Io’s Effect on Energetic Charged Particles as Seen in Juno Data

C. Paranicas1, B.H. Mauk1, D.K. Haggerty1, G. Clark1, P. Kollmann1, A.M. Rymer1, J. Westlake1, R.C. Allen1, J. Szalay2, R.W. Ebert3,4, A.H. Sulaiman5, M. Imai5, E. Roussos6, N. Krupp6, Q. Nénon7, F. Bagenal8, and S. J. Bolton3

1The Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA, 2Department of Astrophysical Sciences, Princeton University, Princeton, USA, 3Southwest Research Institute, San Antonio, TX, USA, 4Department of Physics and Astronomy, University of Texas at San Antonio, San Antonio, TX, USA, 5Department of Physics and Astronomy, University of Iowa, Iowa City, IA, USA, 6Max Planck Institute for Solar System Research MPS, Göttingen, Germany, 7Space Sciences Lab, University of California, Berkeley, CA, USA, 8Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO, USA

Abstract On 12 February 2019, the Juno spacecraft crossed the particle drift shells (L shells) of the moon Io. The energetic particle detector, Jupiter Energetic Particle Detector Instrument (JEDI), found very low fluxes of energetic protons when the spacecraft was inward of about L=6.5. Recent modeling suggests wave-particle interactions may explain why energetic proton fluxes measured at these radial distances are low. JEDI also measured both a wide and a narrow decrease in the energetic electron count rate in Io’s wake. At the time of this decrease, the JEDI detectors were dominated by 0.42 to 10-MeV electrons. The dimensions of the narrow count rate decrease are about three Io diameters and are unlikely to be caused by absorption by moon itself.

1. Introduction

On 12 February 2019, the Juno spacecraft flew through L shells associated with Jupiter’s volcanic moon Io. At the time, the Jovian Auroral Distributions Experiment (JADE) instrument observed changes in the corotation speed of the plasma and also discovered field-aligned signatures. The Jupiter Energetic Particle Detector Instrument (JEDI) recorded a steep drop-off in the intensity of tens to hundreds of keV protons about 30 min before the spacecraft, inbound to Jupiter, reached Io’s L shells. The energetic proton flux remained at a low level as the spacecraft moved well inward of Io’s orbit. The JEDI electron data show a broad minimum associated with L shells occupied by Io, as has been observed during previous spacecraft flybys (see, for instance, the summary in Nénon et al., 2017). In addition, a significant decrease in the hundreds of keV to about 10-MeV electrons was detected over a radial distance of about three Io diameters.

Energetic charged particles can be lost by impact with Io’s surface. It is also possible that this process can be enhanced by the electromagnetics near Io, including the Alfvén wing current system (e.g., Neubauer, 1980). Charged particle drift paths that are altered near Io may lead, for example, to a larger interaction and loss region. But recent work (e.g., Nénon et al., 2017, 2018) has suggested that other mechanisms may be important, especially for the proton losses that are observed over a very wide radial range. It is well known that Io’s atmosphere loses neutrals at a rapid and steady rate. Some of these particles enter circumplanetary orbits, and a significant fraction become ionized near or along Io’s orbit (Thomas et al., 2004). Smyth and Marconi (2006), for example, predicted a peak in the production of pickup ions at Io’s orbit that decreased both toward and away from Jupiter. The Galileo spacecraft measured ion cyclotron waves near Io, associated with pickup ions (e.g., Kivelson et al., 1996). With large numbers of pickup ions, particle losses through resonant interactions with electromagnetic waves can be significant.

In Figure 1, we show a sketch of the flyby projected into the orbital plane of Io. The Juno spacecraft crossed the L shells of Io at about 38° Jovian latitude and about 18° in Jovian longitude downstream from the moon. Io orbits Jupiter at a radial distance of about 5.9 RJ, where 1 RJ is 71,492 km, with a small inclination and eccentricity. Therefore, at the time in question, the spacecraft intersected the L shells associated with Io at about 189,000-km above the equatorial plane and 133,000-km downstream from the moon.
JEDI contains three similar units (JEDI-90, JEDI-A180, and JEDI-270), each with six look directions. It detects electrons from about 30 to 1,200 keV. JEDI also detects energetic protons and heavy ions (from hundreds of keV to over 1 MeV), using a multiple coincidence system that combines a solid state detector (SSD) measurement with a time-of-flight measurement. These higher coincidence measurements are useful in Jupiter's radiation belts for separating true ion counts from background counts caused by energetic electrons. A complete description of the instrument can be found in Mauk et al. (2017).

In this paper, we will examine the influence Io has on energetic charged particles near its orbit, using JEDI and Juno Waves data. We compare the data with findings of previous modeling that attempted to reproduce radial flux profiles of energetic charged particles measured by other spacecraft. Both the electron and proton data we present here, when combined with the results of published models, strongly suggest that losses due to wave-particles interactions play a dominant role in the region.

2. Io Flyby Data

Figure 2 shows the charged particles measured by JEDI in the hours when Juno flew through Io's L shells on Day 2019–043. The top panel shows electron counts per second, including data from all three JEDI sensors. The L shell of Io is apparent in the much lower electron count rate between about 14:55 and 15:03 UT. The bottom panel shows the intensity of tens of keV to 1-MeV protons. The proton flux decreases well before the spacecraft reaches Io's orbital distance (inward of L~6.33) and remains low to the smallest L shell on this plot, L~5.43.

Since JEDI was not designed to study Jupiter's radiation belts, we first discuss some features of the signal in the radiation belts. Trapped particles in magnetospheres usually have an energy spectrum that falls off with increasing energy (e.g., Dialynas et al., 2017). But the top panel of Figure 2 shows a count rate enhancement centered at about 160 keV. This is a common feature of the JEDI SSD-only data in Jupiter's radiation belts. We believe the counts in this plot are due to electrons that come in through the JEDI collimator and then fully penetrate the SSD; this can occur for any electrons with energies >420 keV (Mauk et al., 2018; Paranicas et al., 2018). These electrons deposit only a fraction of their energy in the SSD. The amount of energy deposited is similar for a wide range of electron energies due to a flattening around the minimum in the energy loss per unit length of material as a function of particle energy. Finally, we show the electron data in counts per second, instead of intensity, because we believe electrons that fully penetrate the SSDs are present in large numbers.

At the same time, JEDI observed this reduction in electron flux; the plasma team reported a discontinuity in the corotation energies observed by Jovian Auroral Distributions Experiment. They found this change extended from just before 14:56 to just before 15:03 UT (a similar size to the deepest part of the JEDI electron decrease). They noted that this corresponds to about 2.7 Io diameters and found further structuring in the plasma measurements within this region. The Juno Waves instrument (Kurth et al., 2017) also detected enhanced ~kHz waves, again with the same dimensions, see discussion below.

The lower panel of Figure 2 shows a decrease in energetic proton intensities that has been observed by other spacecraft, for example, Voyagers 1 and 2, starting from just outward and continuing inward through Io's L shells (e.g., Armstrong et al., 1981; Paranicas et al., 1990). Kollmann et al. (2017) reported on a decrease in energetic protons and sulfur ions near the same location, using data from multiple spacecraft. The proton...
intensities that are shown here near and just inward of Io’s orbital distance have a low signal-to-noise ratio so should be interpreted carefully. The brief enhancements (around 15:10 and 16:15), showing that transient populations can exist in this region, are well above the noise level.

In Figure 3, we show some JEDI-A180 singles rates. These rates include counts from ions and electrons above an energy threshold (see discussion in, Mauk et al., 2017). Each separate curve is a different look direction. At this time, we believe the counts that are shown are dominated by energetic electrons. This is supported by the fact that the proton intensity at this time is very low, as noted above. Overall, the data appear to show a very deep decrease, in a region larger than the moon, within a much broader count rate decrease, that has been observed by other spacecraft. For example, in the electron simulations of Nénon et al. (2017), a broad (in radius) local minimum in the integral intensity around Io’s orbit is apparent at different energies. The JEDI data further suggest radial diffusion into the depletion, based on the curved edges on either side of the main depletion. It is important to note that if the deep decrease was due to absorption by an inert moon, it would be smaller than the diameter, not several times the diameter.

Lastly, we consider the energies of the electrons in and around the Io signature. The top panel of Figure 2 shows that the SSDs are dominated by >0.42-MeV electrons at this time (such electrons cause a band in the JEDI spectrogram centered at about 160 keV). Since electrons above 10 MeV can penetrate the collimator blades, and electrons above 15 MeV can penetrate the housing, we believe the count rates shown in Figure 3 are dominated by electrons between about 0.42 and 10 MeV. That is, electrons that come through the collimator and reach the detectors. If the energy spectrum were dominated by higher energies, the rates measured by the shielded and bare detectors would be more comparable.

When many > 0.42-MeV electrons are present in the environment, it can be difficult to quantify the lower energy electrons that JEDI measures. To do this, we use additional details of the instrument. Two of the count rates shown in Figure 3 (from SSD1 and SSD3) are from detectors located behind a shield that prevents most electrons with energies below about 560 keV from reaching the detector by a direct path (the shield also blocks protons below ~12 MeV and heavy ions to much higher energies). SSD2 and SSD4 are bare detectors.
The shielded detectors receive about 8% of the bare detector rates from scattering. Therefore by forming a ratio of the count rates at 14:30, we find about 70% of the bare detector count rate is due to \( >560 \)–keV electrons. The other 30% of the count rate at that time is due to electrons between 30 and 560 keV.

3. Interpretation

We begin by describing the ion data, which show reduced fluxes near Io’s orbit. As noted above, several researchers have observed and analyzed a steep change in charged particle phase space density that occurs in this region of the magnetosphere. Cheng et al. (1983) looked at energetic-charged particle data obtained by previous spacecraft and concluded that wave-particle interactions were principally responsible for this decrease, but that charge exchange can also play a role. More recently, Nénon et al. (2018) modeled similar decreases in flux across Io’s orbit for protons \( >1 \) MeV. To model radial profiles of energetic proton intensities, they considered effects such as Io absorption, wave-particle interactions, charge exchange, and Coulomb collisions. For \( >1 \)-MeV protons, they showed that wave-particle interactions had the most important effect on the flux. They suggested that charge exchange and absorption by Io itself could only create about 10% of the depletion. If these waves, for example, strongly scatter \( >0.1 \)-MeV protons into the planetary loss cone over a wide radial range, then the Galileo wave observations mentioned above provide a basis for the interpretations discussed above.

It is important to recognize that Nénon et al. (2018) focused on energies in the hundreds of keV and above. They found that protons at energies between about 0.3 and 4 MeV are strongly affected by electromagnetic ion cyclotron waves near Io’s L shells. At lower energies, charge exchange cross-sections for proton-neutral collisions increase. For example, for protons on neutral H, the cross-section increases by more than two orders of magnitude between 200 and 50 keV (see, for instance, summary in Paranicas et al., 2008). Therefore, charge exchange may play a larger role in proton losses at the low end of the JEDI energy range and below the tens of keV.

Lastly, Cheng et al. (1983) suggested that radial diffusion coefficients drop off steeply moving inward at Io’s orbit. If the fluxes in this region are shaped principally by radial diffusion combined with a loss process that is somewhat uniform on the surrounding L shells, it is possible to get a change in flux that mirrors the shape of the diffusion coefficient. However, the location where this occurs is at a larger L shell than that predicted by the radial diffusion coefficient profile suggested by Cheng et al. (1983).
Next, we turn our attention to the energetic electrons measured in Io’s wake. For MeV electrons, there is a wide minimum around Io’s orbital distance, with a much deeper signature, a few times the moon’s diameter within it. Earlier spacecraft flybys in the region of Io’s orbit similarly found a wide depletion in electrons at a variety of energies, centered on Io’s orbit (see, for example, Nénon et al., 2017). However, we do not believe the narrow depletion in MeV electrons (i.e., between 14:56 and 15:03), a few times wider than Io’s diameter, has been observed previously. For completeness, we note that the gyroradius of a 1-MeV electron near Io is less than a few kilometer, so the signature is not due solely to an inert moon absorption enhanced by gyroradius effects. The bounce time of the same electron is about 5 s. For a 1-MeV proton near Io, the gyroradius is about 49 km, and the bounce time is about 108 s.

In the Galileo era, Thorne et al. (1999) predicted that the wake region of Io would be nearly devoid of energetic electrons. Their work followed the observation of a 40% decrease in the background magnetic field that was measured just downstream of the moon (Kivelson et al., 1996). Thorne et al. (1999) used a model that recreated a magnetic field decrease near Io and then computed energetic electron drift paths in the region. Thorne’s model creates an exclusion region in Io’s wake that becomes larger with increasing electron energy. To create a signature such as JEDI observes, that is, still much larger than the moon’s diameter after filling in downstream of Io, the fields near the body must lead to associated losses over a very wide region.

Another line of analysis that would produce a localized decrease in the count rate is waves confined to a region very close to Io. The size of the deep decrease is a few Io diameters, and this is not an unreasonable size for an Io interaction region where the particle distribution function is altered. The resulting distribution is convected with the corotating plasma into Io’s wake, and it is unstable to the generation of whistler-mode waves, which interact with the particles. For example, pitch angle scattering can drive the loss process. An example of a similar process in the literature is Santolík et al. (2011), who used a close flyby of Saturn’s moon Rhea to demonstrate multiple wave modes present close to that moon. They concluded that whistler-mode waves in the vicinity of Rhea could be responsible for the overall decrease of energetic electron fluxes that were somewhat wider than Rhea’s diameter. However, they focused on tens to hundreds of keV electrons, not MeV electrons (e.g., Jones et al., 2008).

Nénon et al. (2017) modeled the losses, sources, and transport of Jupiter’s electron radiation belts. They fit the shapes of the energetic electron flux detected by previous spacecraft. They concluded that the decrease associated with Io’s orbit cannot be due to the direct absorption of energetic electrons by Io above about 1 MeV. They also predicted that wave-particle interactions close to Io can drive loss processes that would reproduce the wide decrease centered at Io’s orbital distance.

In Figure 4, we show whistler-mode waves that were detected in the deepest portion of the JEDI count rate decrease. These waves can develop if the plasma conditions are favorable for growth. In this case, the waves...
illustrate that the parameters for wave growth can be very tightly confined in radial distance. This means that a deep drop out in MeV electron fluxes can be confined to a narrow radial region around the moon. In summary, the hypothesis of a wave-particle driven decrease in electron fluxes very close to Io seems to be the most consistent with previous modeling and these data. It is the expectation that over time, these losses and radial diffusion would evolve into the broad minimum around Io’s L shell.

4. Summary and Conclusions

Juno crossed L shells occupied by Io at high Jovian latitude on Day 2019–043. The JEDI data from this flyby are consistent with earlier findings that the energetic proton intensity falls off sharply beginning well outward of Io’s orbit and continuing inward of it. Previous modeling suggests that wave-particle interactions are an important driver of proton losses in this region. Below 100 keV, proton losses to charge exchange may become significant. JEDI found that the energetic electrons dominating the radiation belts at this time are likely about 0.42 to 10 MeV. It measured both a wide and a very narrow decrease associated with Io’s L shells. Earlier modeling predicted that wave-particle interactions are needed to form the wide decrease. The size of the narrow decrease suggests absorption by Io alone would not account for it. It is therefore more likely that wave-particle interactions cause the deep decrease on L shells associated with Io. A future modeling effort of the effect of local whistler-mode waves on energetic electrons needs to be carried out, not only for the wake of Io but also in the vicinity of Europa and Ganymede, where strong whistler-mode chorus waves have been observed by the Galileo spacecraft.

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