High Latitude Zones of GeV Heavy Ions at the Inner Edge of Jupiter's Relativistic Electron Belt

Heidi N. Becker1 †, James W. Alexander1 ‡, John E. P. Connerney2,3 †, Martin J. Brennan1 †, Alexandre Guillaume1 †, Virgil Adumitroaie1 †, Meghan M. Florence1 †, Peter Kollmann4 †, Barry H. Mauk4 †, and Scott J. Bolton5 †

1Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA, 2Space Research Corporation, Annapolis, MD, USA, 3NASA Goddard Space Flight Center, Greenbelt, MD, USA, 4Applied Physics Laboratory, The Johns Hopkins University, Laurel, MD, USA, 5Southwest Research Institute, San Antonio, TX, USA

Abstract Juno has discovered signatures of a high energy heavy ion population (>100 MeV/nucleon) within the inner edge of Jupiter's relativistic electron belt. The particles were detected in narrow zones in the high-latitude lobes of the synchrotron emission region, a location never explored by prior spacecraft (~31°–46° magnetic latitude; radial distances 1.12–1.41 Jovian radii, M-shells 1.5–2.37). The population was revealed by extremely high signal ionization signatures seen in images collected by Juno's Stellar Reference Unit star camera (equivalent to 0.2–0.7 MeV of deposited energy per pixel). Signature morphology indicates a population of GeV ions (Z > 1) with atomic mass as high as sulfur, although species with 2 ≤ Z ≤ 8 potentially account for all of the signatures. The detections have occurred while the spacecraft is magnetically connected to Jupiter's halo and gossamer rings, but not while it is connected to the main ring; similar to equatorial observations of GeV carbon and sulfur ions by the Galileo Probe. We find that the particles reside on magnetic drift shells that suggest they are stably trapped within Jupiter's magnetosphere. Because the cosmic ray albedo neutron decay mechanism can only produce protons and electrons, it cannot be the source of this trapped Z > 1 ion population; other galactic cosmic ray origins are suspected. Inward radial transport of tens of keV heavy ions from the outer magnetosphere is another potential source.

1. Introduction

Prior to the Juno Mission, limited in situ particle data were collected deep within Jupiter's radiation belts. The two predecessor surveys conducted inside radial distances of ~1.6 Jovian radii (RJ) were constrained to the equatorial region. Pioneer 11 performed a high inclination flyby in 1974, achieving a closest approach of 1.6 RJ at 13°S latitude while surveying energetic electrons, protons, and heavy ions (Bolton et al., 2004; Pyle et al., 1983; Trainor et al., 1975; Van Allen et al., 1975); and the Galileo Probe sampled the equatorial electron and ion populations during a single pass inbound to the planet in 1995 (Fischer et al., 1996; Mihalov et al., 2000). Juno is the first spacecraft to sample the inner edge of Jupiter's radiation belts at high latitudes. Juno's unique polar orbit (Figure 1) with a periapsis as close as 1.05 RJ (3,400 km from the 1 bar level) has enabled unprecedented study of Jupiter's innermost radiation belts, leading to the discovery of an equatorial radiation belt of hundreds of keV ions between the atmosphere and Jupiter's rings (Kollmann et al., 2017) and the finding that >10 MeV electron fluxes at the inner edge of Jupiter's relativistic electron belt are an...
order of magnitude lower than predicted by pre-Juno models (Becker, Santos-Costa, et al., 2017). Here we report first detection of >100 MeV/nucleon heavy ions located within the innermost peaks of the synchrotron emission region high latitude lobes (high latitude protrusions of enhanced emission near \(L \sim 2.2\); hereafter “high latitude lobes”; e.g., Santos-Costa & Bolton, 2008) and magnetically connected to Jupiter’s halo and gossamer rings. The regular appearance of the ion signatures at a narrow range of M-shells during 17 observations conducted over a wide range of sampled longitudes suggests a trapped population. We discuss potential species responsible for the observed signatures and suggest possible source origins.

2. Data

Data reported here were collected by Juno’s Radiation Monitoring (RM) Investigation using the Juno Stellar Reference Unit (SRU) star camera between Perijoves 1 (August 27, 2016) and 21 (July 21, 2019). Data from the other RM instruments discussed in Becker, Alexander, et al. (2017) were not conducive the high ionization signature extraction discussed here, due to dynamic range and noise limitations.

3. Unusual Ionization Signatures

Juno’s RM investigation measures omnidirectional >10 MeV electrons at Jupiter by extracting penetrating particle signatures from images collected with the SRU’s heavily shielded silicon CCD (Becker, Alexander, et al., 2017). During the mission, penetrating electron intensities have been low enough for us to discern the signatures of another, unexpected particle population at the inner edge of the electron belt. These unusual ionization signatures are characterized by a very compact morphology (only a few affected pixels) and high signal equivalent to \(\sim 0.2-0.7\) MeV of deposited energy per pixel. They are >100 times brighter than a typical penetrating electron signature and 10 times brighter than typical proton signatures (the data also indicate a light presence of >125 MeV protons in the high latitude lobes; see Text S1 and Table S1; an example compact proton signature is shown in Figure S33). Figure 2 illustrates the sparse occupancy of electron signatures in

Figure 1. Juno’s polar orbit traverses the inner edge of Jupiter’s relativistic electron belt, passing as close as 1.05 Rj (3,400 km) from the clouds at perijove. This artist’s rendition of Juno’s first science flyby, “Perijove 1” (August 27, 2016), illustrates the spacecraft’s high latitude encounters with Jupiter’s extreme electron belt (orange). Magnetic field lines are shown for \(L = 1.3, 1.5, 2, 2.25, 2.5, 3\) based on the VIP4 magnetic field model (Connerney et al., 1998). Juno is the first spacecraft to orbit this close to Jupiter and to explore these high latitude regions. Markers are shown for the closest approach of Pioneer 11 in 1974 (~1.6 Rj) and the nearly equatorial path of the Galileo probe into the atmosphere in 1995. The locations of Juno’s first detections of >100 MeV/nucleon ions (\(Z > 1\)) during Perijove 1 are shown as blue flashes. Credit: M. Stetson, D. Santos-Costa, J. Arballo, H.N. Becker.
Journal of Geophysical Research: Planets

an image acquired during Juno’s passage through the northern high latitude lobe during Perijove 3 (December 11, 2016). The low incidence of overlapping electron impacts facilitates the detection of an atypically bright spot.

Figures of all 118 atypical signatures detected through Perijove 21 are provided in the supporting information (Figures S1–S32). Although most signatures have compact morphology similar to the example in Figure 2, extended high signal “streaks” due to lateral impacts (Figure 3) are occasionally observed in the images (18 of the 118 atypical signatures are streaks). Seventeen images collected in the high latitude lobes (in 14 of Juno’s high-latitude passes) contained bright signatures, compact or streak-shaped, with pixel signal levels that exceed 3000 DN (0.2 MeV deposited energy) per pixel (see Table S1). A total of 114 signatures were detected there, at a rate of 1–21 bright ionization signatures per image. These images were acquired using a 10 or 100 ms exposure and a 250 ms readout period, which yields an average radiation exposure time of 130–175 ms for the CCD pixels (Becker, Alexander, et al., 2017). Three additional compact signatures were detected near Juno’s orbit apoapsis, and a single compact signature was detected in the middle magnetosphere (see Section 5.1).

4. Responsible Species and Energies

At 0.2–0.7 MeV (3,000–13,000 DN) per pixel, the observed signatures are too bright to have been created by penetrating electrons or protons. Geant4 modeling and ground tests of the SRU silicon CCD with relativistic electron and proton beams showed that the typical signal generated by a penetrating electron is only ∼100 DN per pixel, and typical signals expected from penetrating protons are only ∼10 times higher (Becker, Alexander, et al., 2017). Although it is possible for much brighter signatures to be created by protons that have reached the highly ionizing Bragg peak energy at the end of their path (see Figure A2), or by a photonuclear event that originated with a high energy penetrating electron, such events are rare. We observe 1–21
unusually bright signatures in images containing a total of only $\sim 100–6,000$ electron signatures (Table S1), which is too few penetrating electrons for the bright signatures to be explained by photonuclear events. Bragg peak protons are also hard to justify statistically, given the low number of potential proton signatures observed in the images. Figure 4 illustrates the presence of the bright signatures in several images where the penetrating particle population is clearly dominated by electrons. The cumulative distribution of penetrator signals is shown for each flight image and compared to similar distributions for modeled omnidirectional electron and proton signatures (Becker, Alexander, et al., 2017) generated using Geant-4 and external kinetic energy spectra from Garrett et al. (2005) and Divine and Garrett (1983) at $L = 2.2$. Panel (a) shows that the flight data are strongly dominated by penetrating electrons, yet as many as 0.31 percent of the signatures in each image exceed 3,000 DN per pixel (the mean value is 0.22 percent). Fewer than 0.5 percent of all modeled proton signatures are brighter than 3000 DN per pixel (panel b). Hence, for the observed number of >3,000 DN per pixel signals to be attributed to protons, at least half of all flight signals would have to be proton signatures, which isn’t supported by the measured signal distributions. It is also intuitive that the external flux of >10 MeV electrons would be far greater than that of >125 MeV protons (the particle regimes most likely to penetrate the SRU shielding).

Indeed, the external kinetic energy spectrum of protons above 125 MeV is not well constrained. However, only a narrow range of external proton energies ($\sim 125$ MeV, $\pm$ a few MeV) will produce penetrators that arrive at the CCD with the low energies needed to create 3,000–13,000 DN per pixel signals (0.75–5.8 MeV); such protons barely penetrate the SRU shielding. Higher energy protons produce lower signal signatures (see Appendix A), and the SRU sensitivity rapidly spikes by two orders of magnitude between 125 MeV and just 200 MeV (Becker, Alexander, et al., 2017). Even if the external proton spectrum was somehow different
from the model, the spectrum of a given particle species usually has a continuous, more or less power law shaped spectrum. We therefore would not expect a gross change in the weighting of Bragg peak protons within the spectrum of penetrators, unless the external proton spectrum had abruptly rolled off below 200 MeV. This is neither a credible physical solution nor one we can validate with our data. This implies that another species is responsible for the unusually bright signals we detect.

The lateral "streaks" described in Section 3 provide a strong constraint against protons as the responsible species, as they give visibility into how the particles deposit energy over extended path lengths. For example, when we convert from DN to eV, the sum of all pixels in the streak shown in Figure 3 represents 5.07 MeV of deposited energy (~1 DN of signal is generated for every 57 eV of energy deposited in the CCD by a penetrator; see Appendix A). This places a 5.07 MeV minimum on the particle's energy upon its arrival at the CCD. Approximately 13,000 DN were deposited during each 24 μm diagonal step the particle took across the CCD’s rows (amounting to 540 DN/μm), and this uniform signal deposition is observed over a total path length >140 μm. However, as shown in panel (a) of Figure 5, a 5.07 MeV proton will deposit less than 235

Figure 4. Pixel signals from ionization signatures observed in Stellar Reference Unit (SRU) images collected within Jupiter’s innermost radiation belts (<1.4 RJ) are compared to Geant4-modeled signatures (Becker, Alexander, et al., 2017) for penetrating electrons (dashed black line) and protons (solid black line). (a) A cumulative distribution of the brightest pixel signal from each ionization signature is plotted for each flight image. Similar distributions are shown for the modeled ionization signatures. Signal levels are in output analog-to-digital data number, DN. Flight data are from five SRU images collected within the high latitude lobes during Perijoves 1–9. The distributions of the observations overlay the modeled electron distribution, illustrating the absence of a significant proton presence. A handful of very bright signatures form a separate distribution. (b) The highest five percent of the pixel signal distributions, highlighting the separate distribution formed by the bright signatures. Data from an image collected just outside the high latitude lobes (green) are shown to illustrate the absence of bright signatures in regions where ions are not detectable.
DN/μm in silicon. A proton would need an energy less than 1.55 MeV to deposit 540 DN/μm in silicon, and would have a range of only \( \sim 32 \) μm; insufficient to generate the observed streak (see Figure 5b). Neither the length nor the observed signal can be explained by a hydrogen ion. Ions of higher atomic number are able to deposit 540 DN/μm over 140 μm. One example is 40 MeV He (Figure A1). Fourteen of the 18 lateral streaks signatures (listed in Text S1) cannot be attributed to protons, due to similar stopping power and range constraints. The remaining four could be explained by Bragg peak protons but heavier species are also capable of generating them.

We used Ziegler’s (2013) Transport of ions in matter (TRIM) transport analysis software to search for heavier species with sufficient energy to penetrate the SRU shielding and arrive at the CCD with the necessary stopping power to generate the observed signal range, or a portion thereof. Details of the approach are provided in Appendix A. TRIM provides ion stopping power data up to energies of 10 GeV/nucleon which bounds the upper ion energies used in our CCD signal assessments. The analysis shows that several heavy ion species with energy >100 MeV/nucleon can create the observed signatures with ease, allowing us to constrain the responsible species and energies as shown in Table 1. As energy deposition theoretically scales strongly with the atomic number squared (Zombeck, 1982), an alternative is to represent these candidates in terms of their Energy/\( Z^2 \) (where \( Z \) is atomic number). This representation yields a relatively compact range from >76 to >141 MeV/\( Z^2 \).

Ions heavier than sulfur are too highly ionizing to generate any of the observed signals. Sulfur is the heaviest possible species, but it can generate only the brightest observed signatures. Although it is possible that multiple species are responsible for the observations, we note that species from helium to oxygen (\( 2 \leq Z \leq 8 \)) are capable of generating the full range of measured signals.

5. Signs of a Trapped Population

5.1. Detection Locations

The GeV ion population was detected in narrow high-latitude zones of the synchrotron emission region within magnetic latitudes 34.9°S–45.7°S and 30.6°N–46.1°N, M-shells \( \sim 1.5 \) to 2.37, and radial distances from \( \sim 1.12–1.41 \) \( R_J \) (a single detection was also made at 18.4°S, M-shell 1.32). The detections have been made over a wide range of longitudes (Table S1), suggesting that these ions are a stably trapped population. With the exception of three bright signatures observed in housekeeping images collected near Juno’s
Table 1
Ion Species Capable of Generating the Observed High Signal Signatures

| Species | External particle energy [GeV] | External particle energy per nucleon [MeV/nucleon] | Range of observed signals the species can generate [DN/pixel] |
|---------|--------------------------------|-----------------------------------------------|---------------------------------------------------------------|
| H       | ~0.125                         | ~125                                          | Full (3,000–13,000)                                           |
| He      | 0.544–0.564                    | 136–141                                       | Full                                                          |
| Li      | 1.1–1.3                        | 157–186                                       | Full                                                          |
| Be      | 1.7–2.6                        | 189–289                                       | Full                                                          |
| B       | 2.4–5.8                        | 218–527                                       | Full                                                          |
| C       | >3.1*                          | >258*                                         | Full                                                          |
| N       | >4.1*                          | >293*                                         | Full                                                          |
| O       | >5.1*                          | >319*                                         | Full                                                          |
| F       | >6.5*                          | >342*                                         | ~3,500–13,000                                                |
| Ne      | >7.7*                          | >385*                                         | ~4,300–13,000                                                |
| Na      | >9.9*                          | >430*                                         | ~5,300–13,000                                                |
| Mg      | >11*                           | >458*                                         | ~6,200–13,000                                                |
| Al      | >16*                           | >593*                                         | ~7,700–13,000                                                |
| Si      | >18*                           | >643*                                         | ~8,500–13,000                                                |
| P       | >24*                           | >774*                                         | ~9,900–13,000                                                |
| S       | >36*                           | >1,125*                                       | ~12,000–13,000                                               |

Note. The external energies required for ions to penetrate the SRU shielding and arrive at the CCD with the necessary stopping power to generate the observed signals are shown for species from hydrogen to sulfur. Asterisks denote that an upper bound for the signal assessment exists at ~10 GeV/nucleon. Values are for the case where the particle entered the SRU through the lens elements, which is the weakest SRU shielding path. The required energies for particles penetrating from a lateral direction (perpendicular to the optical axis, and through the camera’s heavy tungsten shielding) are only ~37%–46% higher than the values shown in the table. Species from helium to oxygen can create the full range of observed signals, while heavier ions from fluorine to sulfur can generate only a brighter subset of the observations.

Abbreviations: DN, data number; SRU, Stellar Reference Unit.

Hydrogen is included for completeness, but is not considered a viable candidate (see text).

6. Location Within Jupiter’s Ring System

6.1. Magnetic Connection to the Halo and Gossamer Rings

The M-shells of the particles let us constrain where they reside and evolve relative to Jupiter’s rings (note that M-shell has historically been referred to as the “magnetic distance” in some studies, for example in Kollmann et al., 2017). The majority of the detections through Perijove 21 have taken place at M-shells between 1.88 and 2.37 Rₐ within the diaphanous Amalthea “gossamer” ring located between the brighter “main” ring (1.71–1.81 Rₐ; Burns et al., 2004) and the moon Amalthea (2.54 Rₐ; Ockert-Bell et al., 1999). See Figure 8 below. Images collected while magnetically connected to the main ring at M-shell values of 1.71 Rₐ and 1.73 Rₐ did not contain any Z > 1 GeV ion signatures, nor did several images collected inside the main ring’s inner boundary (see Table S1). This suggests that the higher dust particle density of the main ring (optical depth, τ ~ 6 × 10⁻⁶ vs. τ ~ 10⁻⁷ for the Amalthea gossamer ring; see Burns et al., 1999 & Throop et al., 2004) may be leading to energetic particle absorption or efficient energy loss, or that any stably trapped ions from this population are mirroring at lower magnetic latitudes than those crossed by Juno. Absorption by Metis and Adrastea, computed by Nénon et al. (2018) for energetic protons, may also play a
role. No signatures were observed while magnetically connected to regions of the gossamer ring outside the orbit of Amalthea.

Two additional sightings at M-shell values of 1.53 $R_J$ and 1.32 $R_J$ lie within the “halo” ring and its tenuous component inside 1.4 $R_J$ (Burns et al., 2004; Showalter et al., 1987). As a result of Juno’s trajectory, these two observations were made at relatively low magnetic latitudes (30.6°N and 18.4°S, respectively) compared to the detections made while connected to the gossamer ring (magnetic latitudes from 34.9° to 46.1°). Each image contained only one signature (and several other images collected within the halo contained no signatures), which implies that the $Z > 1$ GeV ion fluxes are lower in this region than within the gossamer ring. In the Extended Mission, Juno’s orbits will allow exploration at progressively lower magnetic latitudes within the halo, providing greater insight into this component of the population.
6.2. Comparison to Galileo Probe Observations

The Galileo Probe Energetic Particles Investigation (EPI) instrument sampled high energy alphas and heavy ions during its transit through Jupiter’s ring system, exploring magnetic latitudes from $-5.6^\circ$ to $-3.4^\circ$. The measured energy ranges were 62–136 MeV/nucleon (He), 110–168 MeV/nucleon (C), and $>210$ MeV/nucleon (S) according to Fischer et al. (1996), though an earlier calibration study notes a 110–910 MeV/nucleon energy range for carbon within the HVY channel (Fischer et al., 1992). Although we cannot distinguish the exact species responsible for the SRU signatures, the energies of our helium (136–141 MeV/nucleon) and carbon (>$258$ MeV/nucleon) candidates from Table 1 bear similarity to the populations observed by the EPI. The same may potentially be true for sulfur, although it is not known whether the energies of the sulfur ions detected by the probe extended to $>1,125$ MeV/nucleon. Figure 8 plots EPI omnidirectional uncorrected count rates for helium and heavies, as reported in the Planetary Data System archived data set, as a function of the probe’s M-shell. M-shells of the SRU detections are also displayed. This organization allows us to compare the locations of the Juno and Galileo Probe measurements within the Jovian ring system, even though the observations were made at different magnetic latitudes. It can be seen that both the SRU and Galileo Probe heavy ion detections occurred within the halo and gossamer rings but not within the main ring. Another similarity is that the Probe and SRU observations both indicate that energetic heavy ion fluxes are less intense in the halo than in the Amalthea ring region. The Probe did detect alphas within the main ring, although the peak intensity there was notably less than peaks observed at M-shells.
corresponding to the halo and gossamer rings. Given these similarities in energy and M-shell, it is possible that Juno is observing a higher latitude component of one or more trapped ion populations measured by the Galileo Probe at the equator.

6.3. Comparison to Pioneer 11 Observations

Although designed to measure $\geq 35$ MeV protons, the response of the Pioneer 11 fission cell inside $L \sim 5.5$ was found to be consistent with $\geq 70$ MeV/nucleon "medium-Z" ($Z > 5$) nuclei, presumed to be oxygen or sulfur (Pyle et al., 1983). Following pronounced absorption observed while encountering the $L$ shells of Thebe and Amalthea, the fission cell count rates were observed to increase by about three orders of magnitude below an $L$ of 2.4 then drop precipitously by 200X upon reaching the outer edge of the main ring. The lower energy Pioneer data do not extend inward to $L$ shells that intersect the main ring or halo, but the sharp increase in flux observed between the main ring and Amalthea resembles the profile of energetic $Z > 1$ ion counts measured there by the Galileo Probe, and it is also consistent with the sudden intensity reduction at the main ring implied by the SRU observations.

7. Possible Origins

The source of the GeV $Z > 1$ ion population observed by Juno and its presence to either side of the main ring, but not within it, are puzzles. We offer the following considerations as to their origin.

The cosmic ray albedo neutron decay (CRAND) mechanism is an important source for the proton belts of Saturn and Earth (see for example Cooper & Sturmer, 2018; Kollmann et al., 2013; Selesnick et al., 2013). In this process, cosmic rays bombard the atmosphere or ring material and produce secondary neutrons. Some of the neutrons can decay into protons, electrons, and antineutrinos and provide a source for trapped proton or electron populations. Because our analysis has determined that the candidate ion species are heavier than hydrogen, and CRAND only produces protons and electrons, we rule out CRAND as a possible direct source.

Anomalous cosmic rays (ACRs) are another potential source for trapped ion populations. On Earth, $\geq 15$ MeV/nucleon C, O, N, and Ne were found trapped in a narrow region around $L \sim 2$ by the SAMPEX spacecraft (Selesnick et al., 1995). Selesnick et al. (1995) deduced that these ions had originated as singly ionized interplanetary ACRs which then became trapped in the magnetosphere after undergoing magnetic
rigidity losses from electron stripping in the upper atmosphere. To become constrained by Jupiter’s magnetic field in this manner, ACRs would first require a magnetic rigidity high enough to access Jupiter’s atmosphere. Under the dipole magnetic field approximation of Störmer theory, a particle is allowed access to a magnetosphere if its rigidity exceeds the magnetic cutoff rigidity (Smart & Shea, 2005). For a northward dipole moment such as Jupiter’s, the lowest cutoff rigidity is for arrival in the eastward direction (Cooper & Simpson, 1980) and has a value at the atmosphere of ~900 GV for L = 1.4 (the lowest approximate L shell of the SRU detections). The species capable of generating the full range of observed signals (2 ≥ Z ≥ 8) have rigidities ranging from only ~2–174 GV when singly ionized (see Table S5). Moreover, ACRs with energy greater than a few tens of MeV/nucleon are expected to be predominantly multiply charged (see Cummings & Stone, 2007; Jokipii & Giacalone, 1998; Mewaldt et al., 1996; Strauss et al., 2010). Our candidates (all with energies in excess of 100 MeV/nucleon) are thus likely to have even lower rigidity values, as rigidity is inversely proportional to the charge state (Rigidity = pc/q, where p is momentum, c is the speed of light, and q is charge). Such large differences between the cutoff rigidity at the atmosphere and the rigidities of the trapped ions cannot be accounted for by atmospheric stripping of any remaining electrons. In principle, subsequent collisions with ring material could lead to further rigidity reductions from kinetic energy losses, but a reduction of up to a few orders of magnitude (depending on the species) would be required to explain the Juno observations.

Alternatively, the population may derive from the spallation products of cosmic ray impacts with the Jovian ring material or cosmic ray “sputtering” of helium from the atmosphere. These mechanisms were proposed to explain the strong “reemergence” of EPI helium and heavy particles in the halo following the absorption observed in the main ring material (Fischer et al., 1996) and may serve equally well to interpret the >100 MeV/nucleon ions seen by Juno in the halo and the Amalthea ring.

It has been postulated that the ≥70 MeV/nucleon “medium-Z” ions measured by Pioneer 11 were accelerated by inward radial diffusion. Under the assumption that the fission cell was exclusively counting oxygen ions, Gehrels et al. (1981) utilized the Pioneer data along with lower energy data from Voyager to calculate phase space densities for oxygen, with results that suggested inward diffusion (Pyle et al., 1983). Io was the suggested oxygen source (Gehrels et al., 1981). To address the Juno observations, we note that the magnetic field changes by four orders of magnitude between an M-shell of ~2 (10^4 nT) and the edge of the magnetosphere (1 nT; Khurana & Schwarzl, 2005). If particles are transported between these regions under conservation of the first adiabatic invariant (Roederer, 1970), via radial diffusion for example, their energy will increase by this factor. Hence, 544 MeV helium would have to start with 54 keV at the edge of the magnetosphere. Ions of a few tens to hundreds of keV exist even at these distances with magnetospheric composition (Kollmann et al., 2018; Lanzerotti et al., 1992), and are also found in the interplanetary medium (Fisk & Gloeckler, 2008; Kollmann et al., 2019). This means that the energy of the particles is potentially explainable through adiabatic transport. To examine if their abundance is sufficient, a phase space density analysis is needed. Such an analysis is not possible at this stage for the data presented here. A limitation of the data set is that it does not provide information about the pitch angle distribution (we can only constrain it as being below the equatorial pitch angles that reach the given latitude, and above the pitch angle of the loss cone), nor does it allow us to ascertain the exact mass or energies of the ions (both of which strongly impact the instrument sensitivity). These factors hinder meaningful estimates of the population’s external flux.

8. Conclusions

Juno’s novel orbit and utilization of engineering instrumentation for science exploration has led to surprising discoveries within Jupiter’s innermost radiation belts (Becker, Santos-Costa, et al., 2017; Kollmann et al., 2017). Here we have shown that a trapped population of >100 MeV/nucleon Z ≥ 1 ions is present at the inner edges of the electron belt (distances of 1.12–1.41 R_J), between ~18° and 46° magnetic latitude on field lines that intersect Jupiter’s halo and Amalthea gossamer rings. The composition of the population has been constrained to species with 2 ≤ Z ≤ 8, with possible additional contributions from species as heavy as S. This, and the absence of detections at M-shells corresponding to the main ring, is reminiscent of the profile of equatorial C and S measured by the Galileo Probe, suggesting that Juno may have observed this population at higher latitudes as >258 MeV/nucleon C or >1,125 MeV/nucleon S. It is possible that the population may originate from interactions between galactic cosmic rays and Jupiter’s atmosphere or ring
material. Its existence may also be explained by the inward radial transport of tens of keV heavy ions from the outer magnetosphere.

The evolution of Juno’s orbit during the remaining Prime Mission and Extended Mission orbits enables broader profiling of this population at lower magnetic latitudes and greater radial distances in the South. In particular, measurements at M-shells corresponding to the inner halo region ($M < 1.4 R_J$) could eventually reach the equator, potentially allowing stronger correlations to be drawn between the Galileo Probe and Juno observations to provide additional constraints on species. An operational change which could yield further information about the population would be to vary the orientation of the SRU sensor relative to the local magnetic field vector during imaging. The current observation strategy is to orient the SRU with the plane of the CCD approximately parallel to the magnetic field vector during image exposures, which tends to maximize detection of locally mirroring particles. Variations in the number of lateral “streak” signatures observed at different orientations could provide insight into the pitch angle distribution which in turn could support informed estimates of the external flux.

Appendix A: Identification of Candidate Ion Species

We used a two-step approach to identify heavy ion species capable of generating the observed signatures. First, stopping power in silicon was computed as a function of energy for ions heavier than hydrogen ($Z \geq 2$). The SRIM-2013 “The Stopping and Range of Ions in Matter” computer program (Ziegler, 2013) performed the computations. The stopping power, with units of deposited energy (i.e., eV to MeV) per micron of travel, was converted to CCD signal units per micron of travel (DN/micron) using

$$\text{CCD signal} = \text{stopping power} \times \left( \frac{e^+ \times C}{\text{DN/micron}} \right)$$

where $e^+$ is the average energy required to generate an electron hole pair in silicon (3.7 eV/e-hole pair), and $C$ is the SRU camera gain of 15.47 signal electrons per DN. Figure A1 shows the CCD signal generated by ions ranging from helium ($Z = 2$) to sulfur ($Z = 16$) as a function of particle energy. Iron ($Z = 26$) is also shown to illustrate the increasingly upward trend of signal deposition with increasing atomic mass. Values for Hydrogen ($Z = 1$) based on stopping power values from PSTAR (NIST, 2020) are included for completeness. To create the observed signatures, an ion must impact the CCD with the appropriate energy to generate between 230.8 and 2000 DN/micron. This range of values accounts for the signal levels observed in the compact signatures (3,000–13,000 DN/pixel) and the ~14 micron vertical path length through the active region of a pixel. The range also accounts for the possibility that the measurements may include cases where an ion grazed adjacent pixels along its path through a primary pixel.

Using the data of Figure A1 we identified the particle energies at which each species could deposit the required signal range, or a portion thereof. These energies define the “residual energies” the candidate species would have after passing through the SRU shielding. Ions with $Z > 16$ were not capable of depositing any part of the range of observed signals. In selecting candidate species and energies we consider only energies available within SRIM that are greater than 171 keV, which corresponds to the energy required to create 3000 DN of signal in the CCD. Less energetic particles would be incapable of generating the observed signatures.
The second step was to determine the external energies each ion species would need in order to penetrate the heavy SRU shielding and arrive at the CCD within the required residual energy range. The TRIM (Transport of Ions in Matter) module of SRIM-2013 was used to determine the minimum energy each candidate species would need to completely penetrate the shielding. TRIM models of three shielding paths were implemented: (1) the weakest SRU shielding path, directly through the lens elements; (2) a very heavily shielded lateral path that includes 4.5 mm of tungsten; and (3) a slightly elevated lateral path that misses the 4.5 mm of tungsten. The three models are shown in Tables S2–S4. TRIM runs were performed for each species, increasing or decreasing the energy until the external energy was found where all simulated ions (20 per run) completely penetrated the shielding. Next, this minimum external energy was gradually increased until the simulation showed that the target residual energies had been reached after the ion exited the shielding. The external energies that met this condition defined the energy range of the candidate species, and are shown as “External particle energy” in Table 1.

Protons with external kinetic energy above 125 MeV are the most likely to be detected by the SRU, as most lower energy protons will lose all of their energy inside the SRU shielding before reaching the CCD. Figure A2 illustrates the narrow range of proton energies that can yield 3,000–13,000 DN/pixel signals (~0.75–5.8 MeV). External kinetic energies very close to 125 MeV are required to yield such low energy penetrators.

Given the instrument’s dramatically greater sensitivity to higher energies, and our general expectation that the external spectrum will have a power law shaped distribution, the observed number of >3000 DN per pixel signatures is inconsistent with the low number of penetrating protons indicated by the data (see Section 4). Furthermore, as noted in Section 4, range and signal deposition rate limitations prohibit protons of any energy from generating most of the observed lateral streak signatures.

Figure A1. Signal generated by $Z \geq 1$ ions. Units are output analog-to-digital data number (DN) per micron of travel in the CCD silicon. Species ranging from hydrogen ($Z = 1$) to sulfur ($Z = 16$) are shown. Iron ($Z = 26$) is also included to illustrate the increasingly upward trend of signal deposition with increasing atomic mass. To create the observed signatures, ions must impact the CCD silicon with energies that will generate between 230.8 and 2000 DN/μm. Heavy horizontal grid lines bound this regime.
Data Availability Statement

The data supporting the study are provided in the Supporting Information files and at Becker et al. (2021). The Galileo Probe Energetic Particle Investigation instrument data were accessed from the Planetary Data System archive (https://pds.nasa.gov/ds-view/pds/viewDataset.jsp?dsid=GP-J-EPI-3-ENTRY-V1.0). The SPICE kernel for the Galileo probe trajectory (s960730a.bsp) was accessed from the NASA NAIF website (https://naif.jpl.nasa.gov/pub/naif/GLL/kernels/spk/)

References

Becker, H. N., Alexander, J. W., Adriani, A., Mura, A., Cicchetti, A., Noschese, R., et al. (2017). The Juno Radiation Monitoring (RM) Investigation. Space Science Reviews, 213, 507–545. https://doi.org/10.1007/s11214-017-0345-9
Becker, H. N., Alexander, J. W., Connerney, J. E. P., Brennan, M. J., Guillaume, A., Adumitroaie, V., et al. (2021). Dataset for High latitude zones of GeV heavy ions at the inner edge of Jupiter’s relativistic electron belt [Data set]. Zenodo. https://doi.org/10.5281/zenodo.4268888
Becker, H. N., Santos-Costa, D., Jørgensen, J. L., Denver, T., Adriani, A., Mura, A., et al. (2017). Observations of MeV electrons in Jupiter’s innermost radiation belts and polar regions by the Juno radiation monitoring investigation: Perijoves 1 and 3. Geophysical Research Letters, 44, 4481–4488. https://doi.org/10.1002/2017GL073091
Bolton, S. J., Thorne, R. M., Bourdarie, S., DePater, I., & Mauk, B. (2004). Jupiter’s Inner Radiation Belts, in Jupiter, the Planet, Satellites and Magnetosphere. In F. Bagenal, T. E. Dowling, & W. B. McKinnon (Eds.), (pp. 671–688). Cambridge University Press. New York.
Burns, J. A., Showalter, M. R., Hamilton, D. P., Nicholson, P. D., de Pater, I., Ockert-Bell, M. E., & Thomas, P. C. (1999). The formation of Jupiter’s faint rings. Science, 284, 1146–1150. https://doi.org/10.1126/science.284.5417.1146
Burns, J. A., Simonelli, D. P., Showalter, M. R., Hamilton, D. P., Porco, C. C., & Esposito, L. W. (2004). Jupiter’s ring-moon system (pp. 241–262). Cambridge University Press. Cambridge, U.K.
Connerney, J. E. P., Acuña, M. H., & Ness, N. F. (1981). Modeling the jovian current sheet and inner magnetosphere. Journal of Geophysical Research, 86, 8370–8384. https://doi.org/10.1029/JA086iA10p08370
Connerney, J. E. P., Acuña, M. H., Ness, N. F., & Satoh, T. (1998). New models of Jupiter’s magnetic field constrained by the Io flux tube footprint. Journal of Geophysical Research, 103, 11929–11939. https://doi.org/10.1029/97ja03726
Connerney, J. E. P., Kotsiarios, S., Oliversen, R. J., Espley, J. R., Jørgensen, J. L., Joergensen, P. S., et al. (2018). A new model of Jupiter’s magnetic field from Juno’s first nine orbits. Geophysical Research Letters, 45, 2590–2596. https://doi.org/10.1002/2018GL077312
Cooper, J. F., & Simpson, J. A. (1980). Sources of high-energy protons in Saturn’s magnetosphere. Journal of Geophysical Research, 85, 5793–5802. https://doi.org/10.1029/ja085ia11p05793

Acknowledgments

Daniel Santos-Costa is thanked for assistance with the artistic rendering of Jupiter’s synchrotron emission region. This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004); at the Southwest Research Institute under contract with NASA; and the Johns Hopkins University Applied Physics Laboratory under subcontract with the Southwest Research Institute. © 2021. All rights reserved.

Figure A2. Signal deposition rates for 1 keV–6.5 MeV protons in silicon. The minimum energy which can yield a 13,000 DN/pixel signal is ~0.75 MeV (lower energy protons have insufficient range). The maximum energy which can generate a 3,000 DN/pixel signal is ~5.8 MeV.
