Jupiter’s Ion Radiation Belts Inward of Europa’s Orbit

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Abstract  Jupiter is surrounded by intense and energetic radiation belts, yet most of the available in-situ data, in volume and quality, were taken outward of Europa’s orbit, where radiation conditions are not as extreme. Here, we study measurements of ions of tens of keV to tens of MeV at <10 Jupiter radii (RJ) distance to Jupiter, therefore inward of the orbit of Europa. Ion intensities drop around 6 RJ, near Io’s orbit. Previous missions reported on radiation belts of tens and hundreds of MeV ions located between 2 and 4 RJ. Measurements of lower energies were not conclusive because high energy particles often contaminate the measurement of lower energy particles. Here, we show for the first time that ions in the hundreds of keV range are present and suggest that ions may extend even into the GeV range. The observation of charged particles yields information on the entire field line, not just the local field. We find that there is a region close to Jupiter where no magnetic trapping is possible. Jupiter’s innermost radiation belt is located at <2 RJ, inward of the main ring. Previous work suggested that this belt is sourced by re-ionized energetic neutral atoms coming steadily inward from distant regions. Here, we perform a phase space density analysis that shows consistency with such a local source. However, an alternative explanation is that the radiation belt is populated by occasional strong radial transport and then decays on the timescale of years.

Plain Language Summary  Planets with a magnetic field, like Earth and Jupiter, are surrounded by belts of natural charged particle radiation. These regions are called “radiation belts,” and they pose challenges to space exploration because of their severe effects on spacecraft and humans. Understanding the fundamental nature of radiation belts, for example, formation, structure, and dynamics has also been a scientific pursuit for decades, but there is still much to learn. Some of the most extreme radiation conditions are found at Jupiter, which makes that planet an ideal laboratory to study how radiation develops in space. Even though raw measurements from satellites in orbit of Jupiter exist, they often cannot be used as-is. This is because strong radiation can interfere with radiation instruments in the same way that direct sunlight interferes with a thermometer. Here, we present results of a careful processing of data from the Juno mission to get around the instrument limitations. Our analysis not only extends the observed energy ranges of ions of Jupiter radiation belts but also forms the basis for testing new ideas. For example, our results suggest that the belts may form by ions that originate from a different region around Jupiter.

1. Introduction

Jupiter has the largest magnetosphere in the solar system and electron radiation belts with the highest energies (Mauk & Fox, 2010; Roussos & Kollmann, 2020). It has been visited by several spacecraft (Krupp et al., 2004), yet there are regions in physical space and particle energy that are not well explored (Roussos et al., 2019). High intensities of either electrons or protons can impact the integrity of in-situ radiation measurements (Kollmann, Paranicas, et al., 2020; Mauk et al., 2016; Nénon, Sicard, Caron et al., 2018), which becomes an issue inward of the orbit of Io and makes reliable measurements in this region particularly rare. NASA’s Juno mission—a Jupiter polar orbiting spacecraft—frequently, albeit briefly, visits Jupiter’s radiation belts and is equipped with energetic particle instrumentation. Here we present a careful analysis of data obtained by its JEDI instrument (Section 2.1) and filter the measurements to select reliable measurements (Section 3). We use that data to study the physics of the innermost radiation belt (Section 4). The
following introductory sections discuss the two main regions of interest: distances spanning from the Main Ring to Europa (Section 1.1) and distances inward of the Main Ring (Section 1.2).

1.1. From Europa to the Main Ring

In this section, we describe the behavior of ions with energies of hundreds of keV to hundreds of MeV and electrons with energies of tens of keV to tens of MeV, based on earlier studies, some of which are shown in Figure 1. In Section 3, we will show that this described behavior extends for ions down to at least tens of keV.

The differential intensity (particles per time, area, solid angle, and energy interval) of energetic ions and electrons is continuously rising when moving inward from the outer magnetosphere and across the orbit of Europa (at a distance of \(9.4 \, R_J\) to Jupiter with Jupiter radius = 1 \(R_J\)). The Europa gas torus is known to have a subtle effect (intensity depletion by factor <2) on ions with pitch angles of 70° because neutrals deplete ions via the charge exchange process (Kollmann et al., 2016; Nénon & André, 2019). In fact, this effect is barely noticeable in the mission-averaged radial intensity distribution of both ions and electrons (Kollmann, Roussos, Paranicas, et al., 2018; Kollmann, Paranicas, et al., 2020). (Intensities in Jupiter’s magnetosphere vary by an order of magnitude (Kollmann, Roussos, Paranicas, et al., 2018), meaning that piecing together a radial profile from a few instances in time, albeit high quality (Mauk et al., 2004), can introduce intensity jumps at random locations, including at Europa.)

Intensities of particles with energies of tens of keV to several MeV/nuc are decreasing toward the orbit of Io (5.9\(R_J\)) with onset and slope of the decrease depending on energy and species (de Soria-Santacruz et al., 2016; Garrett et al., 2015; Kollmann, Roussos, Paranicas, et al., 2018; Paranicas et al., 2019). The effect is strong for protons, oxygen, and sulfur (decrease by factor ≈100 over ≈2 \(R_J\) depending on energy) and weak for electrons (factor ≲2 depending on energy). The primary loss mechanism is thought to be mostly due to wave-particle interactions that scatter the particles into the atmospheric loss cone. Electrons randomly
scatter with whistler mode chorus and hiss waves (Nénon et al., 2017) and protons with electromagnetic ion cyclotron waves (Nénon, Sicard, Kollmann et al., 2018). Additional plasma wave modes may generally play roles in scattering and acceleration (Menietti et al., 2012). Superimposed on the $\approx 2 R_J$-wide depletion, a localized intensity enhancement can be sometimes observed at Io's orbit at Juno latitudes. A possible reason may be resonant acceleration by ion cyclotron waves (Clark et al., 2020).

We will refer to the region outward of Io as the “outer” ion belt. Inward of the outer ion belt, reliable measurements become sparse due to contamination. Several discrete ion radiation belts are found roughly in the region between 2 and 4 $R_J$, which are separated by the smaller moons Amalthea (2.5 $R_J$) and Thebe (3.1 $R_J$). We will refer to these discrete belts collectively as the “middle” belts. All potentially reliable ion measurements we are aware of are in the energy range from several hundreds of keV (Kollmann et al., 2017) to hundreds of MeV (Figure 1, Fischer et al., 1996). Interestingly, previous Juno measurements suggested that ions at the lower energies (tens of keV to several MeV) were absent from the middle radiation belts (Kollmann, Roussos, Kotova, et al., 2018). This would be peculiar as ion spectra usually show strong low energy populations. However, the original Juno observations suffered an observational bias (Appendix E) and we are now able to present reliable low energy ion measurements also in the middle belts (Section 3).

1.2. From Main Ring to Planet

Jupiter’s innermost radiation belt is located inward of the Main Ring (1.8 $R_J$) and includes ions from tens of keV (Kollmann et al., 2017, Figure 2 discussed below) to hundreds of MeV (Figure 1, Fischer et al., 1996). This belt is likely losing particles to the ionosphere (Valek et al., 2020) and to a lesser extent also to the Main Ring (Nénon, Sicard, Caron, et al., 2018), requiring it to be replenished with particles at least occasionally.
CRAND (cosmic ray albedo neutron decay) is a common source of energetic protons close to Earth (Selensnick et al., 2007) and Saturn (Cooper & Sturmer, 2018) but it is likely not a main driver of the population in Jupiter’s innermost radiation belt, which includes significant intensities of heavier ions (Kollmann et al., 2017; Nénon, Sicard, Caron, et al., 2018) that cannot originate from CRAND. Kollmann et al. (2017) therefore suggested that the innermost belt is supplied through the stripping of energetic neutral atoms (ENAs) that are produced in the magnetosphere (Mauk et al., 2020), a portion of which rain continuously down onto the planet. This process is also working at the Earth (Gusev et al., 2003; LLera et al., 2017; Petrov et al., 2009) and Saturn (Krimigis et al., 2005; Krupp et al., 2018). However, at these planets the process only leads to an extension of the existing radiation belts. It is not proven yet whether this process is indeed able to yield a full standalone radiation belt. We discuss this possibility in Section 4.3.

Overall, the nature of the innermost radiation belt and several of its properties have remained elusive so far. Even determining its precise location has proven to be difficult due Jupiter’s highly complex magnetic field configuration close to the planet. Significant progress has been made on developing a precise magnetic field model (Connerney et al., 2018). We will show in Section 4.1 that this model allows us to reproduce features in the data unexplainable with older models. However, we show that even with this new model we cannot completely fit the particle data.

2. Data Set

2.1. JEDI

Most data used in this study was acquired by the JEDI instrument (Jupiter Energetic Particle Detector Instrument) that nominally measures protons and oxygen ions from 20 and 50 keV, respectively, to >1 MeV as well as electrons from <40 to >500 keV (Mauk et al., 2013). The precise energy range depends on the data product and applied analysis. For example, our analysis technique is able to potentially characterize ion energies up to a few GeV (Section 3.3), even though JEDI was not originally designed to be sensitive to this population. JEDI measures ≥50 keV particles through their energy deposited in solid state detectors (SSDs) and distinguishes respective ion species through simultaneous measurement of their time of flight (TOF) within the instrument. Electrons are detected through SSDs with a thin flashing meant to block protons with energies <250 keV with little-to-no effect on the measured electrons. Additional technical details on JEDI can be found in Appendix A.

Oxygen and sulfur are only distinguished in the middle of JEDI’s energy range. The precise value depends on the data product. For rate channels after 2019 (see Appendix B for definition), oxygen is distinguished from 300 keV to 14 MeV and sulfur from 400 keV to 16 MeV. Depending on the used data product, we will either calculate an estimate of the pure oxygen intensities over the full energy range (Appendix D) or sum oxygen and sulfur counts together and refer to them as “heavy” ions (Appendix B).

JEDI was operating for safety reasons without its TOF system during the first closest approaches to Jupiter, which means that there is no unambiguous species identification available at these early close-approach times. When it is necessary to show measurements for single orbits at closest approach, we use SSD-only measurements that use JEDI’s large, unflashed SSDs. These counts are dominated by keV ions in the innermost belt (Kollmann et al., 2017) and GeV shielding penetrators in the middle belts (Section 3.3). Because of this ambiguity on particle species, we will refer to these as “total particle measurements.”

2.2. Other Radiation Measurements

To add context to the JEDI observations and to guide our own interpretations, we include the following datasets from the previous missions: (1) Pioneer 11/GTT, sometimes also called University of Iowa instrument (Van Allen et al., 1974); (2) Galileo Probe/EPI (Fischer et al., 1992); (3) Galileo/HIC instrument (Garrard et al., 1992). The particle species and energies of these instruments that are considered here are listed in Figure 1.

Many instruments saturate in the high intensity environment near Jupiter. The Pioneer 11/GTT data were corrected for dead time as described in Appendix F. For Galileo Probe/EPI measurements we use the dead time corrected values from Pehlke (2000). Note that several EPI channels have to be omitted due to
contamination from electrons and helium ions (Nénon, Sicard, Caron, et al., 2018; Nénon, Sicard, Kollmann et al., 2018). The Galileo/HIC instrument appears to be free of artifacts (Garrett et al., 2011; Roussos et al., 2020).

2.3. Magnetic Coordinates

We organize the data based on the JRM09 magnetic field model (Connerney et al., 2018) combined with the “CAN” current sheet model (Connerney et al., 1981). We organize the data in M-shell, which is the radial distance of minimum magnetic field on the respective field line to Jupiter’s center. This quantity has sometimes been referred to as “magnetic distance.” M-shell is only identical to L-shell in a dipole field. We refer to the area of minimum magnetic field along all field lines as the magnetic equator.

Another way of organizing the data is in $L^*$, which is inversely proportional to the third adiabatic invariant (Roederer & Lejosne, 2018). Generally, $L^*$ depends on pitch angle. Because we are mostly interested in the most equatorial part of the particle distribution, we calculate $L^*$ only for local pitch angles of 90°. We will discuss in Section 4.1 that both $L^*$ and M-shell do not organize data near the planet well. Because M-shell is easier to compute, we usually show the data as a function of M-shell.

The equatorial pitch angle of the edge of the loss cone $\alpha_l$ is calculated from the magnetic field $B_l$ where the field line enters the oblate planetary surface and the field $B_{eq}$ at the magnetic equator, where the field reaches its minimum.

$$\alpha_l = \arcsin\left(\frac{B_{eq}}{B_l}\right)$$

Northern and southern loss cone angles are generally different because of Jupiter's magnetic field configuration near the surface. Unless stated otherwise we will refer to “the” loss cone angle as the maximum value of north and south.

A quantity that is useful to calculate for missions in polar orbits is the maximum observable equatorial pitch angle $\alpha_{cut}$ at a respective latitude. As equatorially mirroring particles do not reach higher latitudes $\alpha_{cut}$ is only 90° at the magnetic equator and smaller otherwise. $\alpha_{cut}$ is therefore a measure of magnetic latitude but has the advantage that it can be immediately referenced in pitch angle distributions.

3. Middle Radiation Belts

This section covers the radiation belts located between the Main Ring and Io that show their highest intensities at $2 \lesssim M \lesssim 4$. Data from earlier missions suggest that Amalthea and Thebe split this region into three belts (Figure 1). We do not make this distinction here because it will turn out that our analysis currently cannot resolve this structure (Figure 2).

3.1. Hundreds of keV Ions Over Distance

Particle instruments commonly misidentify the species or energy of penetrating particles. Measured intensities in environments with significant numbers of penetrators therefore often appear higher than they actually are. Particularly the region inward of Io is known to show issues with penetrators in most instruments, including many measurements of Galileo orbiter/EPD (Kollmann, Roussos, Paranas, et al., 2018, Kollmann, Paranas, et al., 2020) and Galileo Probe/EPI (Nénon, Sicard, Caron, et al., 2018; Nénon, Sicard, Kollmann, et al., 2018). JEDI has the same issues in principle but some measurements are accurate because the contamination varies with latitude and possibly time. Fortunately, the multiple JEDI sensors arranged on the spacecraft deck provide optimal pitch angle coverage and sufficient event data are downlinked. Both help us to identify and remove times when the data are contaminated.
There exist two categories of penetrating particles: (1) “shielding penetrators,” which we define as particles that penetrate through JEDI’s shielding or collimator blades and (2) “SSD penetrators” which we define as particles that penetrate the SSD. Shielding penetrators penetrate the shielding and can trigger the detectors typically without passing through the aperture. These penetrators lead to similar count rates for all pitch angles, including within the loss cone (Mauk et al., 2016). When intensities in the loss cones are similar to the rest of the pitch angle distribution, we remove the data. Details and examples are provided in Appendix C. SSD penetrators are identified based on their energy, see Appendix A. Even though these two categories are generally different, we assume here that all penetrators fall in both categories and can be identified through either method in order to clean the data.

Figure 2 shows mission averaged data of protons and oxygen ions. Details on the averaging procedure are provided in Appendix D. The left panels show all available measurements that still include penetrating particles with misidentified species or energy information. The right panels show data with penetrators removed. The cleaned data set is the first time that tens and hundreds of keV ions are unambiguously identified in this region. Earlier measurements were all limited to higher energies. An independent check that protons, oxygen, and sulfur ions over the full energy range covered by JEDI exist in the middle radiation belts will be provided through analysis of event data, a different data product, that are discussed in Section 3.2.

Our data-cleaning procedure (Appendix C) removes most samples (in energy and time) of contaminated data but is not perfect due to uncertainties in the magnetic field model that will be discussed in Section 4.1. These uncertainties can lead to a misidentification of un/contaminated intervals. We use the median average to ensure that outliers with high penetrator intensities cannot dominate the result.

The data set that we derive through cleaning is biased by measurements near the nominal loss cone. Measurements near the loss cone show intensities that are small or even below detection limit. This is because the loss cone has no sharp boundary the same way a planetary atmosphere does not have a sharp cutoff, a fact that can be leveraged to constrain exospheric density profiles from pitch angle distributions (Kollmann, Roussos, Kotova, et al., 2018). An average of the cleaned data set is shown in in the Appendix in Figure C2. This average with its large number of measurements near the loss cone is not representative of the trapped population in which we are interested here. To retrieve a more representative data set, we exclude measurements near the nominal loss cone. Specifically, we require that $\alpha_{\text{cut}} - \alpha_i \geq 5^\circ$ and $\alpha_{\text{cut}}/\alpha_i \geq 1.5$. This filtered data is shown in this section in the right panels of Figure 2. Fluctuations in the mission-average profiles arise because every orbit covers a different equatorial pitch angle range and not every pitch angle is evenly sampled. These limitations introduce noise in the mission-average profiles, which is why the actual profiles are likely smoother than those we show.

The coverage of equatorial pitch angle changes with distance to the planet, as illustrated by the lower panels in Figure 2. Magnetically trapped distributions show by definition the highest intensities for equatorially mirroring particles. When Juno moves to smaller M-shells and is able to sample more equatorial pitch angles, it will observe an apparent intensity increase even if the actual distribution is independent of M-shell. Intensity values at strongly separated M-shells in Figure 2 may therefore not be directly comparable, depending on the steepness and shape of the pitch angle distribution, which we cannot determine at this stage. Intensities measured by JEDI near the loss cone change by orders of magnitude (Figure E1, Kollmann et al., 2017; Mauk et al., 2016; Paranicas et al., 2018), but this cannot be extrapolated because intensities far from the loss cone measured by earlier missions only change by a factor of a few (Fischer et al., 1996; Kollmann et al., 2016; Mauk et al., 2004; Tomás et al., 2004).

The overall shape of the intensity profiles of ions with energies from tens of keV to several MeV shown in Figure 2 is similar to what was discussed in Section 1 for higher energies. A more detailed look at the new data shows that the oxygen belts are less separated than the proton belts. We discuss this more after deriving high resolution energy spectra in the now following Section 3.2.

### 3.2. Spectral Shape

JEDI’s standard data product splits proton spectra into 24 and heavy ions into 15 pre-defined energy steps often called “rate channels.” These channels have a coarse energy resolution, cover a smaller energy
range than what the instrument is able to measure, and require techniques like described in Section 3.1 to identify contamination. Because of this we here make use of another data product called “event data” that is downlinked with the much higher native resolution over the full energy range. Due to the relatively large data volume of each measured event it is only feasible to downlink event data for a subset of counts. The price of using this data is therefore that it requires longer time intervals to accumulate enough counts.

Event data contains a record of the time of flight (TOF) of each ion, the time it takes for the ion to traverse between the entrance (start signal) and back of the instrument (stop signal), as well as the energy deposited (energy signal) in a solid state detector (SSD). 2D histograms of counted particle events as a function of energy and TOF are shown in Figure 3. TOF allows one to calculate the particle's speed because the traversed distance is known. The combination of energy and speed can be used to infer the particle's mass, which should be close to an integer number. Ions with realistic masses line up along a diagonal tracks in a TOF versus energy histogram (Figure 3). SSD penetrating electrons and protons all deposit \( \approx 200 \text{ keV} \), independent on their energy (Appendix A), which leads to a vertical stripe in a TOF versus energy histogram. Such a stripe can be seen in the right panel of Figure 3 that shows a histogram of the middle belts.

Figure 3. 2D histogram of JEDI event data. The y-axis is the ion time of flight within the instrument. The x-axis is the energy deposited within the SSD, which is less than the ambient energy the particle had before entering the instrument. Left: This data shows counts accumulated on days that included closest approaches to Jupiter. It can be seen that most counts form tracks along diagonal lines. The overplotted lines roughly demarcate the regions where protons (lower two lines) and oxygen and sulfur ions (upper two lines) fall. Right: Same as left panel but only for the region of the middle belts (1.8<M<4). It can be seen that the middle belts are populated by the same species and energies than the other belts. Many particles deposit 200 keV, indicating that they result from SSD-penetrating protons or electrons (Appendix B.).

Figure 4. Energy spectra of protons (left) and heavy ions (right) in the outer belt outward of Io (orange), the middle radiation belts (cyan), and the innermost belt (violet and black). All data are mission averages except the black curve that is for a single orbit. Mission average error bars are a measure of variability, error bars for the single orbits are Poisson uncertainties. M-shell values and orbit numbers are given in the legend.
Superimposed on the penetrators are clear tracks associated with protons, oxygen, and sulfur ions. This is an independent confirmation that there are significant intensities of these ions even in the middle radiation belts.

We calibrate the event data as described in Appendix B, which allows us to derive high resolution energy spectra that we show in Figure 4. It can be seen that JEDI measures significant intensities of protons up to \( \approx 20 \text{ MeV} \) and heavy ions up to \( \approx 200 \text{ MeV} \). More energetic particles likely exist and may be present up to GeV energies (see following Section 3.3) but JEDI does not have the TOF resolution and detection efficiency to unambiguously identify them.

Proton spectra in the middle belts (\( 2 \lesssim M \lesssim 4 \)) are lower in intensity in the hundreds of keV range than what is found outside of Io (\( 8 < M < 10 \)). The middle belt proton intensity is lower than in the outer belt. Nénon, Sicard, Kollmann et al. (2018) suggested that protons from a few hundred keV to about 10 MeV suffer strong losses at Io’s orbit because they are scattered by EMC waves into the loss cone. This mechanism resulted in their modeled middle belt proton spectra being flat at these energies, similar to what we are observing in the middle belts. The heavy ion spectrum of the middle belts in the several MeV energy range has a similar amplitude and shape to the spectrum outside of Io. This observation suggests that EMC wave scattering is far less efficient for these heavy ions, at least at the energies considered here.

Heavy ion spectra do fall steeper with energy than protons, even outside of Io’s orbit and its associated losses. This may be a signature of energy and species dependent source or loss processes, for example charge exchange in the Europa gas torus (Nénon & André, 2019) that is more efficient for \( O^+ \) than for \( H^+ \) (by \( \approx 3 \) orders of magnitude at 1 MeV, Paranicas et al., 2008). Quantitative modeling of charge exchange and other effects is needed to explain the spectral shapes. No direct comparisons are possible at other energies due to the lack of reliable event data.

3.3. Presence of GeV Protons?

While we clean our data from penetrators we still keep track of the penetrating radiation. Penetrator counts indicate the presence of particles even though the raw measurements misidentify their species or energies. In this section, we analyze the penetrator data. Our initial processing of the penetrator counts is included in Appendix B.

Shielding penetrators irradiate the instrument from all directions, meaning that the signal is insensitive to the instrument look direction and that we cannot determine their pitch angle. Given that Juno is usually

![Figure 5](image-url)  
Figure 5. Mission average of penetrating particles as a function of M-shell distance and \( \alpha_{cut} \). The average is logarithmic and requires that each bin includes more than two samples. It can be seen that the shielding penetrators appear equatorially trapped and coincide with the middle belts.
at high latitudes, we can still use $\alpha_{\text{cut}}$ to organize the data, which is shown in Figure 5. The penetrator count rates increase with increasing $\alpha_{\text{cut}}$ (decreasing magnetic latitudes). This behavior is consistent with an equatorially trapped population of shielding penetrators. The closer Juno is to the equatorial plane the more penetrating particles are registered. This suggests that the shielding penetrators are the high energy component of the radiation belts (not transient GCRs or auroral beams).

The highest shielding penetrator intensities are found between $2 \leq M \leq 4$. There is a sharp decrease at the Main Ring: the most equatorial particles we observe fall by three orders of magnitude inward of $M = 2$ and only very few shielding penetrators ($<1/s$) are found between ring and planet, where the innermost radiation belt is located Kollmann et al. (2017).

A signature of SSD penetrating particles is that they deposit $\approx 200$ keV into the SSD (We discuss in Appendix A how to calculate this number). Such energies can be provided by $>1.3$ MeV electrons or $>2.5$ GeV protons. Heavier ions would deposit at least 3 times more energy, meaning that we can rule them out as SSD penetrators. In order for these particles to be also shielding penetrators, they need to be either $>5$ MeV electrons or $>40$ MeV protons. Particles that penetrate the shielding and deposit $\approx 200$ keV in the SSD are therefore $>5$ MeV electrons and $>2.5$ GeV protons. Such energies are high but still within Jupiter’s trapping limit (Birmingham, 1982). We will need independent arguments to distinguish electrons from protons.

In order to do that, we compare the radial profiles of the JEDI shielding penetrators with energetic particle measurements of previous missions (Figure 1). It can be seen that $>21$ MeV electrons are unaffected by the rings while $>350$ MeV helium ion intensities change by at least an order of magnitude. The trend is the same for at least an energy range of $>3$ MeV (Fischer et al., 1996) to $>31$ MeV for electrons (Baker & van Allen, 1976) and a range of ion species: $\approx 2$ MeV protons (Trainor et al., 1975) and $\geq 2 M \geq 12$ Z ions (Fischer et al., 1996). This difference between ions and electrons is typical: ions observed at the Gas Giants tend to be more sensitive to the neutral, dust, ring, and moon environments than electrons. That behavior also can be seen at Io’s orbit with its plasma torus (Figure 1, Fillius et al., 1975; Roussos & Kollmann, 2020) as well as through macrosignatures at Saturn’s moons (Kollmann et al., 2011; Roussos, Jackman, et al., 2018) and its tenuous G-ring (Kollmann et al., 2013). The strong depletion of penetrators at the Main Ring that can be seen in Figure 1 can therefore be considered as a signature of ions, not of electrons. This suggests that the JEDI shielding penetrators are dominated by $>2.5$ GeV protons, at least around the location of the Main Ring.

Figure 6. Left panel: JEDI 1 MeV total particle intensity (color coded) from measurements of the unflashed SSDs. Data are filtered for measurements $>10^6$ from the loss cone and projected onto the $xy$–plane of the right-handed (east) SIII coordinate system, which rotates with Jupiter (Archinal et al., 2009). The inner black circle is Jupiter’s surface and the outer black circle is the Main Ring. Blue numbers indicate the orbit number. It can be seen that the innermost radiation belt (red areas near inner circle) was not always detected. Right panel: Magnetic field strength at the magnetic equator, shown at the location where the respective field line cuts through the rotational equatorial plane. Black diamonds indicate regions in the rotational equatorial plane where no stable magnetic trapping is possible.
4. Innermost Belt

4.1. Regions Without Stable Trapping

An initially surprising behavior of the innermost radiation belt is that it is not observed for every Juno orbit, which could be interpreted as a result of strong dynamics; however, we argue that this is only an apparent time variability due to a combination of orbital observation bias and magnetic field topology.

Figure 7. Upper panels: JEDI 80 keV total particle intensity (color coded) over equatorial pitch angle (y axis) and time (x axis). The color bar is optimized for the innermost radiation belt and therefore saturates (in red) in the middle radiation belts visible at the edges. Measurements with zero counts are marked with diamond symbols. Equatorial pitch angles that were not accessible from the respective latitude are left white. The blue curve shows the edge of the loss cone in the JRM09 + CAN magnetic field model. Lower panels: M-shell calculated in the JRM09 + CAN model. Panel A: Well-behaved case where the M-shell is always defined, the loss cone is $\approx 90^\circ$, and the innermost radiation belt is visible. Panel B: No innermost radiation belt is visible because no stable trapping exists, indicated by the gap in the M-shell and $L^*$ values. Panel C: No innermost radiation belt is visible because the loss cone covers most of the field of view. Panel D: The magnetic field model suggests no stable trapping and no drift outside the dense atmosphere but we find trapped particles, indicating that the magnetic field model is not perfect.
The left panel of Figure 6 shows particle intensities along Juno’s orbit, projected on the plane of Jupiter’s rotational equator. Most orbits in the $y < 0$ hemisphere show the innermost radiation belt, while it is commonly absent in the positive quadrant ($x > 0, y > 0$) and there is a transition region in the $x < 0, y > 0$ quadrant.

The right panel of Figure 6 shows the magnetic field strength at the magnetic equator, where this equator can be defined. It turns out there is a region ($x > 0$) where the magnetic field minimum on each field line resides inside the planet (indicated as black diamond symbols on Figure 6 right panel). No stable trapping is expected on these field lines because charged particles encounter the atmosphere and are lost during their bounce motion. We expect vanishing intensities also on neighboring field lines because particles drift around the planet. Such a drift loss cone was already observed in Galileo Probe data (Nénon, Sicard, Caron, et al., 2018). Here we find that also Juno shows this behavior and that JEDI count rates vanish around these regions.

Next we have a closer look at the JEDI data, which will reveal another reason why the innermost belt may not show during some orbits. We will also find inaccuracies when organizing the data even with the highest order field model available. Figure 7 shows pitch angle distributions as well different measures of distance ($M$-shell and $L^*$) from single orbits as a function of time. The nominal loss cone is superimposed on the pitch angle distribution through a blue curve. Panel A of Figure 7 shows a well behaved case: Valid $M$-shells and $L^*$ values exist for almost all times, indicating that magnetic trapping is possible. Indeed, we find the innermost radiation belt around the minimum distance and outside of the loss cone. The middle radiation belts cause contamination in the shown data causing that the loss cone is filled at the left and right edges of the figure.

Panel B of Figure 7 shows another illustration of non-existent trapping already indicated in Figure 6: Low intensities coincide with times that cannot be associated with a valid $M$-shell or $L^*$ value. Panel C reveals an additional reason for the apparent absence of the innermost belt: Sometimes the loss cone approaches 90° and therefore fills the entire field of view. During such times JEDI is unable to sample the equatorially trapped population, explaining the small intensities at small distances.

The JRM09 + CAN magnetic field model (Connerney et al., 1981; 2018) is unlike any other previous magnetic field model in the way that it qualitatively predicts regions where we cannot sample the innermost belt. This property illustrates how valuable a high order field model is for studying radiation close to a planet. However, even this most sophisticated model currently available (JRM09 is a degree 10 spherical harmonic) does not provide accurate timing. In panel C of Figure 7 we find small intensities approximately but not exactly within the duration of ≈90° loss cones. In panel B, the small intensities can be explained with the absence of valid distance, however again the timing is off. Also, there are cases where the qualitative prediction is wrong. Some of the highest intensities found in the innermost radiation belt coincide with times where the field model does not provide valid $M$-shells but predicts that the field line resides inside the planet. Similarly we also find high intensities where $L^*$ suggests that the particle would drift into the atmosphere instead of surrounding the planet. Such cases are illustrated in panel D of Figure 7. These discrepancies may well indicate that higher harmonics are necessary to adequately describe the field near the surface of the planet. JRM09 uses but nine of Juno’s 34 Prime mission orbits; a more accurate field model will ultimately be possible with inclusion of a finer longitude grid that will be achieved with additional orbits.

During some orbits $M$-shell performs better than $L^*$, during others the opposite is true. What we consider as the major issue is that several observations of the innermost belt cannot be shown in intensity over $M$-shell or $L^*$ plots. Because $M$-shell is easier to compute, we show most of our results as a function of this quantity.

The qualitative predictions from the magnetic field model suggest that the innermost radiation belt is not forming and decaying between Juno’s 2-months orbits, but rather that Juno is not always passing through regions where stable trapping exists (indicated through valid $M$-shells and $L^*$ values) and where the particles reach the respective latitude (with $\alpha_1 < 90°$).

The pitch angle distribution is very steep near the enormous loss cone found close to the planet (Figure E1). Small errors in the pitch angle mapping result in large errors in the expected intensities. Because
of these uncertainties we are currently unable to determine if there are more subtle time dependences, for example if the innermost belt is slowly decaying throughout the Juno mission, as we suggest below in Section 4.3.

### 4.2. Spectral Shape

Figure 4 shows high resolution spectra of the innermost, middle, and outer ion belts. It can be seen that all belts show $1\sigma$ standard deviations ranging from factors of a few to almost two orders of magnitude. Such standard deviations do not indicate measurement uncertainties but variability.

For the middle and outer radiation belts, the spectral shapes are relatively similar and only their amplitude is changing. For the innermost radiation belt also the spectral shape is changing. Some spectra are steadily falling with increasing energy, others show a rise in the hundreds of keV energy range. The larger energy range compared to Kollmann et al. (2017) reveals that the spectra fall in the MeV energy range in any case, which had not been known earlier. As an illustration of the variability, Figure 4 includes a mission-averaged spectrum as well as one example of a peaked spectrum. Such peaked spectra are unusual and models trying to explain the innermost belt will need to account for this shape. One mechanism that can lead to such shapes is the stripping of ENAs (Kollmann et al., 2017).

Variability can be a result of time dependence, or a combination of spatial dependence and inaccuracies of organizing the data relative to the magnetic field. Time variability around an order of magnitude is common at the Giant Planets: measurements in the equatorial plane, where it is easier to organize the data with the magnetic field, have shown true time variations in Jupiter’s outer belt (Kollmann, Roussos, Paranicas, et al., 2018) and also at Saturn (Kollmann et al., 2011). For Jupiter’s innermost belt we suggest that variability is mostly spatial in character: Assume that the spectra differ between drift shells but are constant over time. If the actual drift shells are not equal to the JRM09-M-shells we are using and the discrepancy changes over time, which is the case as shown in Section 4.1, then a true spatial variability results in an apparent time variability.

### 4.3. Possible Physics in the Innermost Belt

The distribution of phase space density (PSD) over M-shell or a similar quantity can be a useful indicator of the physical processes acting in a radiation belt. The shape of a radial PSD profile can indicate whether a belt may be supplied through local source process of some kind or if can be simply populated by radial transport of particles from large distances, for example through means of radial diffusion (Lejosne & Kollmann, 2020). According to Liouville’s theorem, PSD is conserved along trajectories of particles as long as there are no particle sources or losses. We typically observe at all magnetized planets that PSD largely decreases toward the respective planet Paonessa and Cheng (1985); Cheng et al. (1987, 1992); Kollmann et al. (2011); Turner et al. (2017). Losses at the planet’s surface itself combined with radial diffusive transport is sufficient to cause falling PSD profiles (Lejosne & Kollmann, 2020). Often losses are enhanced by distributed losses away from the planet, for example from neutral gas tori leading to energy loss (Clark et al., 2014), charge exchange (Kollmann et al., 2011), or waves that scatter particles along the field lines into the atmosphere (Nénon, Sicard, Kollmann et al., 2018). Local increases of the PSD may be caused by a source like the CRAND process (Cooper & Sturmer, 2018) or the stripping of ENAs (Kollmann et al., 2017) that produce new particles, by sudden radial transport for example through large-scale (Roussos, Kollmann, et al., 2018) or small-scale electric fields (Lejosne et al., 2018; Paranicas et al., 2016), or by local acceleration (Horne & Thorne, 2003; Li et al., 2014).

Phase space density $f$ (particles per volume in real space and volume in momentum space) relates to differential intensity $j$ as $f = j/p^2$ with the momentum $p$. The use of momentum instead of velocity space is useful for energetic particles because momentum does not saturate at light speed. PSD particularly at non-relativistic speeds is sometimes defined in velocity space instead, which has different units and requires a different conversion from $j$. 

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f needs to be calculated at constant values of first and second adiabatic invariants. Conversion from j is non-trivial because the j measurements are natively provided at fixed energies and pitch angles. The adiabatic invariants are defined as

\[ \mu = \frac{E (E + 2mc^2)}{2mc^2 B} \sin^2 \alpha \]  

(2)

\[ K = \int_{-\lambda_m}^{+\lambda_m} \sqrt{B_m - B} \, ds \]  

(3)

\( E \) is the kinetic energy of the charged particle, \( m \) is the rest mass, \( c \) the speed of light, \( B \) the local magnetic field, \( B_m \) the magnetic field at the mirror point (where the particle starts moving back to the equatorial plane), \( \alpha \) the local pitch angle between the particle velocity \( v \) and the magnetic field, \( \lambda \) the magnetic latitude, and \( \lambda_m \) the latitude of the mirror point. We calculate both invariants in the JRM09 + CAN field model, which for \( K \) involves a pitch angle dependent integration along the field line.

We limit our analysis to 45 keV–3.6 MeV protons and only use measurements that have the contribution of shielding penetrating particles removed (Appendix C). The results are shown in Figure 8. It can be seen that \( f \) decreases toward the planet until \( M \approx 1.3 \). \( f \) is rising for smaller distances for a range of \( \mu \) and \( K \) values. These trends are persistent throughout the mission even though there is variability from orbit to orbit, as illustrated in Figure 9.

A rising PSD profile rules out that the innermost belt at the respective invariants is a result of steady inward diffusive transport. It is consistent with a local source process, supporting the theory of stripped ENAs (Kollmann et al., 2017). However, inferring a local source from a rising PSD profile is only valid for a steady state, which may not be the case. The innermost radiation belt is observed to be present whenever the spacecraft is magnetically connected to it. Uncertainties in mapping M-shells and equatorial pitch angles are too large to reliably study intensity variations (Section 4.1). It is therefore possible that the innermost radiation belt is not in steady state but has a slow time dependence on the timescale of years. A PSD distribution that is initially flat or decreasing toward the planet may be produced by a period of transient but very rapid
radial transport across the Main Ring, for example through a transient electric field (Roussos, Kollmann, et al., 2018; Lejosne et al., 2018). The flat profile can be turned into the observed rising profile if losses occur mostly at $1.3 \lesssim M \lesssim 1.8$, the region of the ring halo ($1.3–1.8 R_J$) and Main Ring ($1.8 R_J$). If true, the particles in the innermost belt would also be of magnetospheric origin but not transported as ENAs from the outer belt region but as ENAs from the adjacent middle belts.

Preliminary analysis suggests the efficiency of ENA stripping is too low to explain the innermost belt but that occasional radial transport plus losses to the rings may explain both the spectra and the PSD distribution (Kollmann et al., 2019, Kollmann, Mauk et al., 2020). A full analysis will be part of a future publication.

5. Summary

In this paper we unambiguously identify protons and heavy ions for the first time with hundreds of keV energy in the middle radiation belts ($2 \lesssim M \lesssim 4$), see Figure 2. These middle radiation belts also include a population of particles that penetrate the shielding of the instrument (Figure 1) that we interpret as GeV protons (Section 3.3).
Jupiter’s innermost ion belt shows proton spectra that peak in the MeV range (Figure 4). The innermost belt is either populated by a local source or occasional rapid radial transport (Section 4.3). There are regions above Jupiter’s surface where no stable magnetic trapping is possible on individual field lines, see Figure 6.

Appendix A: Identifying SSD Penetrators

Charged particles passing through matter gradually lose energy, for example, via ionizations in the target material. An SSD detector is able to measure most of the ionization part of the energy loss (Knoll, 2000). If the particle comes to a halt within the SSD, the full particle energy can be calculated. It requires at least >320 keV for electrons and >8 MeV for a proton to become a SSD penetrator and traverse through the entire 500 μm of silicon of JEDI’s detectors. These energies are available as tabulated values for different materials (Berger et al., 2005). (Electrons scatter in materials and therefore do not follow a straight-line path, so sometimes even very energetic electrons do not penetrate the SSD. At 1.2 MeV, 90% of electrons are stopped within the detector, Mauk et al. (2018).) The energy dependence of energy loss per distance (Berger et al., 2005) works out in a way that >1.3 MeV electrons and >2.5 GeV protons all deposit the same “minimum ionizing” energy of ≈200 keV energy into the detector. In environments with an abundance of sufficiently energetic particles, there will an artificial spectral peak at ≈200 keV deposited energy (Mauk et al., 2018). This is the reason for the stripes at this energy seen in the left panels of Figures 2 and 4. Heavier ions have a higher minimum ionizing energy and deposit at least 3 times more energy.

>5 MeV electrons, >40 MeV protons, and >5 GeV sulfur ions are energetic enough to penetrate JEDI’s shielding and can trigger any of the start, stop, or energy signals. (We calculate these energy values by integrating tabulated values of the differential energy loss dE/dx in tungsten (Berger et al., 2005), scaled to the density of the tungsten alloy used for JEDI’s shielding (Mauk et al., 2013), and searching for starting energies that decrease to zero after passing the shielding thickness.) Sufficiently energetic particles are fewer in number but can enter the instrument from any direction, whereas lower energy particles have to enter through the narrow apertures to reach the detectors. As the coincidence of three signals within a constrained time window is required for a valid ion measurement, it is much less likely that three independent shielding penetrating particles lead to something that the instrument interprets as a valid ion (Eckart & Shonka, 1938). It does happen however in a sufficiently intense environment, such as the one that exists inward of Io. Such false positive counts can be identified because the inferred mass has an unrealistic value. Such accidental coincidences are more likely at long TOFs. That such coincidences are indeed happening can be seen in the red area at >30 ns and ≈200 keV in the right panel of Figure 3.

We keep track of these accidentals through a special measurement channel (called “TPF0”) that records all particle counts associated with unexpected masses. In high radiation environments, this channel is dominated by shielding penetrators that are typically not organized by local pitch angle. In environments without shielding penetrators, this channel is dominated by particles that enter through the aperture but may have masses just outside the nominal boundaries. To discriminate among these regimes, we calculate the count rate ratio in the local pitch angle ranges of 80°–90° and 40°–60°. For penetrating particles, we require that ratio to be <2.

Appendix B: Calibrating Event Data

JEDI’s electronics use different methods to measure the energy deposited in its SSDs. Below 1.2 MeV the height of electronic signal or “pulse” from the SSD is used, whereas above that energy, the width of the pulse is used. The pulse width calibration is currently not accurate and saturates at ≈10 MeV (Westlake et al., 2019). This is why the slope of the tracks in Figure 3 is changing with energy. When analyzing event data, we therefore do not use the deposited energy but the TOF value to determine the ambient particle energy in space (before energy loss in the foils and SSDs).

When particles penetrate the SSD, the deposited energy typically decreases as the ambient energy of the particle increases. A deposited energy value therefore can have two TOF values for the same energy: one for particles that stop in the SSD and one for SSD-penetrating particles. Protons with TOF < 1 ns pene-
trate the SSD and are expected to deposit <3 MeV, a combination that we do not observe. The latter suggests that TOF < 1 ns events are not meaningful, which is consistent with JEDI’s TOF resolution at MeV energies showing FWHM ≈1 ns Mauk et al. (2013). We therefore discard events with TOF < 1 ns. This limits the energy range for which we can calculate energy spectra to <19 MeV protons and <160 MeV oxygen.

JEDI provides measurements in different formats. A standard product are “rate channels” that keep track of all particles but with limited energy resolution. These rates are less downlink intensive, and are preferred for this reason, than event data we describe next. “Event data” have higher energy resolution than rate data but only include a subset of the detected particles and are downlinked to the ground less regularly. In principle, event data counts can be converted to differential intensity the same way as rate channel counts. For rate channels the intensity $j_r$ calculates as

$$j_r = \frac{N_r}{\Delta E \Delta T G} \quad (B.1)$$

with the counts $N_r$ and the energy interval $\Delta E$ of the respective channel, the duration of the chosen time interval $\Delta T$, and the effective geometry factor $G$ that accounts for efficiencies, detection area, and solid angle (Mauk et al., 2013). We measure $\Delta T$ by finding instances where rate data are available and summing over the respective integration times.

We filter the event data with the same criteria as the rate channels (same species and $\Delta E$ energy range, no scattering allowed, etc.) and call the resulting number of events $\tilde{N}_e$. We sum oxygen and sulfur event counts together and calibrate them under the assumption that these heavy ions are all oxygen. We then calibrate with

$$\tilde{j}_e = \frac{\tilde{N}_e}{\Delta E \Delta T G} \quad (B.2)$$

Because $\tilde{N}_e \leq N_r$, $\tilde{j}_e$ is a relative intensity that describes the shape of the energy spectrum.

The absolute intensity is calculated by multiplying $\tilde{j}_e$ with the fraction $R = j_e / j_r$. $R$ is generally different for each rate channel but approximately constant in our case due to the “raw” mode with which JEDI is here recording event data. Now we can bin the event data in the energy and mass range of each channel with higher resolution. $N_e$ is the number of events within a smaller energy interval $\delta E$. The absolute intensity $j_e$ from the event data is then

$$j_e = \frac{N_e R}{\delta E \Delta T G} \quad (B.3)$$

We construct mission-averaged event-based spectra by first compiling spectra for the inbound and outbound legs of each orbit. Error bars for single spectra are determined by the Poisson uncertainty with their absolute value calculated as $j_e / \sqrt{N_e}$. Bins that have less than 10 events are discarded. In the region of the middle belts we also discard data around the 200 keV minimum ionizing energy to avoid considering SSD penetrators (Appendix A). The mission average uses the logarithm of the single spectra and requires that each bin was populated during at least four orbits. Mission average error bars are calculated from the standard deviation of the log ($j_e$) values and are a measure of the variability.

**Appendix C: Removing Penetrating Radiation**

Counts that result from shielding penetrating particles (Appendix B) are not organized by pitch angle. Such false counts are approximately the same no matter how the instrument is pointing. The loss cone is empty for all energies (Figure C1, upper panel) when observing magnetically trapped particles. If intensities inside and outside of the loss cone are found to be similar at a given energy (Figure C1, lower panel), this is an
indication that the respective measurements may be contaminated. We require that the linear averages of each loss cone be at least a factor of 10 below the linear average of the remaining pitch angle range. If this is not the case or if only data inside or outside the loss cone are available, we remove particles at this energy and species for all pitch angles. This analysis is done energy by energy. We find that high energy measurements are usually more robust because the time of flight is shorter so that there is less chance for accidental coincidence.

The data-cleaning process used here is meant to be more aggressive than is absolutely necessary because we prefer to have less data over possibly contaminated data. The process also removes times where the loss cone is populated due to a physical reason like auroral acceleration of some kind (Mauk et al., 2018; Paranicas et al., 2018). If the loss cone is not observable due to spacecraft attitude and orbit, we also remove the data.

**Appendix D: Averaging Rate Channels Over the Mission**

Figures 2 and C2 show measurements that were cleaned as described in Appendix C and where we averaged the data over the Juno mission. Averaging is complicated by the fact that the channel definitions changed on 2019 DOY 127 UTC 21. Since then JEDI provides heavy ion channels up to 160 MeV instead of the earlier
used 8 MeV. Before averaging, we therefore interpolate the new channel definitions onto the old definitions. No extrapolation is done in our analysis.

JEDI is able to measure oxygen and sulfur from $\approx 50$ keV to $\approx 160$ MeV but can distinguish these two species only from $\approx 400$ keV to $\approx 14$ MeV. In order to approximate an oxygen channel spectrum over the full energy range, we determine the O/S count rate ratio at intermediate energies and use it to scale the indistinguishable O + S counts at high and low energies.

**Appendix E: High Latitudes Mostly Capture Loss Cone**

Figure E1 shows oxygen intensities for the inbound and outbound legs of one orbit. It can be seen that only the inbound part of the orbit shows significant intensities in the $2 < M < 4$ range, while the outbound portions show no signatures of the middle radiation belts. The lower panels in the figure show pitch angles. It can be seen that inbound and outbound differ in the covered equatorial pitch angles $\alpha_{\text{cut}}$. In the pass without radiation belt signature, we find that $\alpha_{\text{cut}} \approx \alpha_{\text{p}}$, meaning that JEDI was mostly observing the loss cone, where usually no particles are found (unless some auroral process is involved).

Figure E1 shows a typical behavior. Orbits without middle radiation belt signatures have the observational bias of mostly measuring the loss cone. Orbits with radiation belt signature on the other hand may be contaminated.
Appendix F: Pioneer Data

Data from the Pioneer 11/GTT instrument (Van Allen et al., 1974) are available through the planetary data system (PDS). These data have the dead time corrections from the original publications (Van Allen et al., 1975) undone and an updated correction applied that we document here. Iowa’s GTT uses Geiger-Müller counters, the classical example of a detector that has a dead time and is paralyzable. The latter means that for rising true rates the counted rates first plateau and then decrease. Detectors A, B, C, and G use identical types of Geiger-Müller tubes with different shielding. Uncorrected data from detectors B and C plateau at Jupiter. (Corrected data from detector C are shown in Figure 1.) Laboratory calibration of these tubes showed that the measured rates saturate at different values depending on the incident radiation. The plateau observed at Jupiter was in-between the plateaus observed in the laboratory. Because dead time corrections are very sensitive to the exact value where saturation occurs, a curve was constructed that fits the observed in-flight maximum rate at Jupiter. This curve was used to correct the data available in the PDS.

Also this correction is not perfect and sometimes yields >31 MeV electron fluxes that exceed the >21 MeV electron fluxes, which is usually not observed for electrons at Jupiter (Garrett et al., 2016; Kollmann, Rouskos, Paranicas, et al., 2018). In such cases we revert back to the originally published values where this issue does not exist.

Data Availability Statement

Juno/JEDI, Galileo/HIC, and Pioneer 11/GGT data are available from the Planetary Plasma Interactions Node of NASA’s Planetary Data System (https://pds-ppi.igpp.ucla.edu/). Galileo Probe count rates were retrieved from Pehlke (2000).

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Acknowledgments

The authors thank Charles E. Schlemm and David B. LaVallee (both JHU/APL) for their continued support of JEDI operations, Lawrence E. Brown and James M. Peachey (both JHU/APL) for their roles in developing and maintaining the data flow and display software, Bruce Randall (University of Iowa) for providing the corrected Pioneer/GTT data to the PDS and discussing the corrections with us, and John E. Connerney (NASA/GSFC) for developing the JRM09 model and useful discussions. NASA’s New Frontiers Program funded this work for Juno via subcontract with the Southwest Research Institute. The part of the research performed by H.B. Garrett was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA (80NM0015D0004).
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