Radiation near Jupiter detected by Juno/JEDI during PJ1 and PJ3

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Abstract
After its capture into Jupiter orbit early in the summer of 2016, the Juno spacecraft made three close flybys of the planet to date. The Jupiter Energetic Particle Detector Instrument (JEDI) made continuous measurements during perijovens in late August and early December. Here we describe the radiation (approximately hundreds of keV to more than 10 MeV charged particles) that was measured close to Jupiter. The purpose of this paper is to present some of the first direct energetic charged particle measurements ever obtained at high magnetic latitude very close to Jupiter and to interpret these data using techniques that rely on the instrument design. We generate an electron energy spectrum in an intense radiation region where the JEDI foreground is only about 40% of the rate due to >15 MeV electrons.

1. Introduction

On 27 August 2016 and 11 December 2016, the Juno spacecraft made close north-to-south passes of the planet Jupiter. During these times, all three sensors that make up the Jupiter Energetic Particle Detector Instrument (JEDI) made continuous measurements. In this work, we will abbreviate the names of the sensors as follows: J09 (JEDI-90), J18 (JEDI-A180), and J27 (JEDI-270), where the names in parentheses are those given in the JEDI instrument paper [Mauk et al., 2013]. JEDI measured fluxes of both precipitating and trapped energetic charged particles in species-dependent energy channels ranging in some cases down to 10 keV and in others up to >10 MeV. J09 and J27 are mounted so that they view approximately perpendicular to the spacecraft spin axis, whereas J18 views angles between the spin and antispin directions. A description of JEDI including complete details about all the detectors, their response, and look directions are given in Mauk et al. [2013]. With sufficiently high time resolution magnetometer measurements, JEDI data can also be separated by local pitch angle.

This article will describe the radiation observed by JEDI close to Jupiter. Bolton et al. [2004, and references therein] review Jupiter's inner magnetosphere from the point of view of radiation. This paper is meant to be an overview of the most intense radiation regions visited by Juno along its high-latitude and polar trajectory. An emphasis here is on the distribution of >15 MeV electrons in the radiation belts of Jupiter, using unique JEDI capabilities for detecting very energetic particles.

In this paper, we will focus on the data obtained by Juno on the two days 2016-240 (including perijove 1 or PJ1) and 2016-346 (which includes PJ3), Mauk et al. [2017] and Connerney et al. [2017] have presented an overview of the JEDI data obtained during PJ1. Mauk et al. [2017] have focused on precipitating flux, whereas this paper will examine trapped particles and the structure of the Jovian radiation belts at high latitude.

2. Radiation Parameter

Figure 1 shows projections of the Juno trajectory on days 2016-240 and 2016-346. It is plotted in cylindrical coordinates where the z axis is aligned with the magnetic dipole of Jupiter and \( \rho \) is in the perpendicular direction. The units are given in equatorial Jovian radii, where 1 RJ = 71,492 km. Model magnetic field lines created by combining the VIP4 and CAN models are also shown [Connerney, 1981].

Jupiter's magnetic field lines are stretched from a dipolar configuration due to the planetary ring current and other currents [e.g., Connerney, 1981; Khurana, 1997]. For locations off the magnetic equator, the equatorial crossing point of the field line can be very distant from Jupiter. As the planet rotates, Juno can move...
across field lines with very different equatorial crossing points and therefore flux levels. It is useful to keep in mind that the dipole L shell used in the plots below is qualitative only. The radial distance and magnetic latitude are better proxies for the equatorial crossing distance of the field lines. Since the most intense particle flux tends to be present on the most dipolar field lines (i.e., those close to the planet), Figure 1 gives a sense of how the radiation experienced by Juno would vary with time even close to Jupiter.

In Figure 2, we show data obtained by JEDI on day 2016-240, between the hours 03:00 and 07:30 UTC; peri jove was ~12:51:20. Due to the limitations on spacecraft storage and downlink, JEDI is commanded into its highest data-taking modes only in the hours around closest approach. The low-rate data shown at this time are 10 min averaged. The gray points are the J18 ion detector singles measurements in the small pixel mode (using a bare solid-state detector or SSD), and the black points are a radiation parameter, derived from JEDI data. Singles rates are essentially summed count rates of both ions and electrons above the energy threshold of the detector, frequently dominated by tens of keV electrons.

The radiation parameter shown in Figure 2 is an average of the J18 SSD1 and SSD3 rates from the small ion pixels (each behind a 0.064 cm titanium witness shield) with a subtraction of ~8% of the rates from neighboring SSDs. This subtraction is meant to account for scattering into the detectors. The two witness shields

![Figure 1](image1.png)

**Figure 1.** Projection of Juno’s trajectory into cylindrical coordinates, where the vertical axis is along Jupiter’s planetary dipole. The tick marks are given every hour for the PJ1 (blue) and PJ3 (green) passes. Large tick marks at 12 h intervals are annotated.

![Figure 2](image2.png)

**Figure 2.** Comparison of the radiation parameter (black circles) and the J18 SSD2 count rate (gray plus signs). These data show a period when Juno was inbound to PJ1.
prohibit electrons <700 keV and protons <10 MeV from being counted. The shield will also block heavy ions with energies well above 10 MeV, but these are not likely to dominate the count rate. The radiation parameter is available only when data are taken by the J18 sensor in the small ion pixel mode.

The rise in rates observed in Figure 2 occurs when Juno begins to dip down in magnetic latitude (see Figure 1) so that it is on field lines whose equatorial crossing points are in Jupiter’s inner magnetosphere. The rates of >700 keV electrons (assuming that these are the particles dominating the radiation parameter) also start to increase steeply after about 03:00 UTC, but they are below the singles rates at these times measured in the unshielded detector. A comparison of unshielded and witness-shielded SSDs informs JEDI’s response to energetic particles (e.g., ~10–700 keV electrons) at times of high counts due to >15 MeV electrons (see discussion below). It allows a rough estimate of the spectral shape at energies beyond the nominal electron energy range of JEDI. In Figure 2, the data show that the rates of <700 keV electrons are still the dominant ones.

3. Data Obtained During PJ1

In this section, we describe the population of charged particles that JEDI observed around PJ1 in greater detail. In Figure 3 (middle), the blue curve shows the J18 bare ion detector SSD3 count rate behind the witness shield and the red curve shows the J18 electron SSD3 count rate. The JEDI electron SSDs are behind a thin (2 μm Al) flashing so that they efficiently measure 30–700 keV electrons, but other particles, such as
electrons with energies less than about 30 keV and protons below 250 keV, are excluded. Because the flashing excludes ions to higher energies than electrons, it is expected that the electron singles rates will usually be dominated by energetic electrons when the spacecraft is inside the magnetosphere. Figure 3 (top) shows the local pitch angle distribution of the witness data represented by the blue curve in Figure 3 (middle). We chose to show the SSD3 rates and not the similar radiation parameter because they correspond to the pitch angle plot. Figure 3 (bottom) shows the proton intensities derived from the J09 time of flight versus energy (TOFxE) data. We show a few of the channels that measure protons that can pass through the flashing and add counts to the “electron” singles (Figure 3 (middle), red curve).

The detector behind the witness shield would usually measure much lower rates than the flashed electron detector since it is sampling a smaller portion of the foreground that is above threshold. However, JEDI observed that the two SSD rates (＞30 keV and ＞700 keV) become nearly identical in the approximate time intervals, 12:18–12:36 and 12:59–13:22 UTC (where the blue and red curves in Figure 3 (middle) overlap). For these rates to be nearly the same, particles that dominate both detectors have enough energy to penetrate the witness shield. It is worth noting further that even when the singles rates drop close to Jupiter (e.g., around 13:00 UTC), the two different measurements continue to track each other very well. This means that the lower energy foreground count rates in this region are probably very low and not just obscured by the rates associated with more energetic particles. Finally, the electron energy spectra created at these times (not shown) are identical for the bare detector and the witness data, so energy spectra observed at these times below 700 keV should be considered with extreme caution.

A careful examination of the pitch angle distributions at these times shows that there is more flux when the detectors are viewing 90° pitch angles. This means that one part of the signal is due to particles that are entering the detector through the aperture (and by penetrating the witness shield). However, due to the low contrast in pitch angle from these particles reaching the detector by way of the aperture, it is likely that the majority of the signal is electrons above 15 MeV, which can penetrate the JEDI housing and cause counts in the detector. Electrons ＞15 MeV have a much higher geometry factor than the ones entering through the aperture, so they can dominate the count rate when they are present in high enough numbers. Furthermore, Mauk et al. [2017] find a lot of so-called accidentals during these times, i.e., as seen when JEDI’s time of flight versus pulse height rates stop tracking the higher coincidence TOFxE rates. That observation suggests that there have to be important contributions to the signal from high-energy particles penetrating the housing.

If we assume that the signal is dominated by electrons, there is evidence that the count rates at these times include contributions from both the 0.7–15 MeV electrons (electrons that go through the witness shield but do not penetrate the housing) and ＞15 MeV electrons. We can therefore form a coarse energy spectrum in the few MeV energy range for these points close to the planet as follows. We use 2 min of data between 13:10:30 and 13:12:30 UTC and estimate the ＞15 MeV electron (or housing penetrator) count rate as ~3600 c/s. To determine that the counts are housing penetrators, we only use data obtained when the telescope is viewing into or close to the planetary loss cone. These directions should be empty, but the pitch angle assigned is based on the look direction of the aperture and not the true arrival direction of the particles (which is some direction through the housing). For housing penetrators, the responsive detector area in cm² sr is ＾2πxy [Sullivan, 1971], where x = 0.155 cm and y = 0.128 cm [Mauk et al., 2013]. We integrate between 15 and 100 MeV. When SSD3 is viewing 90° local pitch angles, the count rate is about 2400 c/s above background and the geometry factor of the aperture is 4 × 10⁻⁵ cm² sr. If these rates are due to electrons with a spectral form ＾1/E, then, ＾A ~ 6.15 × 10² and ＾γ ~ 3.49, where ＾E is in MeV and ＾j is in electrons per cm² sr MeV. This fit for 4 MeV electrons is very close to estimates from Galileo Energetic Particles Detector data near Io’s orbit [Krupp et al., 2016]. Comparing with data near Europa’s orbit [Paranicas et al., 2001], this fit has a steeper spectral slope in the few MeV energy range but the overall intensity at 10 MeV is within a factor of 2.

Finally, close to PJ1 (at ＾12:52 UTC), from about 12:41–12:49 UTC, the singles rates are very different in the two detectors, with the witness rates well below the electron SSD rates. Because of this ordering, we can hypothesize that in this region very close to Jupiter, the singles rates are dominated by ＾700 keV electrons and/or energetic ions, including protons below 10 MeV. The increase in Figure 3 (bottom) at ＾12:38 UTC suggests that energetic protons are contributors, but those channels are not sampled in the
high-voltage safing period (12:42 to 13:02 UTC). Kollmann et al. [2017] examine these measurements in much greater detail.

Lastly, the outbound points in Figure 3, between 13:30 and 13:45, show two intense spikes in the witness rate. The first spike has higher rates in particles moving along the field line and away from Jupiter, whereas the second spike has a population also moving toward Jupiter. For these spikes to be visible in Figure 3 (top), which shows witness data only, the particles must be one or more of the following populations: > 0.7 MeV electrons, >10 MeV protons, and/or tens of MeV heavy ions.

4. Data Obtained During PJ3

In this section, we discuss the radiation observed around PJ3, which occurred on day 2016-346 at ~17:04 UTC. These data are similar in many respects to PJ1 data with some important differences. We have focused on the northern portion of the orbit because the radiation belts are sampled at lower latitude there (see Figure 1).

In Figure 4, we show the same channels as in Figure 3. These include the local pitch angle of one of the witness shield rates in Figure 4 (top), a comparison of the flashed and witness shield detector responses in Figure 4 (middle), and TOFxE protons in Figure 4 (bottom).

The period leading up to closest approach, just after ~15:30, shows a spike in the witness rate, but the maximum value is still smaller than the most intense regions near the planet. The energetic protons shown in Figure 4 (bottom) can penetrate the flashing that covers the electron detectors, so they can contribute to the associated singles rates. These protons would not, however, add counts to the witness rate. In both PJ1 and PJ3 data on either side of the regions where the two singles rates are very close, these energetic
The region right around PJ3 is very similar to the one around PJ1. The witness shield singles rate and the electron singles rate become nearly identical, suggesting that the rates are dominated by >700 keV electrons. As we showed earlier, these intense radiation regions are dominated by the count rates associated with >15 MeV electrons although some 0.7–15 MeV electrons are present at these locations. The population very close to the planet that is the subject of P. Kollmann et al. (submitted manuscript, 2017) is again observed during PJ3, but it is weaker. We do not know if the differences are real changes in the intensity or due to the geometry of the flyby.

5. Summary

JEDI has observed intense flux at high magnetic latitude during the PJ1 and PJ3 passes. The radial distance and magnetic latitude of the spacecraft are very important in determining the level of radiation experienced by the spacecraft. This is due to the changing magnetic latitude as the planet rotates and the fact that the magnetic field lines are highly stretched. Radiation levels experienced by the spacecraft when it is close to Jupiter can vary greatly depending on the magnetic field lines that are occupied and their equatorial crossing points. This is both a radial distance and magnetic latitude effect.

Very close to the planet, we found evidence of a population of particles that is present on PJ1 and weaker on PJ3. Just prior to and just after perijove, JEDI observed the most intense radiation on the two orbits where data were obtained. This is indicated by the relative count rates of the flashed detector and the witness-shielded ones. During these times, we have found that the >15 MeV electrons dominate the count rates with a smaller contribution (<40%) from 0.7 to 15 MeV electrons. Excluding the population right near perijove [Kollmann et al., 2017], we did not find a strong contribution to the count rates in these high-latitude regions from <700 keV electrons. Near the planet, hundreds of keV to 1 MeV protons measured by Juno are found to vary strongly with the exact position of the spacecraft. We used the details of the instrument to extract an electron energy spectrum during these intense measurement periods that is applicable to the MeV energy range.

References

Connerney, J. E. P., et al. (2017), Jupiter’s magnetosphere and aurorae observed by the Juno spacecraft during its first polar orbits, doi: 10.1126/science.aam5928.