitude show similar shapes at both planets, albeit those at Jupiter appear closer to the planet when normalized to a planetary radius. The histograms of normalized electron conics versus local time show similar shapes at both planets, with the peak occurrence shifted by just one bin.
Some questions remain for future studies. What causes the altitude dependency of the electron conic energy? To date, no statistical surveys have been done to constrain an altitude range for Jupiter's auroral acceleration region. At Jupiter, it is unclear if there is any altitude range for auroral acceleration because the Juno data show downward beams over many science orbits, indicating there is still auroral acceleration occurring above Juno (Allegrini et al., 2017; Mauk et al., 2017). While the JADE-E and JEDI data have shown consistent patterns in the electron distributions over the main auroral region and polar cap (Allegrini et al., 2021; Mauk et al., 2020), stochastic...
acceleration dominates Jupiter's main auroral region, producing the most powerful aurora in contrast to discrete aurora at Earth (Allegreni et al., 2020; Carlson et al., 1998; Salveter et al., 2022).

What are the main electron conic generation mechanisms at Jupiter, and how do these compare to Earth? Louarn et al. (2018) showed that Alfvén waves can generate electron conics at almost any altitude along a magnetic field line mapping to Jupiter's main auroral region, but is it possible there are others, and if so, what determines whether one mechanism dominates versus another? Is there a solar illumination dependence for electron conics as there is for the polar aurora (Greathouse et al., 2021)? Are there electron conics within 30° of Jupiter's equator as there are at Earth (Peterson et al., 2015)? Furthermore, why are there no downward electron conics at Earth, and what does this say about the differences between Earth's magnetospheric dynamics and Jupiter's?

Data Availability Statement

All JADE data used for this study were taken from JNO-J/SW-JAD-3-CALIBRATED-V1.0 located on NASA’s PDS website. These data were version 04 high rate science electron files which had an orbit dependent background subtracted, as well as version 02 high rate science ion species files. To calculate the electron pitch angles, the JNO-J-3-FGM-CAL-V1.0 MAG data available on NASA’s PDS website were used. Version 02 MAG data was used where available. Version 01 otherwise. The specific MAG data files utilized were in payload coordinates at 1 s resolution. To calculate invariant latitude, we used data from the Juno MWG website at UL, which is http://space.physics.uiowa.edu/juno/mwg/magfootprint.html. The website is password protected, and the reader will need to contact Masafumi Imai for access. Masafumi Imai provided magnetic footprint latitude for using the JRM09 + CAN model for orbits 00–34 at 1 min intervals. We interpolated Juno’s magnetic footprint latitude at the 1-bar pressure level to the 1 s resolution of the JADE data and subsequently converted that latitude from planetocentric latitude to invariant latitude using the JRM09 + CAN model. All data from Figures 2–13 are available as text files at https://doi.org/10.5281/zenodo.6925936. Figure 1 is available as a PNG image at the same Zenodo repository as the text files.

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