Pitch angle diffusion at Jupiter's moon Ganymede

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Abstract. The magnetic field of Jupiter's moon Ganymede, provides a unique, large B value mirror point near the equator of Jovian field lines that intersect the moon. Ganymede creates a large loss cone in the distributions of all charged particles populating those field lines, emptying them of particles that mirror at radial distances $<\sim 8\ R_J$. Such a loss cone is seen when the Galileo energetic particles detector (EPD) views along the field line toward Ganymede. When the EPD views in the antimoon direction, the loss cone is nearly filled in for low energy electrons and remains empty at high energies. Because these electrons travel between their Ganymede mirror points and their near-Jupiter mirror points much faster than they drift across the Ganymede magnetosphere, they are effectively trapped between the moon and Jupiter for several bounce periods. Thus the amount of filling observed in the antimoon viewing loss cone gives a direct measure of the amount of pitch angle scattering occurring during the electrons half-bounce period. Using general wave-particle scattering theory, we have fit the pitch angle distributions within the antimoon viewing loss cone and have extracted values of the diffusion coefficient and its variation with energy. We find weak diffusion to dominate, yielding lifetimes of $\sim 10^3$ s at low energies to $\sim 10^4$ s at high energies. The diffusion coefficient, assumed independent of pitch angle, varies as $\sim E^{-1}$ or equivalently $\sim \gamma^{-3.5}$ (E is the electron kinetic energy and γ is the relativistic correction factor) at energies above ~ 50 keV. Finally, we note that the existence of loss cones in the antimoon direction is evidence that Jovian field lines intersecting Ganymede effectively move with the moon.

1. Introduction

The NASA Galileo satellite encountered Jupiter's moon Ganymede (G2) on September 6, 1996 (the second of four encounters). Measurements made with the energetic particles detector (EPD) [*Williams et al.*, 1997] support the existence of an intrinsic magnetic field and magnetosphere at Ganymede [*Gurnett et al.*, 1996; *Kivelson et al.*, 1996]. The EPD measurements provide additional insights into the interaction between Ganymede's magnetic field and the Jovian environment. In this paper we present direct observations of electron pitch angle scattering that occurs during the electron's half-bounce period along the Jovian field line connecting to Ganymede. The geometry of the situation is unique and provides the first measure of pitch angle scattering over these short timescales at Jupiter.

The EPD [*Williams et al.*, 1992] measures the spectral and angular distributions of ions above 20 keV, electrons above 10 keV, and elemental species from protons through iron above approximately 10 keV/nucleon. The EPD's two bidirectional detector heads are mounted on a stepper motor platform and when combined with the satellite spin provide up to a full 4π steradian sample of the unit sphere. The stepping program used during G2, a pass over the north pole of Ganymede with a closest approach distance of 260 km, provided very good coverage of particle pitch angle distributions throughout the encounter.

As reported by *Williams et al.* [1997], two main signatures characterized the EPD observations when within the Ganymede magnetosphere during the G2 polar pass: (1) a pronounced decrease in observed convective flow anisotropies and (2) a dramatic loss cone signature in all particle channels. Anisotropies observed in ion distributions outside Ganymede's magnetosphere gave convective flow speeds of approximately 150 km/s, ~80% of full corotation. Within Ganymede's magnetosphere, anisotropies were very small, and upper limits to the convective flow were estimated to be 25–45 km/s. The positions where these flow transitions occurred agreed well with the magnetopause positions identified by the magnetometer [*Kivelson et al.*, 1997] and the plasma wave detector (D. A. Gurnett, personal communication, 1997).

The EPD observed clear loss cone signatures in all particle channels when inside Ganymede's magnetosphere. *Williams et al.* [1997] used measurements of the size of the electron loss cones when looking along the field line in the direction of Ganymede to obtain an estimate of Ganymede's surface magnetic field along Galileo's subsatellite track. The results agreed well with extrapolations of the Ganymede magnetic field model developed from the magnetometer observations [*Kivelson et al.*, 1996]. When looking along the field line in the antimoon direction, all ion channels were observed to have a full loss cone. Also in the antimoon direction, electrons were observed to have nearly full loss cones at low energies that evolved to empty loss cones at high energies. Figure 1 presents an example of this energy dependence. It is this latter signature that we investigate in this paper. Because of their much smaller gyroradii in the Ganymede system (<several kilometers), we concentrate on the electron distributions at this time.

The following picture, illustrated in Figure 2, emerges from these Galileo observations [*Gurnett et al.*, 1996; *Kivelson et al.*, 1996; *Williams et al.*, 1997; *Frank et al.*, 1997]. External to Ganymede's magnetosphere, charged particles ExB drift at a speed ~80% of the expected corotation speed. Within Ganymede's magnetosphere this drift speed is much lower,

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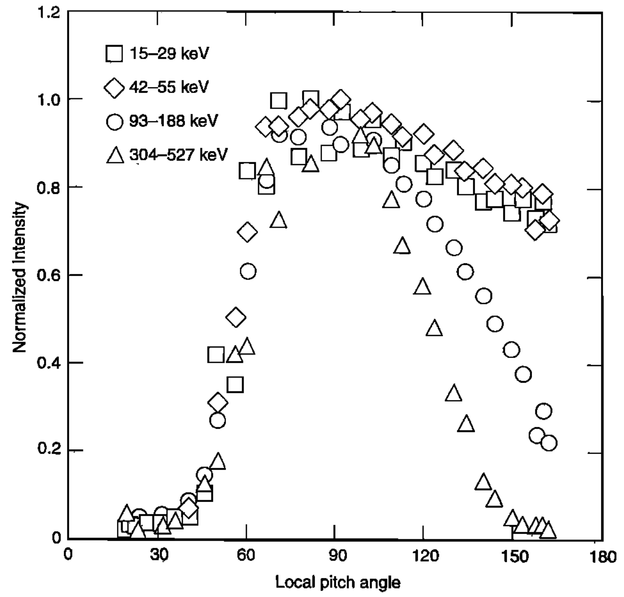

Figure 1. Pitch angle distributions measured by the Galileo energetic particles detector (EPD) over the polar cap of Ganymede at 1901:22 hours UT. The intensity at each energy was normalized to the maximum intensity during the satellite spin. The distinct loss cone created by Ganymede near local pitch angles of ~60° is clear. The slope of this loss cone is due to the finite angular aperature of the detector. In the antimoon viewing direction (large pitch angles) the loss cone is nearly filled in at low electron energies and remains nearly empty at high energies. The magnetic field magnitude at Galileo was 1024 nT at this time.

and the particles will take at least a few minutes to cross the Ganymede system. The maximum half-bounce period for EPD electrons is ~30 s. Therefore energetic (>15 keV) electrons will be trapped for several bounce periods between Ganymede and a mirror point much closer to Jupiter. Because the scale size of the Ganymede interaction region is only several R_G (a few tenths of a Jupiter radius [*Kivelson et al.*, 1996]), the electrons spend most of their time on a Jupiter-like field line and

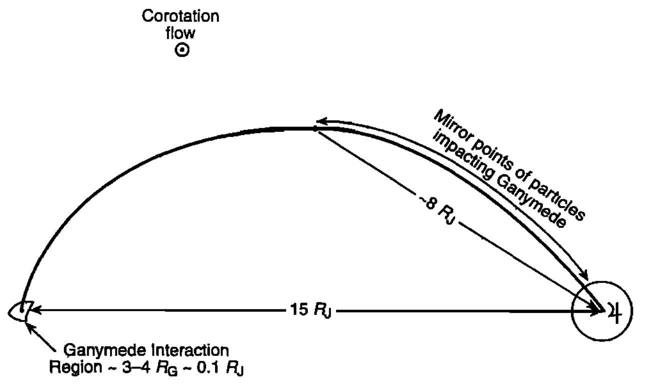

Figure 2. Schematic illustrating the electron-trapping geometry on Jovian field lines intersecting Ganymede. Electrons bounce several times between their Ganymede mirror point and their near-Jupiter mirror point as they drift across the Ganymede system. Ganymede removes all particles below ~8 R_J on field lines intersecting the moon, at least over the polar cap. Corotational flow is out of the plane of Figure 2 toward the reader.

only a very short time in the Ganymede system. A large local loss cone is established at Ganymede by the presence of the moon. Observations in the antimoon loss cone provide a direct measure of pitch angle diffusion occurring during one transit along the field line to the Jovian mirror point and back. From a dipole approximation the size of the local loss cone over Ganymede's pole (~60°) indicates that the mirror point toward Jupiter for all particles observed by EPD is at or above ~8 R_J from Jupiter. Ganymede effectively empties Jupiter's field line of energetic particles below ~8 R_J.

We shall now use this unique trapping geometry to estimate the pitch angle diffusion coefficient and its energy dependence along Jovian field lines connecting to Ganymede's magnetic field. Note that because of their much slower bounce times, the full antimoon loss cones observed for ions can readily be supplied by convection.

2. Data and Analysis

The local pitch angle distributions observed over Ganymede's pole display large and clear loss cones that allow accurate fits to be made to the shape of the pitch angle distribution in the antimoon (returning) loss cone. For reasons of improved accuracy the fits are done in the local pitch angle distribution frame. Results are then transformed into the equatorial pitch angle frame.

Denoting the particle pitch angle by α and assuming conservation of the first adiabatic invariant, we have along any magnetic field line

$$\sin^2(\alpha_1)/B_1 = \sin^2(\alpha_2)/B_2$$

Figure 3 demonstrates the portion of the equatorial pitch angle distribution sampled when over Ganymede's polar cap. To make this transformation, we have used the field strength measured at the point of observation over Ganymede's pole (where field strengths reached ~1200 nT) and a Jovian equatorial field strength of ~118 nT (the approximate field strength observed prior to entry into the Ganymede magnetosphere). Figure 3 specifically applies to 1901:22 hours UT on September 6, 1996, where the altitude above Ganymede's pole was ~300 km and the magnetic field strength was 1021 nT. Two sets of data points in each graph show directions along the field toward the moon and away from the moon and clearly show the filling-in of the loss cone at low energies. Little if any filling-in occurs at high energies.

These loss cone signatures are a persistent feature throughout the Ganymede magnetosphere and are particularly large and clear over the pole where Ganymede's field maximizes. Figure 4 shows a series of local pitch angle distributions obtained from four consecutive satellite spins over an ~80 s period over Ganymede's pole. The data have been normalized to the maximum intensity in each spin and are superimposed to test for their stability. Although some spreading due to time variability can be seen, the shape of the distributions is quite stable, and the loss cone signatures are clear. The slope of the loss cone edge, particularly at small pitch angles (the direction of Ganymede), is due primarily to the combination of the angular width of the detector and the satellite spin. Also, small changes in the edge of the loss cone at small pitch angle are due to the changing field magnitude at Galileo [*Williams et al.*, 1997]. The antimoon loss cone is nearly full for 15–29 keV electrons, while for 304–527 keV electrons it remains nearly empty.

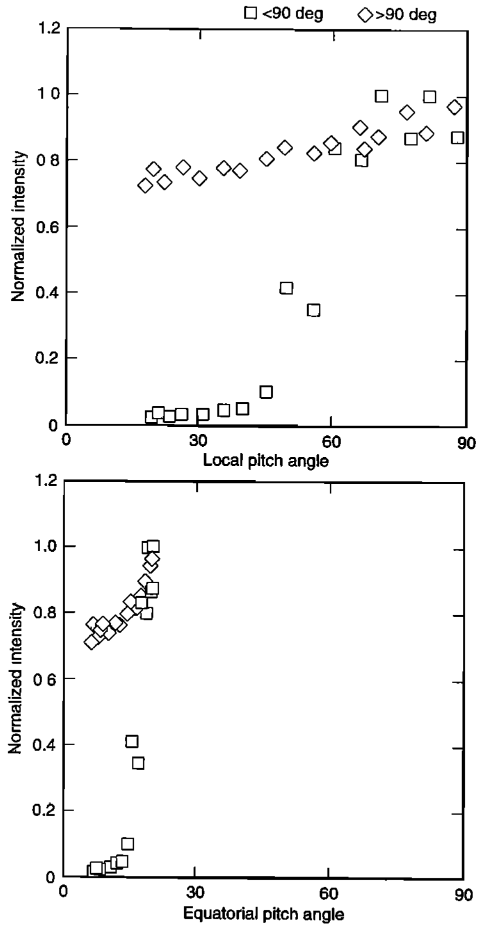

Figure 3. Example of the transformation of the local pitch angle distributions measured by Galileo at Ganymede to equatorial pitch angle distributions on Jupiter's field line. Distribution is for 15–29 keV electrons at 1901:22 hours UT. The >90° pitch angle measurements are overlaid on the <90° measurements to show the filling of the antimoon viewing loss cone. The equatorial field strength was taken to be ~118 nT, the value observed before and after encountering the Ganymede magnetosphere. Owing to Ganymede's large field strength the Galileo EPD samples but a small portion of the equatorial pitch angle distribution when over the moon's polar cap.

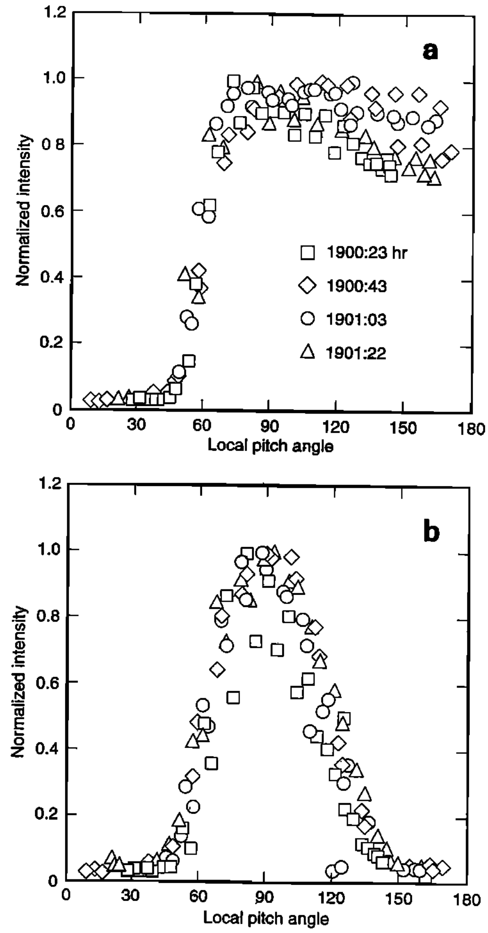

Figure 4. Stability of the electron pitch angle distributions over Ganymede's polar cap. Four consecutive satellite spins (~80 s) are shown over the polar cap near closest approach. The magnetic field magnitude at Galileo was 1133 nT, 1103 nT, 1067 nT, and 1024 nT for the times 1900:23, 1900:43, 1901:03, and 1901:22 hours UT, respectively. (a) Distributions for 15–29 keV electrons. (b) Distributions for 304–527 keV electrons. The slope of the small pitch angle portion of the distribution is due to the finite angular width of the detector. Significant filling-in of the antimoon viewing loss cone (large pitch angles) is seen at low energies, while very little filling is seen at high energies.

As discussed previously, energetic electrons will be trapped and bounce several times between Ganymede and a near-Jupiter mirror point (>8 R_J) during their drift across the Ganymede magnetosphere. As the Ganymede-viewing loss cone is reestablished every bounce, the filling-in of the antimoon loss cone must occur during the travel time to the near-Jupiter mirror point and back. This time varies from ~33 s for the lowest EPD electron channel (15–29 keV) to ~10 s for the highest (527–884 keV). Solving the diffusion equation governing pitch angle diffusion within the loss cone gives the following solution for the shape of the pitch angle distribution in the loss cone [see *Kennel*, 1969, and references therein]:

$$h(\alpha) = D_0^{-1}\{z_0^{-1} I_0(z)/I_0(z_0)\}$$

where

$$z = (\alpha^2/D_0\tau)^{1/2}$$

$$z_0 = (\alpha_0^2/D_0\tau)^{1/2}$$

where, I_0 is Bessel function of order zero, α is equatorial pitch angle, α_0 is loss cone edge, D_0 is diffusion coefficient (independent of α), and τ is scattering time. By fitting the antimoon loss cone, values of $D_0\tau$ are extracted from the data.

As discussed above, the maximum scattering time is the bounce time T_B from Ganymede to the near-Jupiter mirror point and back. From the known values of T_B and an analysis of all energy channels an estimate of D_0 and its energy dependence can be obtained. This solution is valid only within the loss cone. We determine the extent of the loss cone from observations along the field line in the direction of the moon [*Williams et al.*, 1997] and fit the solution given above within this loss cone in the antimoon viewing direction. Figure 5 presents the results of this procedure. Values of D_0T_B are given for the best fit curves shown at each energy for the antimoon loss cone.

The values of D_0T_B shown in Figure 5 describe the shape of the pitch angle distribution in the loss cone quite well and also

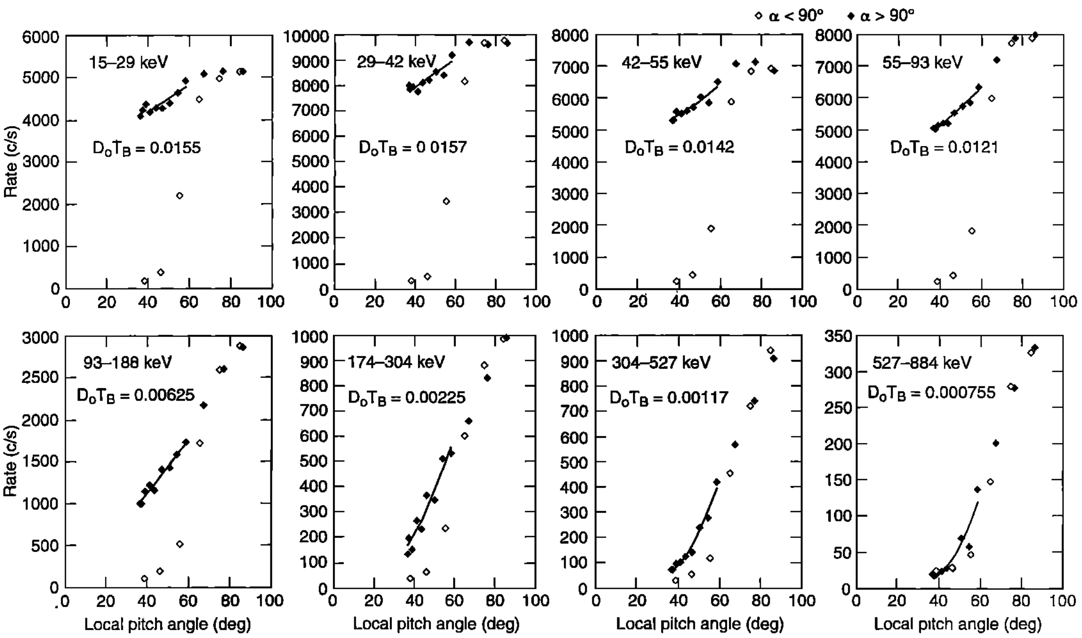

Figure 5. Fits of $h(\alpha)$ (see text) within the antimoon viewing loss cone. Electron pitch angle distributions are shown for Ganymede at 1900:23 hours UT on September 6, 1996. Extracted values of D_0T_B are shown in each energy graph.

reproduce the energy dependence of that shape. Although the energy dependence of D_0 can readily be extracted from the fits shown in Figure 5, we point out that for each energy D_0 has been assumed to be independent of α within the loss cone. Further work is required to investigate whether or not a pitch angle dependence, usually expressed in the simple form $D_0 \Rightarrow \sin^n \alpha \approx \alpha^n$ can be inferred from the data.

Figure 6 shows the energy dependence of the pitch-angle-independent diffusion coefficient D_0 both as a function of kinetic energy E and as a function of the relativistic correction factor $\gamma = (1 - v^2/c^2)^{-1/2}$, where v is the particle speed and c is the speed of light. Above the three low-energy channels, $D_0 \sim E^{-1}$ or $\sim\gamma^{-3.5}$. The relative size of the Ganymede interaction region with respect to the length of the Jovian field line makes it likely that the EPD measurements are representative of scattering distributed along the field line as opposed to scattering only at Ganymede. If D_0 is related to electromagnetic fluctuations in the following simple way [*Thorne*, 1983], $D_0 \approx (\omega_e/\gamma)\,(\Delta B/B)^2$, then the fluctuation spectrum affecting electron energies $>\sim$50 keV will vary as $\omega_e(\Delta B/B)^2 \approx \gamma^{-2.5}$. Comparisons with the Galileo plasma wave observations and modeling the wave particle interaction process along the Jupiter-Ganymede field line will help determine the amount of scattering distributed along the field line and that concentrated in the Ganymede interaction region.

The magnitudes of the diffusion coefficient shown in Figure 6 are characteristic of a weak diffusion process. This is understandable for the higher energies where the loss cone is only slightly filled in during the trip from Ganymede to the near-Jupiter mirror point and back. However, it is somewhat surprising at the lower energies where the measured portion of the loss cone is nearly filled during the transit along the field line. To see how these values compare to possible strong diffusion effects, we note that for strong diffusion, $D_0T_B/\alpha_0^2 \gg 1$, or $D_0 \gg \alpha_0^2/T_B$ [*Kennel*, 1969]. We show in Figure 6a values of α_0^2/T_B, obtained from electron half-bounce times and

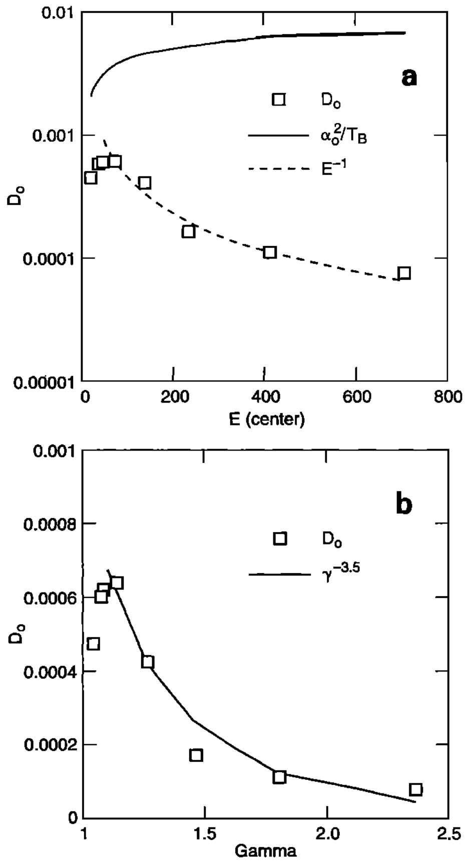

Figure 6. Variation of the diffusion coefficient D_0 with (a) energy and with (b) $\gamma = (1 - v^2/c^2)^{-1/2}$. The lines through the higher energy points are an eyeball fit to the data, giving a rough guide to the variation of D_0. The heavy line in the energy panel (Figure 6a) shows the values that D_0 must greatly exceed for strong diffusion to be operative.

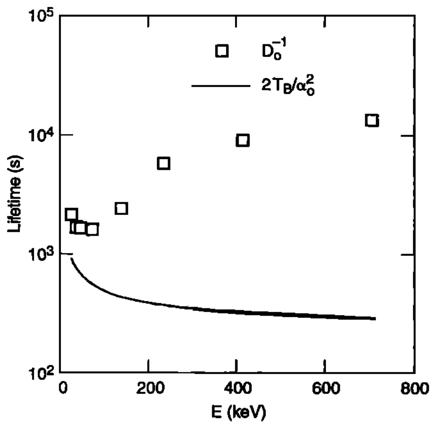

Figure 7. Electron lifetimes on the Ganymede field line, based on a weak diffusion process. The line shows minimum lifetimes expected from strong diffusion.

the equatorial loss cone edge of ~15° over the polar cap. Strong diffusion is expected at values well above this curve. The extracted values of D_0 remain well below expected strong diffusion values at all EPD energies.

Figure 7 shows particle lifetimes based on the weak diffusion limit, or $\tau \cong D_0^{-1}$, ranging from ~10^3 to 10^4 s. For comparison, minimum lifetimes expected from strong diffusion, $T_M = 2T_B/\alpha_0^2$, also are shown.

3. Summary

Ganymede offers a unique geometry for studying electron pitch angle diffusion. Owing to the absorption of particles traveling along magnetic field lines toward Ganymede, a large loss cone is established in the local pitch angle distributions observed in all EPD particle channels. Because the electrons on these field lines bounce between Ganymede and Jupiter much faster than they drift across the Ganymede system, they are trapped for several bounces between their near-Jupiter mirror point and Ganymede's magnetic field. Observations of the antimoon viewing loss cone provide a direct measure of pitch angle diffusion into the newly established loss cone over the bounce period (<~30 s). Further, the very existence of a returning loss cone in the energetic electron distributions shows that the Jovian field lines intersecting Ganymede move with the moon, at least down to altitudes defined by the edge of the loss cone (~8 R_J).

By fitting the pitch angle distributions observed within the loss cone, we have extracted values of $D_0\tau$, the product of the pitch angle independent diffusion coefficient and the scattering lifetime, and its variation with energy. The unique trapping geometry at Ganymede gives a maximum scattering time equal to the electron bounce time T_B between Ganymede and the near-Jupiter mirror point. Using these values for τ gives values for D_0 that are consistent with weak diffusion and yields lifetimes ranging from ~10^3 s at low energies to ~10^4 s at high energies. Although the loss cone distributions observed at Ganymede may be responsible for at least a portion of the observed local wave spectrum [*Gurnett et al.*, 1996], the relative amounts of time energetic electrons spend in the Ganymede system compared to the time spent on the Jovian field line indicates that the scattering most probably is distributed along the Jovian field line connecting to Ganymede. However, the relative importance of scattering along the field line and scattering in the Ganymede interaction region is not known. Comparisons with plasma wave data and modeling wave propagation and interaction effects should resolve this issue.

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