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Key Points:
- Significant pitch angle scattering was observed on Perijove 1 in the north and Perijove 3 in the north and the south polar regions
- Modeled diffusion plots fit well for Perijove 3 in the south, but not enough to explain observations in the north for Perijove 1 and Perijove 3
- Interactions with whistler mode waves contributes to the overall pitch angle scattering of the electron beams

Supporting Information:
- Supporting Information S1

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Pitch Angle Scattering of Upgoing Electron Beams in Jupiter's Polar Regions by Whistler Mode Waves

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Abstract The Juno spacecraft's Jupiter Energetic-particle Detector Instrument has observed field-aligned, unidirectional (upgoing) electron beams throughout most of Jupiter's entire polar cap region. The Waves instrument detected intense broadband whistler mode emissions occurring in the same region. In this paper, we investigate the pitch angle scattering of the upgoing electron beams due to interactions with the whistler mode waves. Profiles of intensity versus pitch angle for electron beams ranging from 2.53 to 7.22 Jovian radii show inconsistencies with the expected adiabatic invariant motion of the electrons. It is believed that the observed whistler mode waves perturb the electron motion and scatter them away from the magnetic field line. The diffusion equation has been solved by using diffusion coefficients which depend on the magnetic intensity of the whistler mode waves.

1. Introduction

One vital consequence of wave-particle interactions in planetary magnetospheres is pitch angle scattering and diffusion of energetic electrons. The importance of pitch angle diffusion was initially recognized in radiation belt physics via the papers by Kennel and Petschek (1966), Kennel and Engelmann (1966), and Kennel (1969). Waves propagating in the whistler mode have been shown to be important in the loss of trapped particles and particle precipitation due to pitch angle diffusion (Kennel et al., 1970). The waves perturb the electron motion and diffuse them toward the loss cone. Many early studies dealing with wave-particle interactions were motivated by their role in the particle dynamics of Earth's magnetosphere. However, pitch angle scattering by waves is also applicable to various planetary magnetospheres and astrophysical plasmas. Indeed, the existence of a Jovian equivalent of terrestrial whistler mode emissions interacting with electron motion was speculated by Sentman and Goertz (1978). However, confirmation of such interaction was not possible without in situ plasma wave measurements. Although broadband whistler mode waves, detected by Voyager 1 in the Io torus, have been shown to be capable of pitch angle scattering and diffusing electrons (Scarf et al., 1979), no evidence has suggested that a similar process occurs in the Jovian polar regions due to lack of measurements.

Much work on Jovian pitch angle scattering has focused on the equatorial region because of its ability to provide an explanation for energetic particle precipitation into the ionosphere by filling the loss cone. Scattering within the Io torus region gained early interest because Jovian density models suggested that the high-density Io torus regions are where the strongest cyclotron resonant interactions between energetic electrons and whistler mode waves occur (Ioannidis & Brice, 1971).

This paper will focus on a new type of pitch angle diffusion that deals with upgoing electron beams scattering via interaction with whistler mode waves in the polar cap. We define the term "polar cap" as the region poleward of the main auroral oval. Therefore, it is important to note the difference between pitch angle diffusion in the radiation belt and pitch angle diffusion in the polar regions. From radiation belt physics, electrons can be precipitated into the atmosphere by violation of the first adiabatic invariant motion of the particles that are normally trapped within the magnetic field, leading to pitch angle scattering into the loss cone. In contrast, Jovian polar cap pitch angle diffusion deals with upgoing electrons scattering away from the magnetic field line as they move further out. We believe that these field lines are open because no reflected component of the electrons is observed.

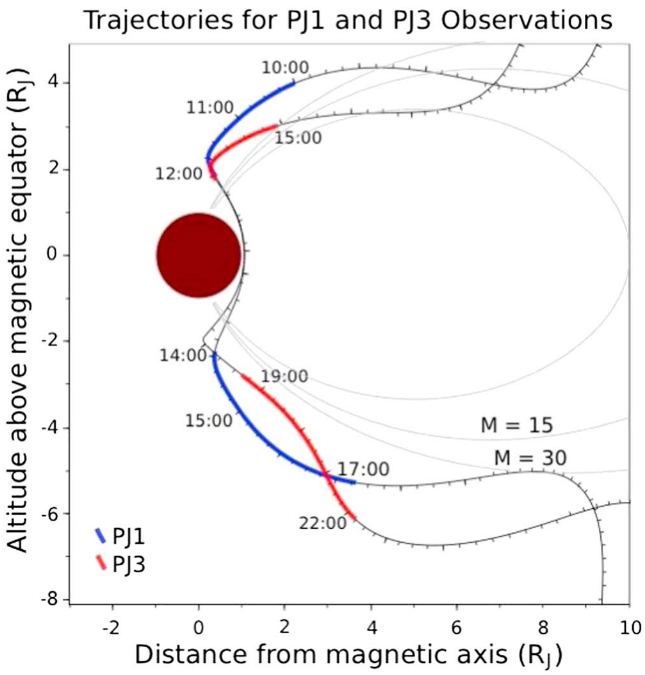

Figure 1. Plot showing the two PJ trajectories (PJ1 in blue and PJ3 in red) and locations of all observations used in this study. The grey lines indicate M-shells of 10, 15, and 30, using the VIP4-CS magnetic field model.

Many studies have been done on both Ulysses and Galileo data, revealing evidence of energetic electron pitch angle diffusion (Frank & Paterson, 2002; Lanzerotti et al., 1993; Seidel et al., 1997; Williams & Mauk, 1997). These studies dealt with pitch angle diffusion due to interaction with whistler mode chorus waves near 15 Jovian radii (R_J) at the equator, mapping to the main auroral oval. This study differs from previous pitch angle diffusion studies due to the location of the field lines on which the electron beams are located. The field lines within the Jovian polar cap regions map much farther out than main auroral oval field lines. This means that pitch angle diffusion on the polar cap field lines could not be explained by pitch angle scattering from equatorial chorus (near 15 R_J) but could be caused by interaction with whistler mode hiss in the polar cap.

Juno is the first mission to obtain in situ plasma and plasma wave measurements in both the northern and southern polar regions of Jupiter (Kurth et al., 2017). Intense broadband whistler mode emissions in the Jovian polar cap regions have been observed by the Juno Waves instrument (Tetrick et al., 2017). Both the Jupiter Energetic-particle Detector Instrument (JEDI) and the Jovian Auroral Distributions Experiment have also observed very field-aligned, unidirectional (upgoing) electron beams throughout the entire Jovian polar cap region (Allegrini et al., 2017; Mauk, Haggerty, Jaskulek, et al., 2017; Mauk, Haggerty, Paranicas, et al., 2017). Pitch angle versus intensity profiles for these (30 to 800 keV) upgoing electron beams have been analyzed for two perijoves with good pitch angle coverage: Perijove 1 on 27 August 2016 and Perijove 3 on 11 December 2016 (Connerney, Benn, et al., 2017; Connerney, Adriani, et al., 2017). For a complete list of times, M-shells, radial distances, and magnetic latitudes for the observations see Table S1 in the supporting information. The pitch angle intensities ranging from 2.53 to 7.22 Jovian radii (R_J) show not only inconsistencies with the expected adiabatic invariant motion of the electrons but also broadening of the beams as Jovian radial distance increases. Hence, the unidirectional electron beams show signatures of pitch angle diffusion possibly due to wave-particle interactions. This paper will show results from solving the pitch angle diffusion equation by utilizing the whistler mode wave magnetic field intensities to determine proper diffusion coefficients. It will be shown that the whistler mode waves in the polar regions can diffuse the electrons to higher pitch angles and contribute to the overall pitch angle scattering.

2. Broadening of Upgoing Electron Beams

During Juno's first and second pass over the northern and southern Jovian polar regions, upgoing (pitch angles from 0 to 15° and 165 to 180°, respectively, with energies of ~30 to 800 keV) electron beams were observed by the JEDI instrument (Mauk, Haggerty, Paranicas, et al., 2017). Also, over the Jovian polar cap regions, the Juno Waves instrument, which measures the electric (50 Hz to 40 MHz) and magnetic (50 Hz to 20 kHz) field components of radio and plasma waves, detected intense broadband whistler mode emissions (Tetrick et al., 2017). Significant correlations were found between the energetic electron beams and the whistler mode waves in the polar cap, indicating possible wave-particle interactions (Tetrick, 2017; Tetrick et al., 2017).

Intensity versus pitch angle plots of the upgoing electron beams were analyzed for a range of Jovian radial distances corresponding to when Juno passed over the polar cap regions (see Figure 1). The full width at half maximum field of view (FOV) for the JEDI instrument is about 9° × 17°. By using a 4.5° resolution on the pitch angle, and insisting that data be present within the pitch angle bin closest to either 0° or 180°, intensities closest to the field line will be included. A table providing specific time periods, M-shells, radial distances, and magnetic latitude values for each observation can be found in Table S1 in the supporting information. Figure 2a shows an example from the northern polar region on 27 August 2016 (from 10:00 to 12:06 UT,

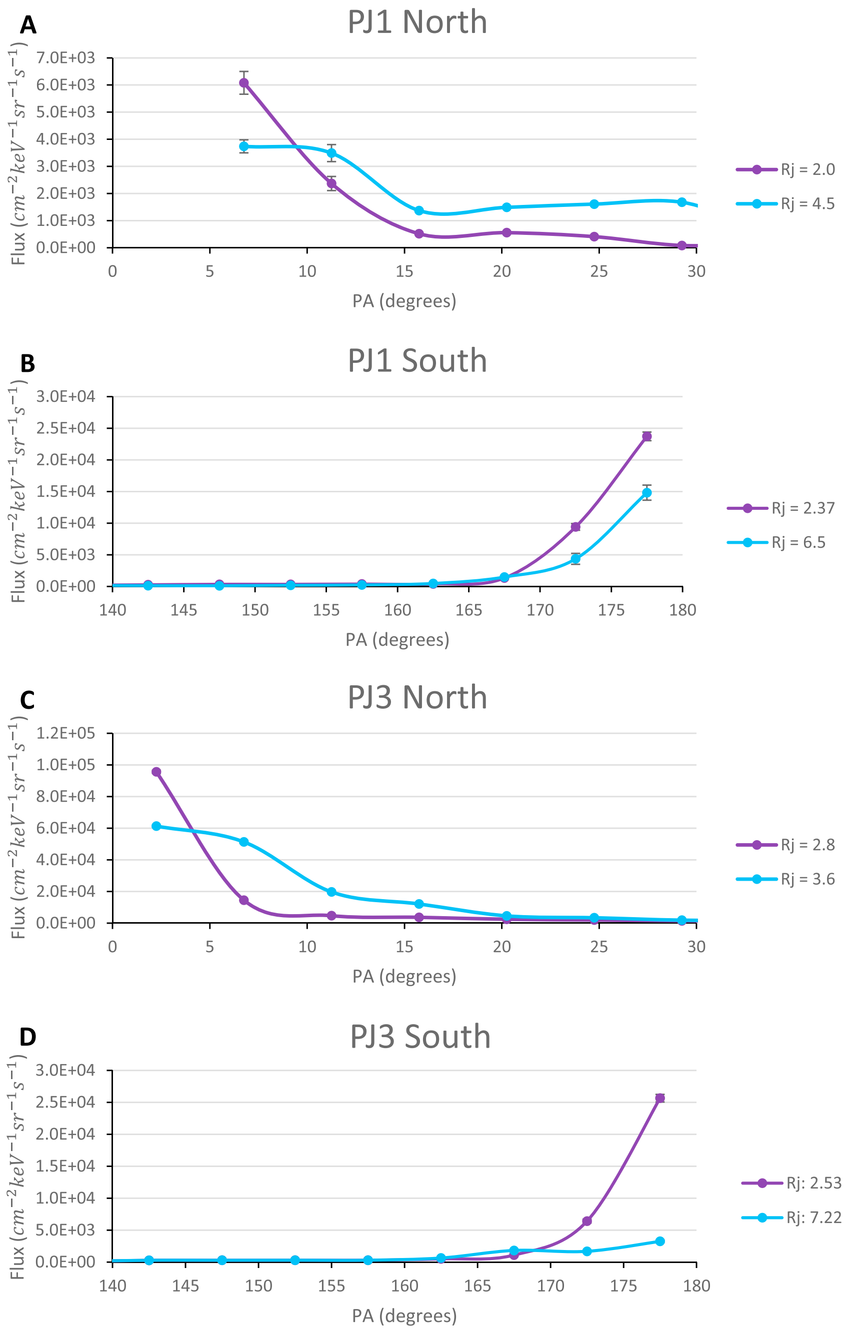

Figure 2. Electron upgoing beam observed over the northern and southern polar regions of Jupiter for PJ1 (and B) and PJ3 (C and D). Two curves depicting the closest radial distance of Juno during these time periods (shown in purple) and the farthest radial distance (shown in blue). These radial distances were selected because both upgoing electron beams and whistler mode emissions were observed. Significant broadening of the beams can be seen for the northern regions for both PJ1 and PJ3 from about 10 to 20°. There is also noticeable broadening seen in the south for PJ3 from about 172 to 160°, but only a very slight broadening is observed for PJ1. Intensity values (the average intensity value within each pitch angle bin) with a couple of characteristic error bars (1 standard deviation) are shown to demonstrate variability in the flux measurements. These data were generated by using 4.5° resolution on the pitch angle and insisting that data be present within the pitch angle bin that is closest to 0 or 180°.

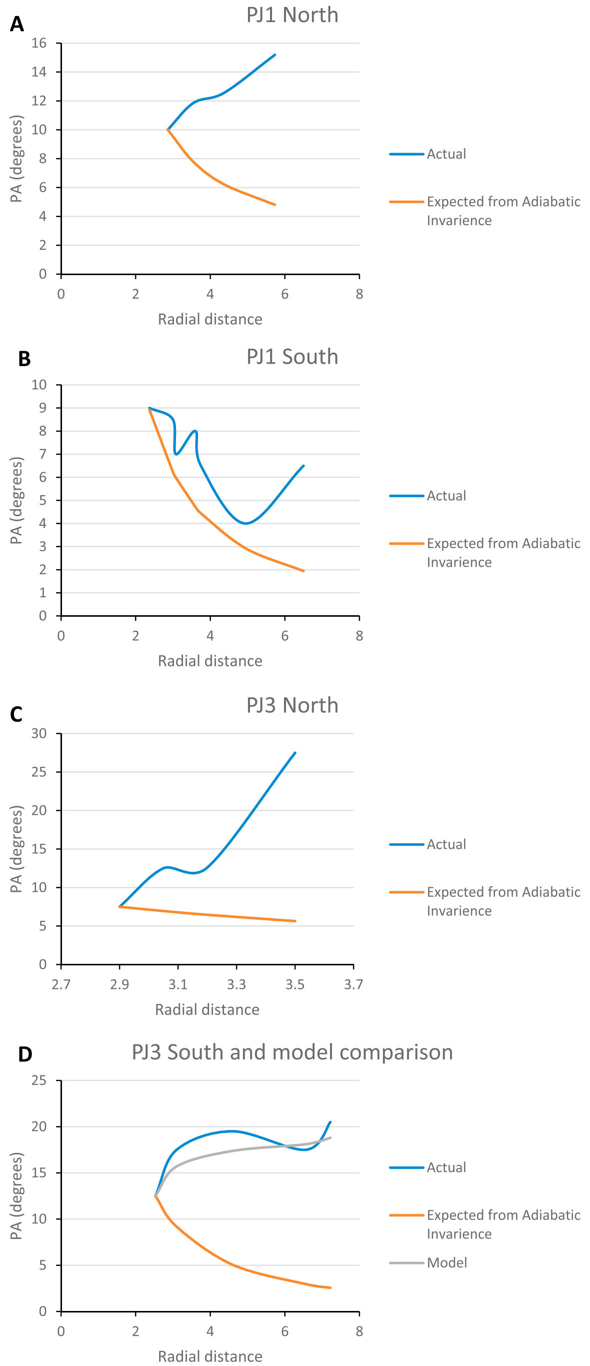

Figure 3. Plots showing the expected pitch angle variation as a function of radial distance (shown in orange) compared to the actual variation (shown in blue). For PJ1 in the north and PJ3 in both the north and south, significant deviation from the expected adiabatic motion of the particles is shown. The actual curve has overall positive slopes rather than the expected negative slope. For PJ1 in the south, the actual curve has a negative slope until about 5 Jovian radii but seems to follow the general predicted trend. Figure 2d shows a comparison of the actual pitch angle vs. radial distance data (blue), the adiabatic invariant motion model (orange), and the modeled curve From solving the diffusion equation using diffusion coefficients derived From the whistler mode magnetic wave intensity. The modeled curve fits reasonably well with the actual data, indicating that the whistler mode waves contribute significantly to the observed scattering.

M-shell = 67.57). Broadening of the pitch angles (roughly from 10 to 20°) is observed when the electrons go from a Jovian radial distance of 2 to 4.5 R_J. This broadening is not expected if the upgoing electrons were to follow motions described by the first adiabatic invariant, that is, $\sin^2\alpha = B/B_{max}$, where α is the pitch angle (Gurnett & Bhattacharjee, 2005). From this equation, we see that as magnetic field becomes weaker, the pitch angle should decrease, becoming more field aligned. Figure 3a demonstrates this inconsistency by comparing the observed pitch angle versus radial distance, at a flux of 1,000 $cm^{-2}keV^{-1}sr^{-1}s^{-1}$, to that expected for simple adiabatic invariant motion. We find that the observed pitch angle values exceed the expected values, indicative of pitch angle diffusion via wave-particle interactions.

Similar broadening of the pitch angles is observed for Perijove 3 in both the northern (from 15:03 to 16:19 UT, M-shell = 67.44) and southern polar regions (from 18:37 to 22:15 UT, M-shell = 71.67), as shown in Figures 2c and 2d, respectively. The southern polar region on Perijove 1 (from 13:55 to 17:20 UT, M-shell = 65.31), however, does not show significant broadening but is somewhat consistent with the adiabatic invariant motion of the electrons (see Figure 2b). This paper will focus on the regions in which pitch angle broadening is observed (i.e., north of Perijove 1, and north and south of Perijove 3), but an explanation for the lack of broadening in the southern region of Perijove 1 will be provided.

3. Whistler Mode Waves and Diffusion Coefficient

To solve the equation for pitch angle diffusion, one needs to obtain applicable diffusion coefficients. In one of the first studies on this topic, Kennel and Petschek (1966) provided a simplified diffusion coefficient that depended on the whistler mode wave magnetic field intensity:

$$D \approx \frac{|\Omega^-|}{|\cos\alpha|} k^* \left(\frac{B_k}{B}\right)^2$$

where $k^* = \frac{|\Omega^-|}{v_\parallel}$, Ω^- is the electron cyclotron frequency, B is the magnitude of the planetary magnetic field, and α is the pitch angle.

This study also recognized that $B_k^2 k^*$ is a good estimate of the total magnetic wave intensity of the whistler mode when the spectrum of the wave is reasonably smooth (Kennel & Petschek, 1966). Because the polar cap whistler mode waves have a relatively smooth magnetic component, we have utilized this estimate in our calculations. It should be noted that to accurately determine the diffusion coefficients responsible for scattering the electrons along field lines would require knowing the amplitude and polarization properties of the whistler mode waves along the entire path of the electrons, from their source location to the point of the observations. Because of Juno's orbit, this is not possible and we therefore must use the local wave amplitudes to estimate the wave intensity along the electron path. Because of the smooth wave magnetic component throughout the entire polar cap region, we can assume that the variation along a field line is also smooth. Figure 4 shows plots of the diffusion coefficients for the north and south on PJ1 and PJ3. An upward trend is observed for PJ1 in the north and PJ3 in both the north and the south; however, the values are relatively flat for PJ1 in the south. We have also calculated the average

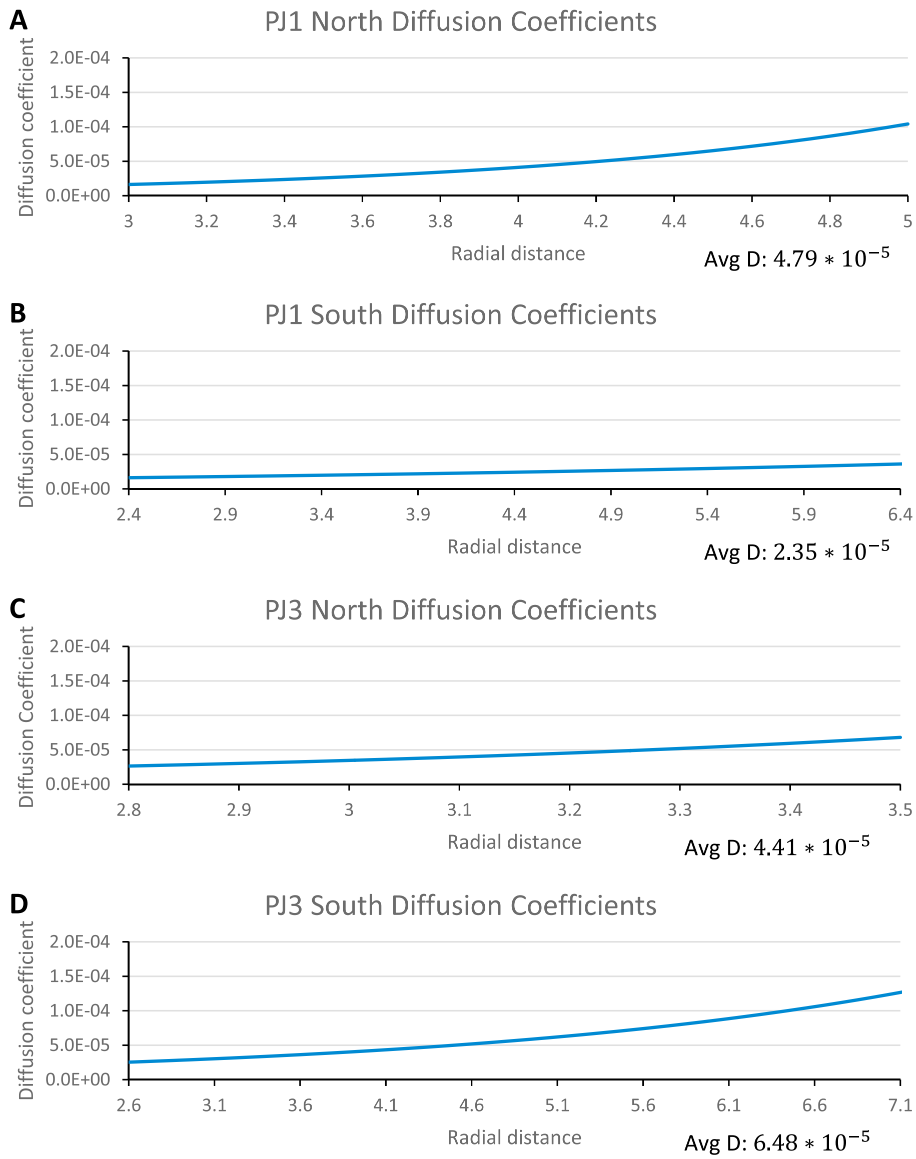

Figure 4. Calculated diffusion coefficients for PJ1 north (a), PJ1 south (b), PJ3 north (c), and PJ3 south (d). An upward trend in the coefficients can be seen in (a), (c), and (d), but no significant increase is observed in (b). The average diffusion coefficients are indicated for each data set.

diffusion coefficients for these time periods and found PJ1 in the south to have a significantly lower value because the whistler mode waves have lower magnetic intensities. We believe that this explains why there is lack of pitch angle scattering of the electrons for this time period; the diffusion coefficients are simply too low. The average values for the diffusion coefficients were used to solve the diffusion equation for each observation.

It should be noted that these diffusion coefficient values could be compared to previous computed values, such as those by Williams and Mauk (1997). However, previous studies dealt with pitch angle diffusion into the loss cone by whistler mode chorus waves mapping to the auroral oval. Our study deals with scattering polar cap electron beams away from the magnetic field line. There are two key differences between previous studies and this current study: the location of the field lines of interest (i.e., auroral versus polar cap field lines) and the direction of the pitch angle scattering (i.e., toward the loss cone versus away from the loss cone).

Our calculated diffusion coefficients are approximately a factor of 10 lower than previously published values, but care should be taken when comparing the two values because they are not directly related.

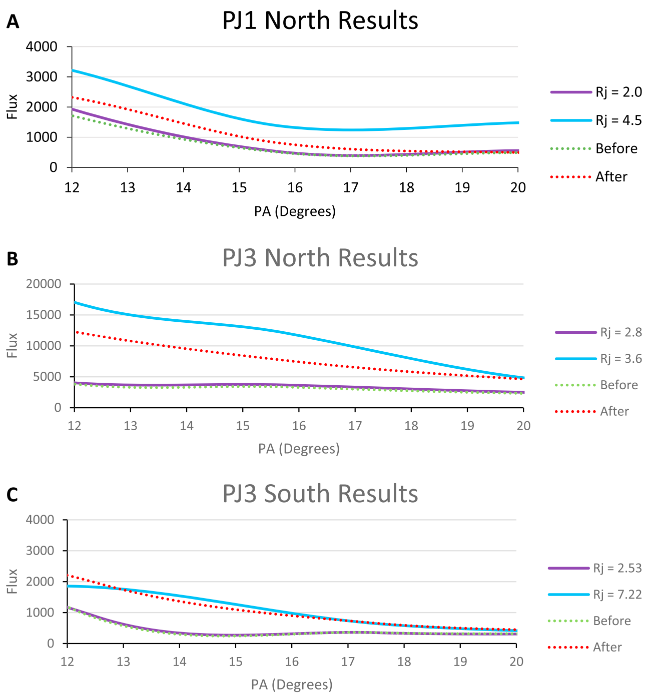

Figure 5. Results of solving the diffusion equation for PJ1 north (a) and PJ3 north (b) and south (c) showing the flux as a function of pitch angle. The observed broadening is shown by the solid lines and the modeled is shown by dashed lines. The modeled "after" curves show development of the diffusion equation for 7 s. The model fits well for (c) where the modeled curve nearly overlaps the observations. The model fits somewhat for (a) and (b), but the modeled curve is not enough to explain what is seen in the data set but does show that the waves contribute to the overall pitch angle scattering.

4. Solving the Diffusion Equation

We utilized the following diffusion equation from both Kennel and Petschek (1966) and Lyons et al., (1972):

$$\frac{\partial f(\alpha,t)}{\partial t}=\frac{1}{\sin(\alpha)}\frac{\partial}{\partial \alpha}\left[D\sin(\alpha)\frac{\partial f(\alpha,t)}{\partial \alpha}\right]$$

where D is the diffusion coefficient

In order to solve this equation, an initial condition and two boundary conditions are needed. Data from both PJ1 and PJ3 were used to construct these conditions. A power law function was fit to the shape of the initial electron distributions (purple lines in Figure 2) by using a least squares (a log-linear representation of this fit is shown in Figure S1 in the supporting information). From the fitted functions, the boundary conditions were then chosen by taking the function value at 0° and at 180°. By using a boundary condition at 0° that was not equal to zero implies that there is an initial flux of electrons, or a beam. Once the boundary conditions were chosen, a numerical differential equation solver was implemented and the diffusion equation was solved as a function of time and pitch angle.

The diffusion equation was solved for all three data sets where pitch angle scattering was observed: PJ1 north, PJ3 north, and PJ3 south. Figure 5 shows the results of the output showing $t = 0$ (the original distribution) and $t = 7$ s plotted over the observations of electron beam broadening. By utilizing the electron time of flight, we estimated the amount of time it would take such an electron to travel between the radial distance of interest to be roughly 7 s. We can see that for PJ3 in the north, the beam has been broadened significantly by the waves due to pitch angle diffusion but does not match perfectly with what is observed. For PJ1 in the north the modeled broadening is quite small compared to the observed, but an increase in the pitch angle is still obtained from the model, showing contribution from the whistler mode waves. The nonperfect agreement between predicted and observed beam width could well be due to the nonconstant whistler mode wave amplitude along the electron path. Lastly, for PJ3 in the south, the modeled broadened beam matches the observed the best out of the three time periods. Because of the good agreement with the data for PJ3 in the south, we investigated the pitch angles (modeled and observed) as a function of radial distance. Although the modeled equation is only a function of time and pitch angle, profiles as a function of radial distance can be produced by computing an electron time of flight. Because of the regularity in the intensity of the whistler mode waves over all polar caps from both PJ1 and PJ3, we have assumed that the variation is a function of radial distance. From this assumption, the bounce period can be used to find the equatorial time of flight and then scaled according to the radial distance the beams travel. Figure 3d shows that the modeled pitch angle curve (gray line) fits relatively well with the observed and contains the opposing trend when compared to the adiabatic curve.

5. Conclusions

This paper has analyzed the pitch angle scattering of upgoing electron beams observed by the Juno JEDI instrument and its relation to diffusion by wave-particle interactions. Significant pitch angle scattering was observed on PJ1 in the north, and PJ3 in both the north and the south polar regions. By incorporating diffusion coefficients calculated from whistler mode waves observed by the Juno Waves instrument, wave-particle interaction can explain a subset of the pitch angle diffusion that is observed. We found that for PJ3 in the north the modeled pitch angle profiles fit somewhat well with the observed and for PJ3 in the south the modeled fit extremely well with the observed. However, for PJ1 in the north, the scattering caused by the waves was not significant enough to explain what was observed. Also, for the southern regions on PJ1 there was no significant pitch angle scattering observed. We believe that this may be due to the lower diffusion coefficients calculated from the whistler mode waves and the relatively flat distribution of diffusion coefficients as a function of radial distance when compared to the upward trend in the other three time periods. The higher diffusion coefficient (more intense wave magnetic component) can therefore cause the electrons to pitch angle scatter away from the magnetic field line. We conclude that the interaction between whistler mode waves and energetic electron beams in the Jovian polar regions contributes to the overall pitch angle scattering observed.

Acknowledgments
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