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Properties of Ganymede's magnetosphere as revealed by energetic particle observations

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Abstract. Energetic particle observations made during the Galileo satellite's close encounters with Jupiter's moon Ganymede provide a measure of many characteristics of Ganymede's magnetosphere, a magnetosphere larger than that of Mercury. Changes in energetic ion anisotropy signatures, caused by Jupiter's corotating magnetic field, show that Ganymede's magnetosphere significantly slows down the ambient nearly corotating Jovian plasma. The data further indicate that this convection slowdown apparently extends at least several Jupiter radii away from Ganymede along Jovian field lines connected to the moon. The locations of these anisotropy signature changes occur at the locations of magnetometer and plasma wave magnetopause identifications that match surprisingly well the predictions of a simple model comprised of an intrinsic dipole field superimposed on Jupiter's ambient field. Loss cones measured throughout Ganymede's magnetosphere provide a quantitative estimate of the moon's surface magnetic field along the subsatellite track that agrees well with model field predictions and provides verification of Ganymede's intrinsic magnetic field. On Jovian field lines connected to Ganymede, electrons are trapped between the moon and a near-Jupiter mirror point for several bounces as they convect across Ganymede's magnetosphere. This unique geometry allows a measurement of the amount of electron pitch angle scattering occurring in a single bounce between the Ganymede and near-Jupiter mirror points. The energy-dependent pitch angle diffusion coefficient and scattering lifetimes have been extracted from these observations. The consistency of these results from encounter to encounter demonstrates the stability of these processes, at least over the several month interval between encounters. Evidence for loss cone signatures established one Jovian rotation (~10 hours) earlier indicates that the entire Jovian L shell region traversed by Ganymede provides an electron scattering environment similar to that measured on Jupiter-Ganymede field lines. Measurements from Galileo's last close encounter with Ganymede show electron pitch angle distributions characteristic of particles trapped on closed magnetic field lines in a distorted magnetospheric configuration. Thus with its distorted magnetic field and apparent radiation belt, Ganymede takes its place as a unique member of the solar system family of magnetospheres.

1. Introduction

During its orbital tour of the Jovian magnetosphere, the NASA Galileo satellite performed four close flybys of the moon Ganymede. Data from these encounters have provided many surprises including the discovery, verification, and initial studies of Ganymede's magnetic field, its magnetosphere, its trapped particle populations, and its interaction with the Jovian environment [*Gurnett et al.*, 1996; *Kivelson et al.*, 1996, 1997; *Frank et al.*, 1997; *Williams et al.*, 1997a, b; *Williams and Mauk*, 1997]. In a recent report, *Kivelson et al.* [1998] present an overview of magnetometer measurements and results from the four Ganymede encounters. In this report we summarize results from the Galileo energetic particles detector (EPD), present new data and results that corroborate earlier results, and present new features of Ganymede's environment and its interaction with Jupiter's corotating magnetic field and particle populations. The new results provide a measure of the stability of the Ganymede-Jovian magnetosphere interaction, show that energetic particle signatures stemming from this interaction extend at least 10 hours in duration (360° in longitude), and indicate that the slowing down of the Jovian plasma extends at least several Jovian radii along the Ganymede flux tube.

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Charged particle observations from Voyager 2 provided the initial indication of Ganymede's effect on Jovian particle populations [*Bridge et al.*, 1979; *Krimigis et al.*, 1979; *Vogt et al.*, 1979]. Plasma dropouts and enhanced energetic particle activity were observed for a several hour interval surrounding the closest approach of Voyager 2 to Ganymede, a wakeside passage some 17 R_G downstream of and 18 R_G below Ganymede's orbital plane. While these results clearly showed effects most likely caused by Ganymede's interaction with the corotating Jovian plasma and energetic particle populations, the large flyby distance precluded a detailed investigation of the cause of those effects. In addition, recent results (*Mauk et al.*, 1997) show that some of the enhanced energetic particle activity may have been due to transient, time-dispersed particle injection events that are common in this region of Jupiter's magnetosphere. The present Galileo results, because of the closeness and geometry of the flybys, greatly extend the Voyager results and provide an opportunity to study details of Ganymede's interaction with the Jovian particle populations.

The EPD measures the spectral and angular distributions of ions above 20 keV, electrons above 15 keV, and elemental species from

Table 1. Galileo EPD Ganymede Encounters

Encounter	Date	Time of Closest Approach, UTC	Closest Approach Altitude, km	Encounter Geometry
G2	Sept. 6, 1996	1900	262	polar
G7	April 5, 1997	0710	3095	wake
G8	May 7, 1997	1557	1596	upstream

protons through iron above approximately 10 keV/nucleon (*Williams et al.*, 1992). The EPD's two bidirectional detector heads are mounted on a stepper platform. Platform motion combined with satellite spin allows the detector heads to view up to a full 4π steradian sample of the sky. The Ganymede encounters are labeled G1, G2, G7, and G8 according to the orbit in which they occurred. Because of an onboard software problem the EPD was shut down and did not operate during the G1 encounter. The problem was fixed, and the EPD has since operated normally. Results from each Ganymede encounter (including G1 [*Gurnett et al.*, 1996; *Kivelson et al.*, 1996]), have been used in determining the EPD stepping sequence for the subsequent encounter. This has proven to be an important factor in obtaining sufficient pitch angle coverage to determine many of the characteristics of the Ganymede magnetosphere.

2. The Encounters

Table 1 presents a general description of the encounters during which EPD operated, i.e., G2, G7, and G8. On the basis of the magnetic field results from the G1 encounter [*Kivelson et al.*, 1996] the EPD was programmed for G2 in a three-step sequence designed to maximize the pitch angle coverage and minimize the time required for that coverage. For the G7 encounter the full 4π scan was used including a step behind the background/calibration shield after each scan. The G8 encounter used the same sequence as G7 with a background check only at the start of the encounter.

Figures 1 [after *Williams et al.*, 1997a], 2, and 3 present data for each of these encounters. The panels in each figure show the highest time resolution data obtained through the encounter as the EPD rotates according to the combination of its platform motion

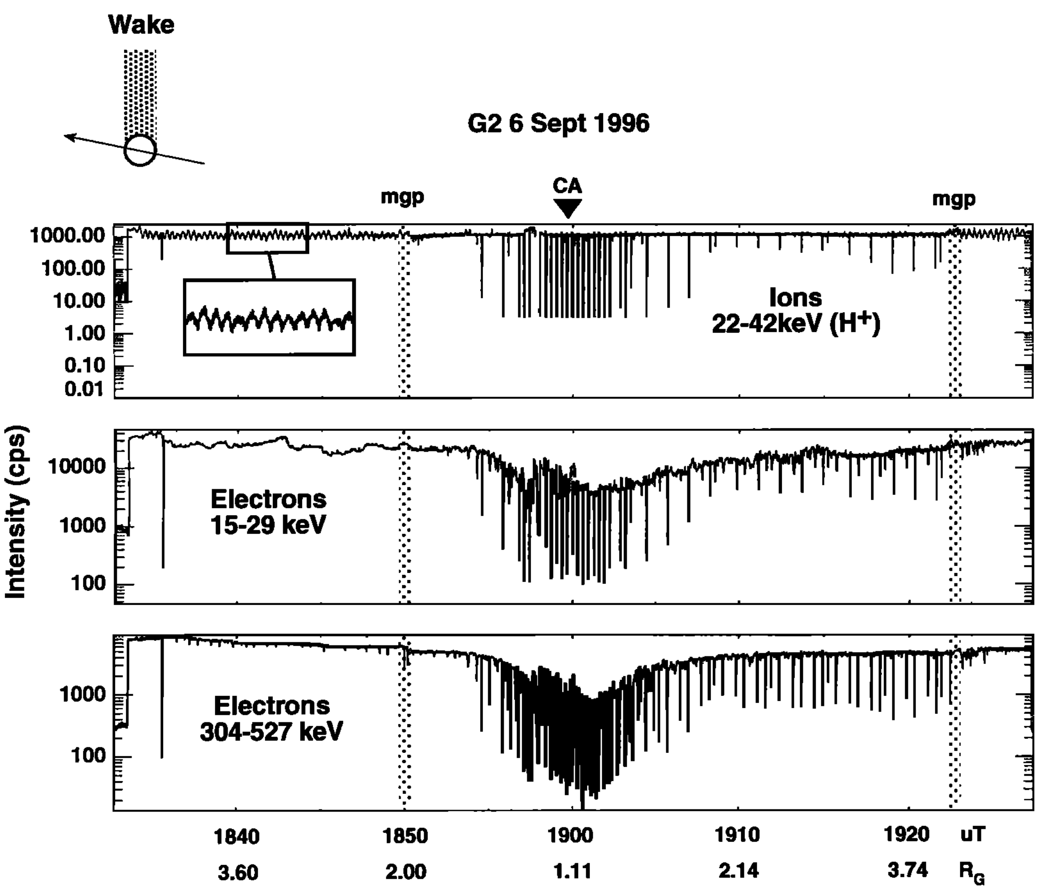

Figure 1. Energetic ion and electron intensities during the Galileo satellite's G2 encounter with Ganymede. The data shown are representative of the observations from all EPD ion, species, and electron channels. Magnetometer magnetopause locations are shown at the top of the figure, and the geometry of the encounter projected into Jupiter's corotation plane is given in the upper left portion of the figure. Spin modulation of the ion intensities (shown amplified in the insert) due to corotational convective flow anisotropies is seen prior to entry into Ganymede's magnetosphere and following exit. The spike-like decreases within Ganymede's magnetosphere are loss cone signatures.

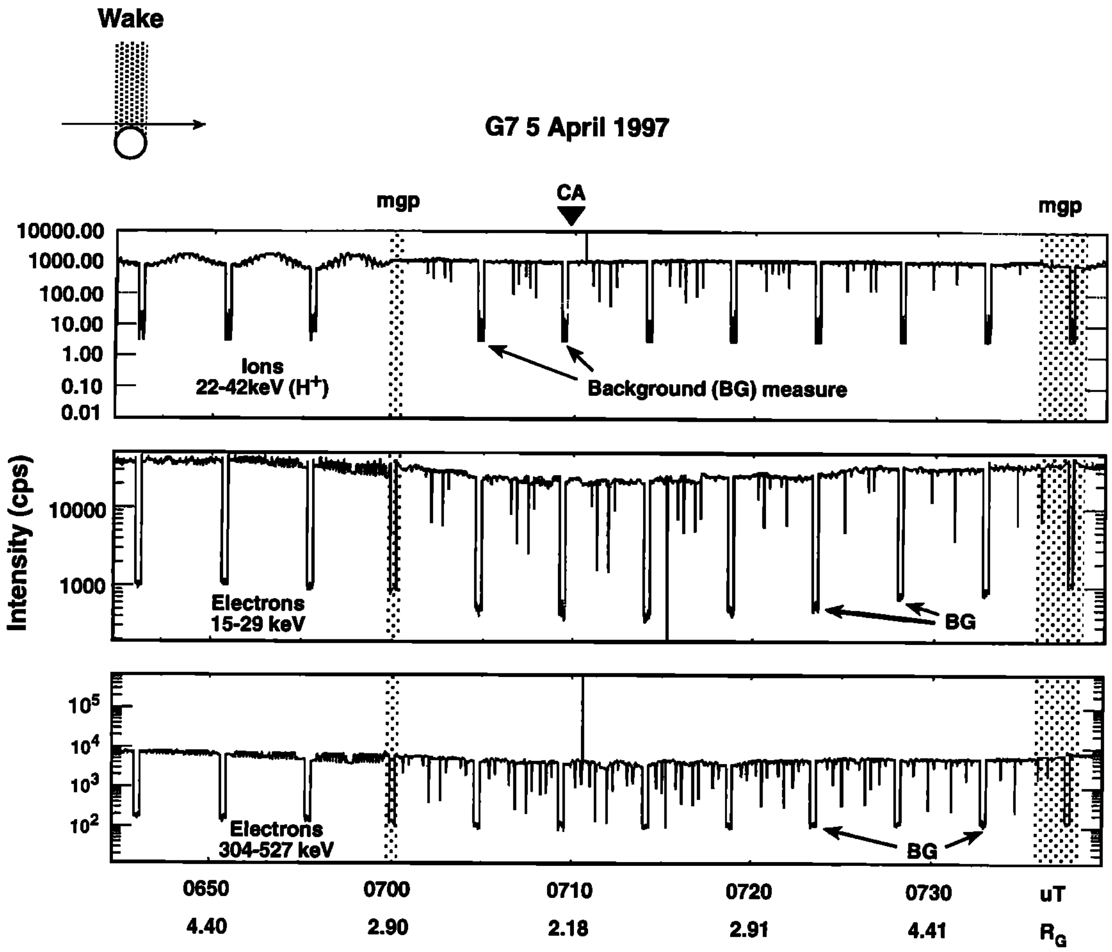

Figure 2. The Galileo G7 encounter in the same format as Figure 1. The different perspective results from both the different encounter geometry and the different stepper motor sequence used for EPD during the encounter. Background measurements are identified. The data show similar corotational convective flow anisotropy changes and loss cone signatures as are seen in the G2 encounter.

and satellite spin. The ion and electron intensities shown represent well the overall response of all EPD channels. The time of closest approach and Ganymede magnetopause determinations from the magnetometer data [*Kivelson et al.*, 1998] are shown for each encounter. A schematic of the encounter geometry is shown in the upper left of each figure.

Figure 1 shows data from the G2 encounter, a polar pass at a closest approach altitude of 262 km. A measurement taken behind the background shield is seen at the beginning of the pass. A striking feature characterizing the ion data is the pronounced decrease in observed convective flow anisotropies, due to Jupiter's corotating magnetic field, when within Ganymede's magnetosphere (~1850–1923 UT). Anisotropies observed in ion (and elemental species) distributions outside Ganymede's magnetosphere give convective flow speeds perpendicular to **B** of approximately 150 km/s in Galileo's (or effectively Ganymede's) frame of reference, a magnitude ~85% of full corotation. Within Ganymede's magnetosphere, anisotropies are very small and upper limits to energetic ion convective flow estimates range from ~25 km/s (near closest approach) to ~45 km/s (near the magnetopause). The positions where the flow transitions occur (e.g., where the ion anisotropies show a pronounced decrease as in Figure 1) agree well with the magnetopause positions identified by the magnetometer [*Kivelson et al.*, 1998] and the plasma wave detector (D. A. Gurnett, personal communication, 1996).

A second dramatic feature seen in the G2 data of Figure 1 is the series of spike-like decreases observed for all ion and electron channels when within Ganymede's magnetosphere. *Williams et al.* [1997a] show these to be loss cone signatures caused by particle impact on and absorption by the moon. All ion channels display a clear loss cone when EPD views along the field line toward the moon and full loss cones when viewing along the field in the anti-moon direction. Electrons also display clear loss cones in the direction toward the moon. However in the anti-moon direction, electron loss cones evolve from nearly full at low energies to nearly empty at high energies. These electron loss cone signatures have provided a unique measure of the pitch angle diffusion coefficient on field lines connecting Ganymede and Jupiter [*Williams and Mauk*, 1997] and will be discussed in a later section.

Although the encounter geometry plus the EPD motor stepping sequence provide quite different perspectives of the Ganymede system for each of the encounters, all the main features seen in the G2 encounter (Figure 1) are seen in G7 and G8 (Figures 2 and 3). Figure 2 (G7; EPD in full scan including a background measurement) shows clearly the ion convective flow anisotropy signature when outside Ganymede's magnetosphere and the greatly decreased

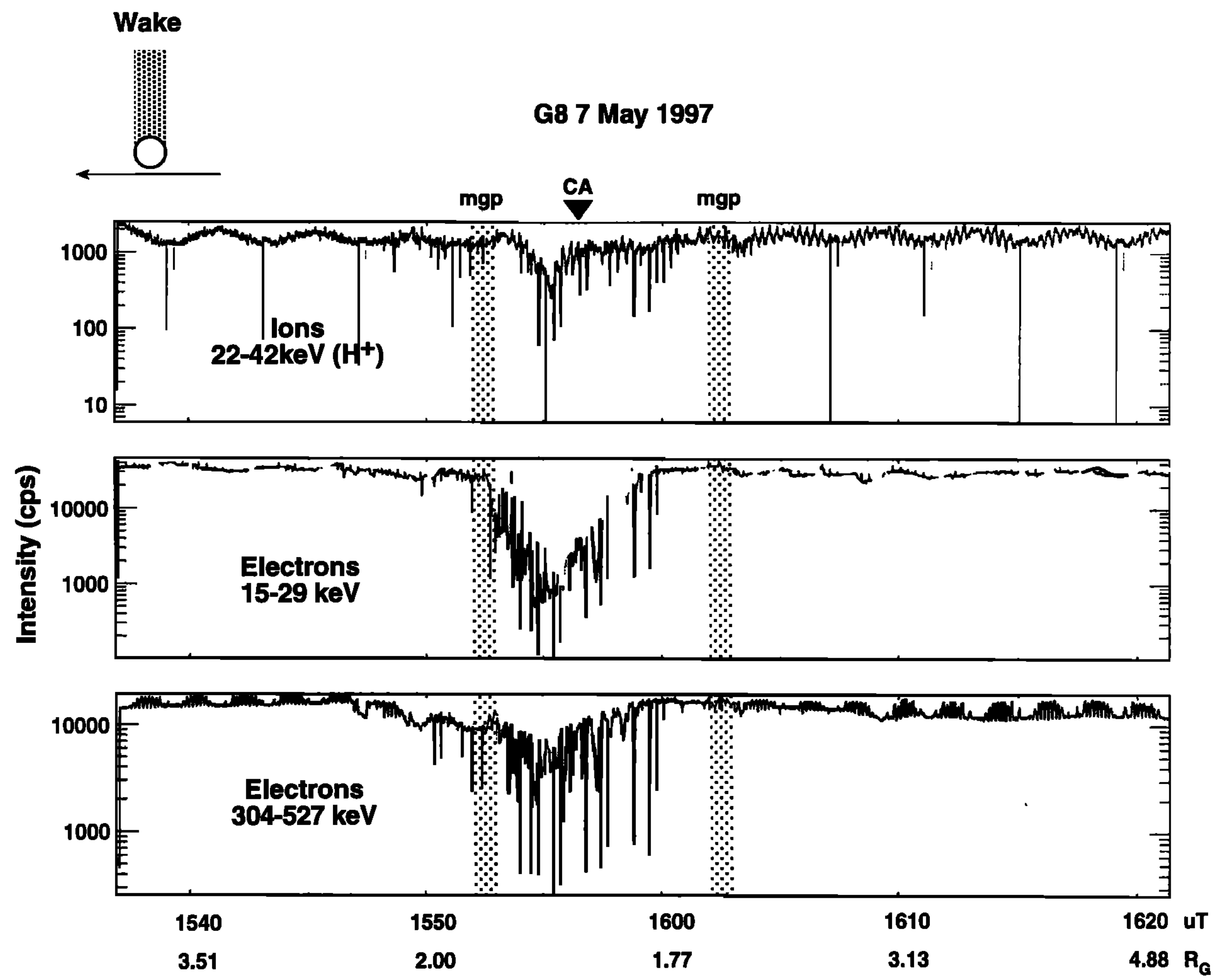

Figure 3. The Galileo G8 encounter in the same format as Figure 1. Again, the corotational convective flow anisotropy changes and loss cone signatures are similar to those seen in Figures 1 and 2. However, for the G8 encounter, ion intensities show a substantial decrease within Ganymede's magnetosphere in contrast to the G2 and G8 encounters. Also, electron intensities decrease much more in G8 than in G2 or G7. This indicates that the region of the Ganymede magnetosphere entered in G8 provided a higher degree of shielding from the ambient Jovian environment.

signature inside (the convective anisotropy is revealed in this encounter by the broad intensity peaks between each background sample). Also, when within Ganymede's magnetosphere we see again the spike-like decreases (in evidence between the background samples) caused by loss cone structures measured when EPD views along the magnetic field. Figure 3 (G8; EPD in full scan with background check only at the beginning of the pass) shows similar effects: ion convective flow decrease and loss cone signatures within Ganymede's magnetosphere. However, for this upstream pass, electrons show a substantially larger decrease than observed during G2 and G7 and, also unlike these previous encounters, ions show an overall intensity decrease within Ganymede's magnetopshere.

3. Pitch Angle Distributions

We now present details of measured electron pitch angle distributions within Ganymede's magnetosphere for each of the encounters. These distributions highlight the existence and strength of Ganymede's magnetic field, the stability and particle trapping capability of its magnetosphere, and the effects of scattering on Jovian field lines intersecting Ganymede. We use electron distributions for these analyses because their small gyroradii (<~25 km for <1 MeV electrons and $B > 200$ nT) make them an excellent fine scale probe of Ganymede's magnetic field configuration. Although the ion pitch angle distributions are qualitatively similar to those of the electrons, their large gyroradii (at least ~40 times as large as the same energy electron) require particle trajectory calculations to correct for finite gyroradius effects.

Figure 4 presents pitch angle distributions measured within Ganymede's magnetosphere for the G2, G7, and G8 encounters. We construct each set of pitch angle distributions from four satellite spins, a time interval of ~80 s. Although intensity variations occur over this time interval, the main features of the distributions are clear. The bottom panel shows Galileo's trajectory through a model of Ganymede's magnetic field configuration (J. Warnecke, personal communication, 1997) developed from G1 magnetometer results [*Kivelson et al.*, 1996]. The configuration shown is a simple vacuum superposition of a Ganymede dipole field on the ambient Jovian field. While this configuration is recognized to be an oversimplification in the sense of not including other magnetic field sources, the model does provide a very useful guide to visualizing

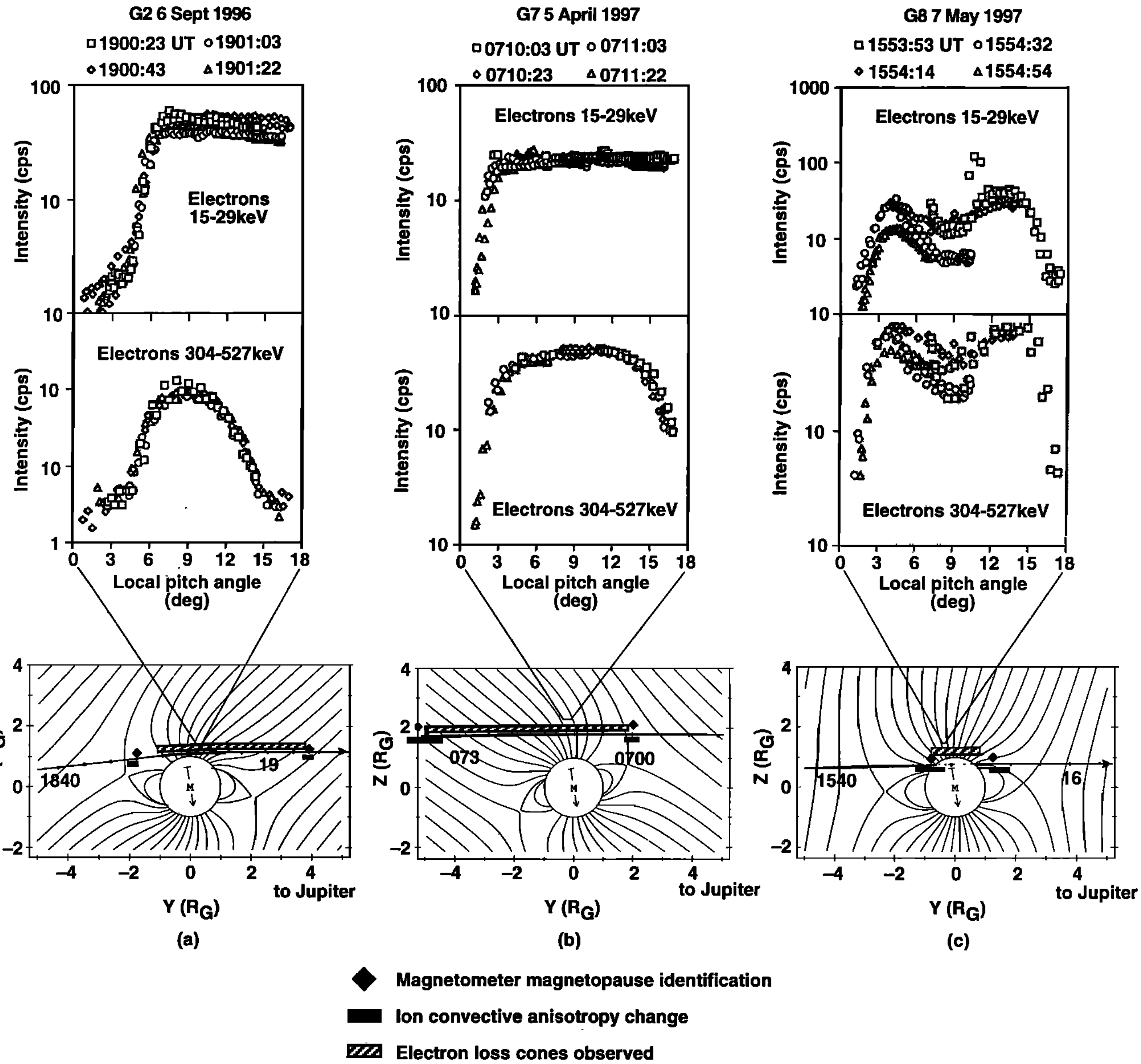

Figure 4. Local pitch angle distributions measured by EPD during the (a) G2, (b) G7, and (c) G8 encounters. The top two rows of panels show the pitch angle distributions of 15–29 keV and 304–527 keV electrons, respectively. The distributions are constructed from four satellite spins (~80 s). The bottom row shows the Galileo trajectory for each encounter through the Ganymede magnetic field as represented by the simple dipole model developed from the G1 encounter. The corotational flow direction is out of the plane of the figure. Magnetometer magnetopause identifications and the locations of ion anisotropy changes and electron loss cone observations also are shown.

observational positions in the Ganymede system. In fact, it does surprisingly well in identifying various boundaries of the system, such as the boundary between Jovian field lines and those connecting Jupiter and Ganymede (the magnetopause).

The coordinate system used in the bottom panels of Figure 4 is Ganymede centered with X along the direction of corotation, Y pointing toward Jupiter, and Z along the moon's spin axis. The view in all panels is from the wake looking at the moon. The panels also show the magnetometer identifications of the magnetopause [*Kivelson et al.*, 1998], the time over which the EPD ion convective flow anisotropy changed (Figures 1, 2, and 3), the region where EPD directly measured loss cone structures, and the location of the pitch angle distributions shown in the panels above.

In Figure 4, the region in Ganymede's magnetosphere where EPD observed electron loss cones during the G7 encounter extended from the magnetopause encountered at entrance to that encountered at exit. The lack of loss cone measurements just after magnetosphere entry at G2 and just prior to exit at G8 is due to the fact that EPD did not sample along the field lines during these intervals. Therefore the EPD data are consistent with all high-latitude field lines within Ganymede's magnetosphere, including those at or very near the magnetopause, being connected to both

Jupiter and Ganymede. We note that all loss cones measured by EPD during the Ganymede encounters are much larger than those expected from interactions with Jupiter's atmosphere (at this altitude, <~1°) and are thus interpreted as being due to absorption by the moon.

Figure 4a shows data from the G2 encounter, a polar pass at a closest approach altitude of 262 km. *Williams et al.* [1997a] report loss cone measurements throughout the loss cone region shown in Figure 4a. They use the size of the electron loss cones obtained when looking along the field line in the direction of Ganymede and the measured magnetic field to obtain an estimate of Ganymede's surface magnetic field along Galileo's subsatellite track. The results agree well with extrapolations of the Ganymede magnetic field model developed from the magnetometer observations [*Kivelson et al.*, 1996]. We conclude that this measurement of Ganymede's surface magnetic field using EPD electron loss cone determinations provides verification of its intrinsic field [*Kivelson et al.*, 1996; *Gurnett et al.*, 1996].

All energetic particle channels showed empty loss cones during the G2 encounter when EPD viewed along the magnetic field toward Ganymede. However, in the anti-moon direction, electrons displayed nearly full loss cones at low energies that evolved to empty loss cones at high energies (Figure 4a). *Williams and Mauk* [1997] noted that energetic electron bounce times between Ganymede and their near-Jupiter mirror point are much smaller than the drift times across the Ganymede magnetosphere. This allows energetic electrons to be trapped for several bounces between Ganymede and Jupiter as they drift across the system. Using this unique geometry, *Williams and Mauk* [1997] determined the amount of pitch angle scattering occurring during one bounce, and from that determination estimated the magnitude of the energy-dependent pitch angle diffusion coefficient D_0 on these Ganymede-Jupiter field lines. The magnitude of D_0 is consistent with weak pitch angle diffusion and gives scattering lifetimes ranging from ~2×10^3 s at ~22 keV to ~1.5×10^4 s at ~705 keV.

All ion channels (not shown) on the other hand display full loss cones in the anti-moon direction. This can be explained in terms of the very long ion bounce times with respect to the drift time through the Ganymede system. The anti-moon loss cones are supplied by ions drifting onto these field lines from the ambient, nearly corotating Jovian environment.

Figure 4b shows data from the G7 encounter, a wake pass at a closest approach altitude of 3095 km. These data show characteristics similar to those seen at G2 (Figure 4a), clear loss cone signatures in the direction of the moon and electron loss cones in the anti-moon direction that evolve from full at low energies to nearly empty at high energies. Again all ion channels show full loss cones in the anti-moon direction. The loss cones measured near the G7 closest approach are smaller than those measured near the G2 closest approach by an amount consistent with the smaller local magnetic field encountered by Galileo during G7. These G7 data fully support the EPD results reported from G2 [*Williams et al.*, 1997a; *Williams and Mauk*, 1997] and indicate that Ganymede's magnetospheric configuration and processes acting on field lines connecting it to Jupiter remained stable for at least the 8-month period between the G2 and G7 encounters.

Figure 4c shows data from the G8 encounter, an upstream pass at a closest approach altitude of 1596 km. The pitch angle distributions differ from those measured during G2 and G7. The distributions measured in Ganymede's upstream magnetosphere have loss cone signatures near 0° and 180° pitch angles at all energies and an intensity decrease near 90°, thereby forming a "butterfly" distribution. *Williams et al.* [1997b] have interpreted these double loss cone, butterfly distributions as representative of electrons trapped on closed magnetic field lines in a distorted Ganymede magnetosphere. During the interval when these distributions were observed, the Z component of the magnetic field changed sign and the X component became dominant [*Kivelson et al.*, 1998]. These changes are consistent with Galileo entering a region of closed Ganymede field lines and support the trapped electron interpretation for the electron distributions. If as at Earth, the source location is in the downstream Ganymede hemisphere, the electrons observed by EPD on upstream closed field lines must drift through ~180° local Ganymede time. Shell-splitting effects associated with that drift in a distorted magnetic configuration can explain the double loss cone, butterfly distributions observed at Galileo's location.

4. Extended Interaction Signatures

It is of interest to learn how far downstream of the interaction region the electron loss cone signatures extend and whether the result is consistent with the pitch angle scattering lifetimes measured in Ganymede's magnetosphere [*Williams and Mauk*, 1997]. Plate 1 adapted from *Williams et al.* (1997a) shows an overview of EPD pitch angle distributions measured during the G2 encounter. All data are color-coded in a satellite spin sector versus time grid. The three panels show from top to bottom the pitch angles measured, 15–29 keV electron intensities, and 304–527 keV electron intensities. The distinctive double loss cone structure at 304–527 keV and the single clear loss cone at 15–29 keV are prominent within Ganymede's magnetosphere. A close inspection of the time prior to entry into Ganymede's magnetosphere (prior to 1850 UT) shows indications of remnant loss cone structures in the 304–527 keV electron intensities (Figure 1 shows a hint of such remnant loss cones with the very small downward intensity spikes seen prior to entering Ganymede's magnetosphere). If generated by Ganymede they would have been created approximately 10 hours earlier, the time it takes the particles to convect around Jupiter and arrive again in the vicinity of Ganymede. No such structures are observed in the 15–29 keV electron intensities.

Figure 5 shows pitch angle distributions typical of those seen prior to entry into Ganymede's magnetosphere at ~1850 UT during the G2 encounter. These distributions comprise several satellite spins in order to cover the full pitch angle range available. They are therefore subject to time aliasing. However the general features of the distributions remain clear. Figure 5a shows that at electron energies of 15–29 keV there is no discernible feature at pitch angles of less than ~30° and greater than ~150° that can be associated with an interaction with Ganymede. However, at 304–527 keV a slight intensity decrease can be seen at those pitch angles, quantifying the display presented in Plate 1. Figure 5b is a linear plot of the 304–527 keV electron intensities and shows a remnant loss cone signature consistent in size with that expected from an interaction with Ganymede.

We conclude that the slight intensity decreases observed along the magnetic field line prior to entry into Ganymede's magnetosphere are remnant loss cones caused by the energetic particle population's interaction with Ganymede one Jovian rotation (~10 hours) ago. The angular extent of these loss cone signatures is consistent with Ganymede absorption. The fact that they are seen only at high energies is consistent with the energy dependence of the pitch angle diffusion coefficient found by *Williams and Mauk* [1997] in the vicinity of Ganymede. One Jupiter rotation represents ~20 scattering lifetimes for low-energy electrons and is consistent with the observation of no remnant loss cone structures. At high energies however, one Jupiter rotation represents ~2.5 scattering

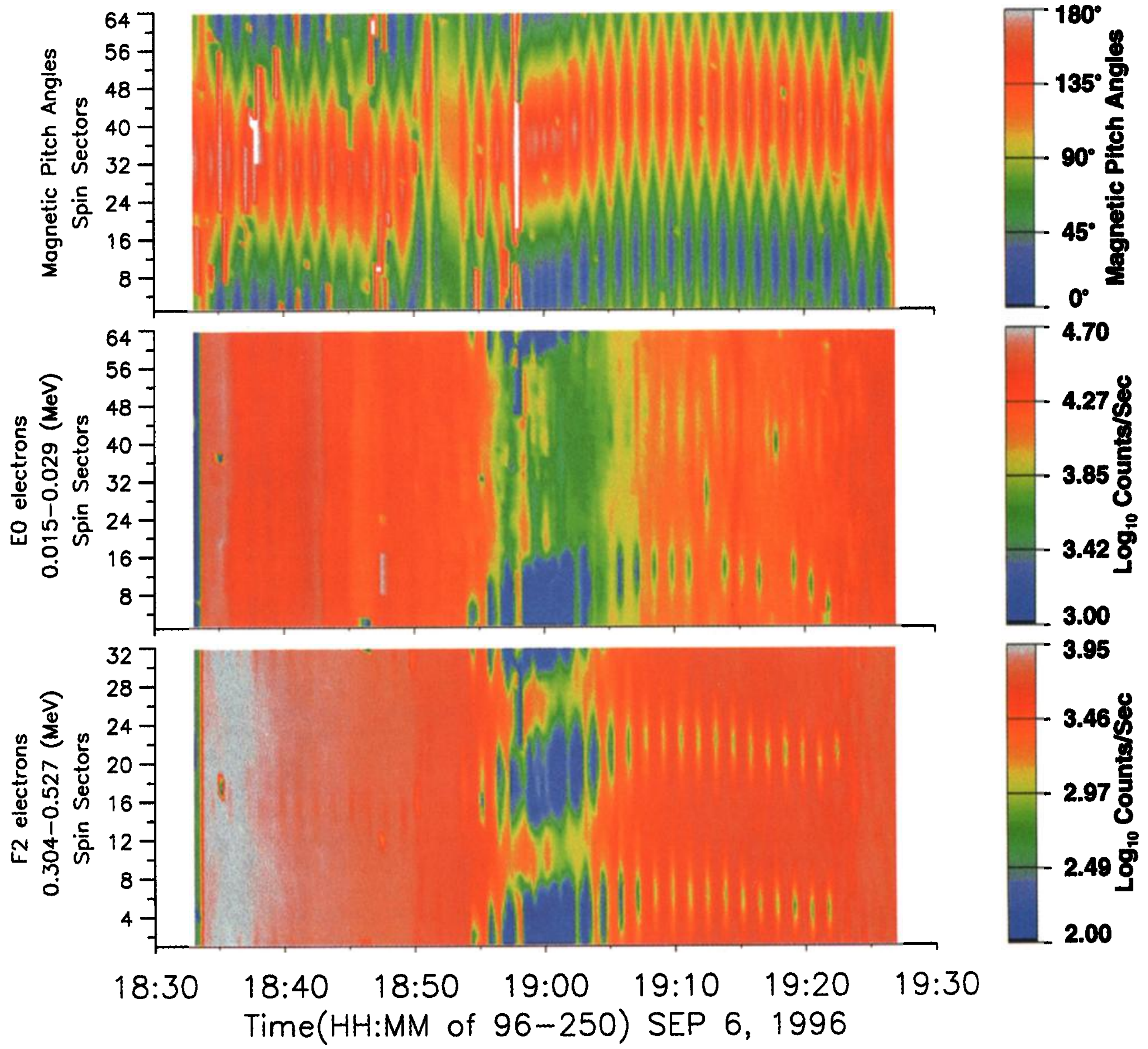

Plate 1. Measured pitch angles and electron intensities during the G2 encounter are shown on a satellite spin sector versus time grid. Shown from top to bottom are sampled pitch angles (64 samples per spin), 15–29 keV electrons (64 samples per spin), and 304–527 keV electrons (32 samples per spin). The pitch angle sampling sequence is a result of the EPD motor stepping sequence used for the encounter. Electron loss cone signatures are clear within Ganymede's magnetosphere, ~1850–1923 hours. Of interest here are the faint loss cone structures seen in the 304–527 keV electron distributions prior to entry into Ganymede's magnetosphere (i.e., prior to 1850 hours).

lifetimes and is consistent with the observation of barely observable remnant loss cones.

Williams and Mauk [1997] inferred that the scattering process was distributed along Jovian field lines. The present results indicate that the scattering remains distributed along corotating Jovian field lines and that the entire Ganymede *L* shell region should be scattering electrons in a weak pitch angle diffusion mode.

5. Extent of the Ganymede Flow Interaction Region Along the Ganymede Flux Tube

A key question involving Ganymede's interaction with its surrounding environment is: how far away from Ganymede, along those Jovian field lines that, for a time, connect directly to Ganymede, is the plasma flow substantially depressed in comparison with the surrounding plasmas (flowing at nearly corotational speeds)? A critical aspect of the observed flow depression close to Ganymede is that it occurs suddenly at a position where there is no corresponding strong change in the magnetic field strength (see Figure 1 of *Williams et al.* [1997a] and Figure 1 of *Kivelson et al.* [1997]). Thus the sudden flow depression cannot be explained on the basis of a classic linear MHD Alfvén wing-type interaction. With an MHD Alfvén wing, the flow depression occurs in association with a magnetic field change, moderated by a standing Alfvén wave (see, for example, Figure 10.3 of *Hill et al.* [1983]). With the Ganymede interaction, the flow depression must occur predominantly by a depression in the perpendicular electric field within the Ganymedian magnetosphere.

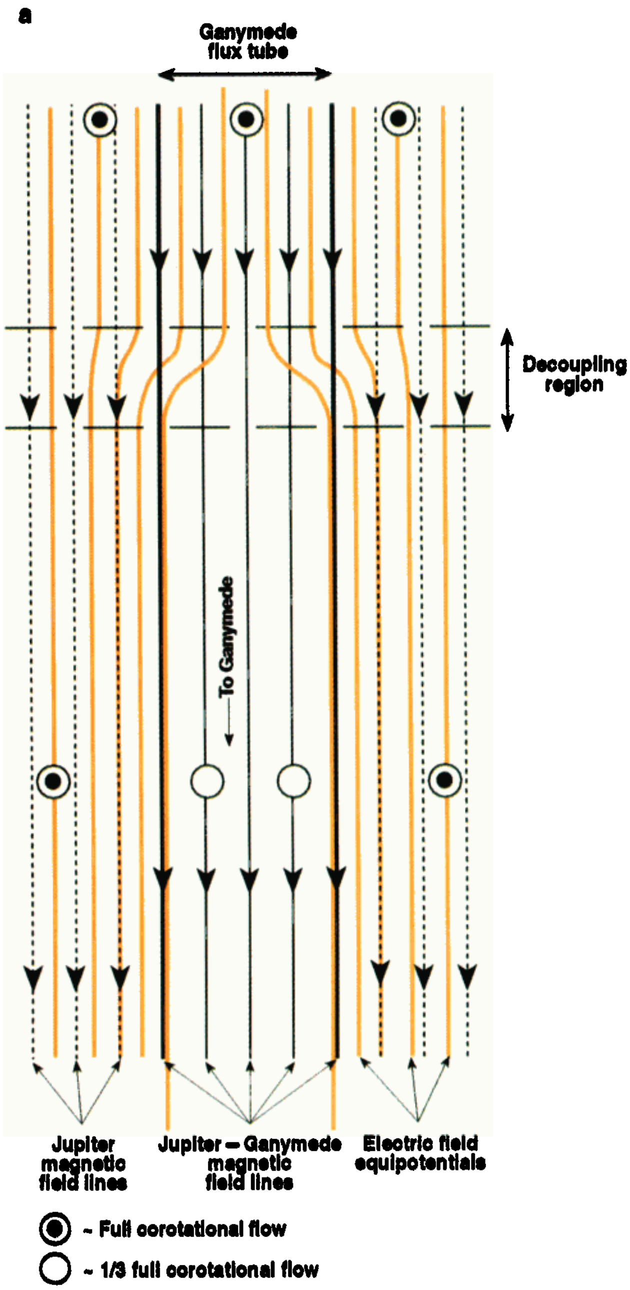

Plate 2. (a) Schematic of region decoupling nearly full and partial corotational flow in the Ganymede flux tube. Flow is out of the plane of the figure. Energetic particle data indicate that the decoupling region is several Jupiter radii away from Ganymede along the moon's flux tube. (b) Sketch of the encounter geometry in a plane within the depressed flow region and perpendicular to that shown in Plate 2a. The magnetic field is into the plane of the figure. The geometry of Galileo's trajectory qualitatively explains the overall shape of the energetic electron intensity decrease observed throughout the encounter.

The question now becomes: how far along the Ganymedian flux tube does the electric field remain depressed. If the depressed field region does not extend all the way to Jupiter, in the absence of an encounter with a high-density reflecting boundary, there must be a magnetic field aligned electric field at some position along the flux tube that decouples the nearly corotational flows far from Ganymede from the depressed flows close to Ganymede. Plate 2 shows a greatly simplified schematic of this situation. Plate 2a shows a cut along the Ganymede flux tube perpendicular to the direction of corotation (which is out of the plane of the plate), illustrating the decoupling region. Plate 2b shows a projection in a plane perpendicular to Plate 2a and located within the depressed flow region (below the decoupling region shown in Plate 2a) and above Ganymede's polar cap. We have configured the sketch so that most of the parallel electric field in Plate 2a occurs within a relatively narrow decoupling region. Although this need not be the case, Plate 2 does provide a simplified geometry for explaining energetic particle signatures and estimating the distance to such a decoupling region. The total parallel potential drop, based on the Plate 2a configuration and the flow and field parameters involved (118 nT, 150 km/s), would have to be ~ ±95 kV (sign dependent on the appropriate region in the figure) for the observed factor of ~3 depression in the flow speed (Figure 1).

The energetic ion data show that the parallel decoupling electric field region, if it exists, cannot be close to Ganymede. The low-energy ion channels would be very perturbed by such a potential, both in terms of intensity and pitch angle structure. The top panel of Figure 1 and detailed plots of pitch angle distributions (not shown) show that the low-energy ions are almost unaffected when the flow depression region is entered. These ion observations can be explained if the parallel decoupling electric field is moved some distance away from Ganymede. In this way the ions can flow into the Ganymedian flux tube in the portion of the flux tube between Ganymede and the decoupling region. A comparison of the flow transit times and ion bounce times indicates that the decoupling region must be at least several Jovian radii away from Ganymede to explain the ion characteristics.

Consistent with the indications from the ion data, electron data suggest that the decoupling region must occupy a region that is essentially at or beyond the near-Jupiter mirror point of the locally observed charged particles, shown by *Williams and Mauk* [1997] to be ~8 R_J from the center of Jupiter along the Jupiter-Ganymede field line. Evidence for this stems from the general depression in electron fluxes seen at closest approach (Figure 1). The electron

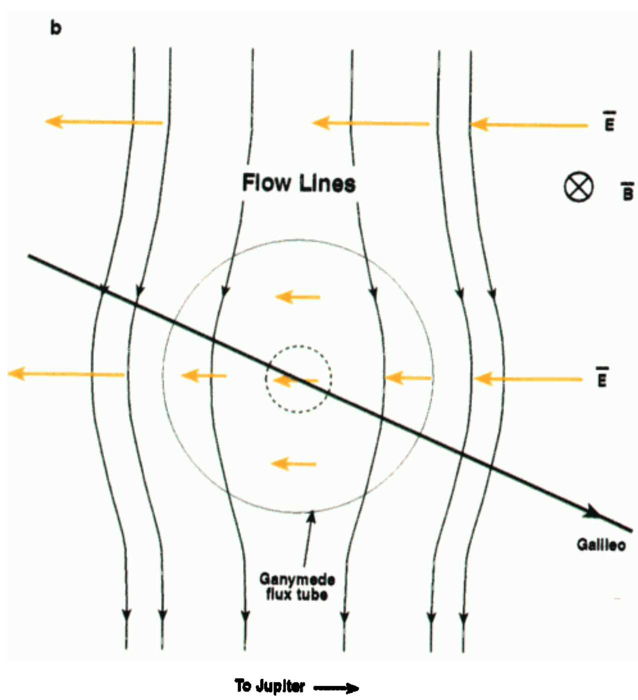

Plate 2. (continued)

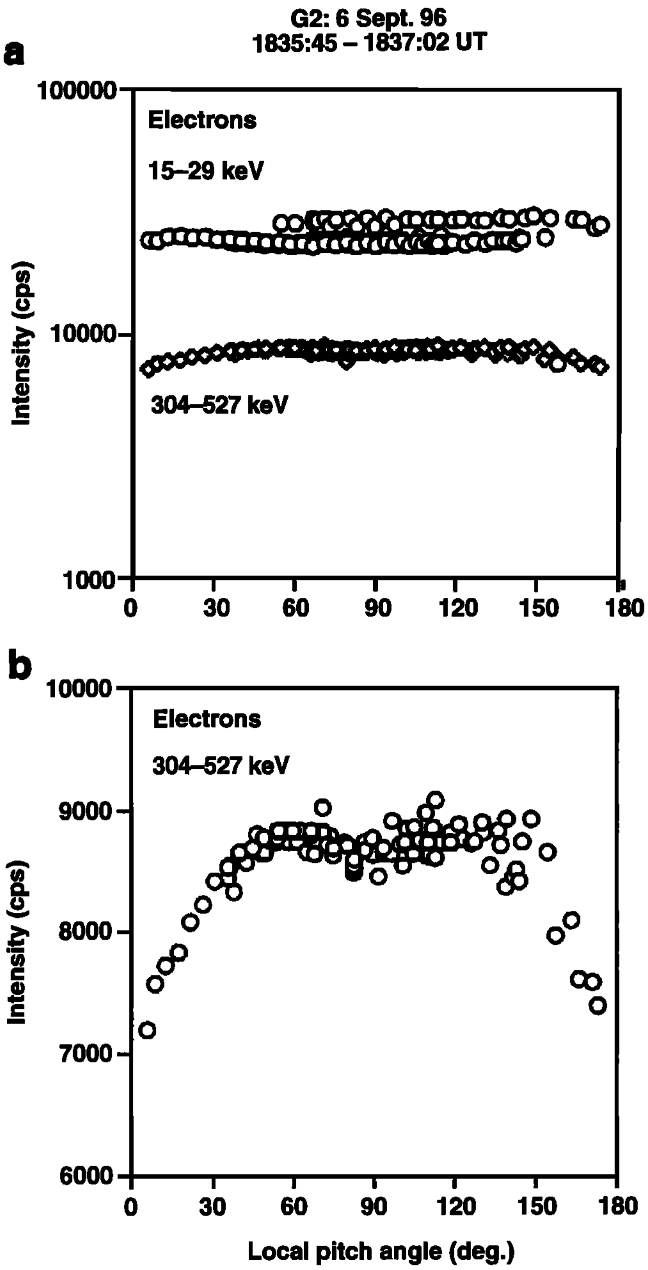

Figure 5. (a) Sample of electron pitch angle distributions measured prior to entry into Ganymede's magnetosphere during the G2 encounter. (b) Linear plot of the 304–527 keV electron distribution showing the remnant loss cone signature.

pitch angle distributions in the ambient Jovian environment (outside of Ganymede's magnetosphere) are isotropic for the low-energy electrons (15–29 keV) measured by EPD. Quantitative analysis shows that the losses observed through the encounter cannot be explained by the adiabatic transformation of Jovian distributions from the weak ambient magnetic field region (~110 nT) to the strong field region (~1200 nT) in close vicinity to Ganymede. As an example, Figure 6 shows that if the ambient distribution has a $\sin^n\alpha$ shape, where α is the local pitch angle, a factor of 4 depression in ~90° fluxes can be explained if n ~ 1.1 However, in that situation, within the ambient medium the ratio I[90°]/I[10°] would be ~7. Such a ratio is not observed.

We conclude that the overall depression in the electron fluxes is caused by electron losses through impact with Ganymede followed by scattering into the newly created loss cone as the electrons travel to their near-Jupiter mirror point and back [*Williams and Mauk*, 1997]. At the closest approach position during G2, the loss cone associated with Ganymede was ~57°. The fraction of total solid angle that this one-sided loss cone represents is ~0.22. If the low-energy electrons are isotropized during their bounce transit between Ganymede and Jupiter, then ~22% of the electrons observed by Galileo will be lost for every bounce period. On the basis of that result, we use the following expression between the fractional losses and the number of electron bounces:

$$I/I_0 = \exp[-0.22m], \tag{1}$$

where m is the number of bounces. From Figure 1 the maximal fractional loss of 15–29 keV electron is ~5, which means that m ~7 (or higher if the scattering does not generate isotropic intensities).

The finding that these low-energy electrons must have bounced at least ~7 times between the time they entered the Ganymedian flux tube and the time they encountered Galileo (at a position about half way across the flux tube) puts a strong constraint on the bounce-averaged flow velocity of these electrons during that time.

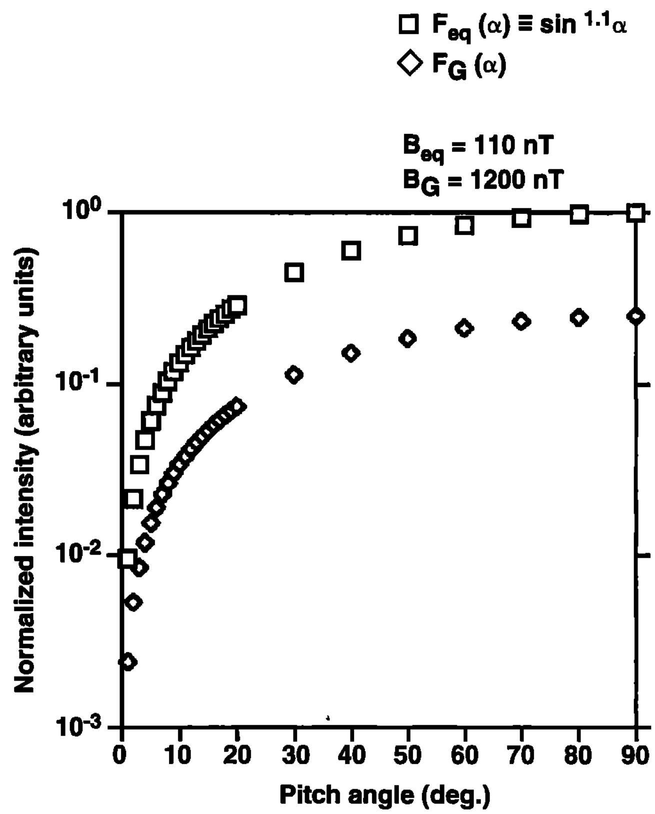

Figure 6. Illustration of the effect of sampling a pitch angle distribution at B_G=1200 nT when the minimum B (B_{eq}) on the field line is 110 nT. The functional form of $\sin^{1.1}(\alpha)$ used in this example shows a factor of ~4 change between the measured equatorial and local 90° pitch angle fluxes. Although this decrease in 90° electron fluxes is in agreement with EPD observations during the G2 encounter, the ratio of 90° to 10° fluxes in the ambient Jovian environment ($\sin^{1.1}(\alpha_{eq})$) is ~7, in disagreement with EPD observations. The ambient electron pitch angle distribution is nearly isotropic, and adiabatic effects are unable to explain the general intensity decrease observed.

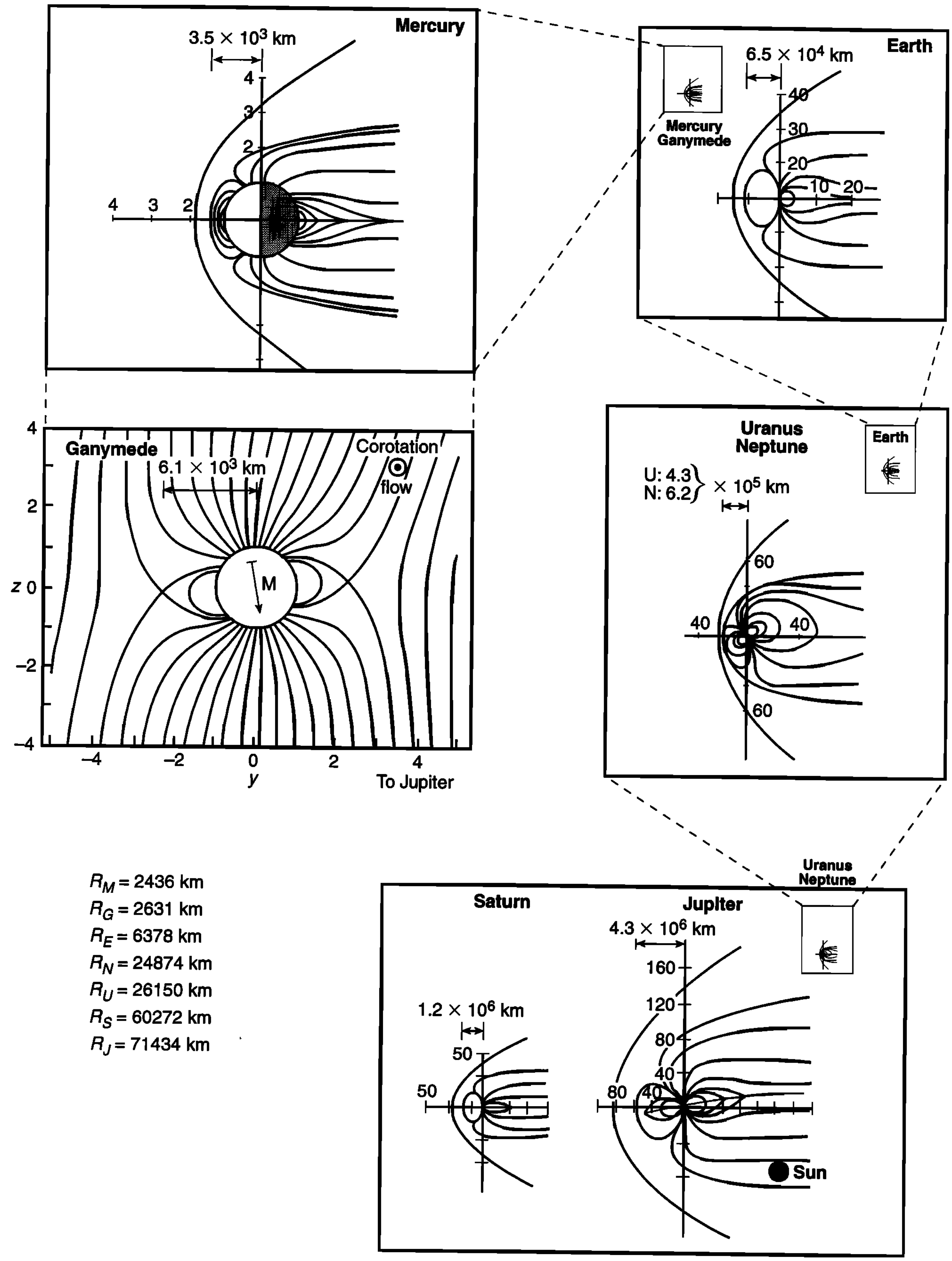

Figure 7. Schematic showing the known solar system magnetospheres. The axes are scaled in units of the radius of the body, given in the lower left for each body.

Because a bouncing electron spends most of its time at its near-Jupiter mirror point, the bounce-averaged flow velocity is dominated by the flows that are far away from Ganymede. *Williams and Mauk* [1997] showed that low-energy electrons (15–29 keV) were nearly isotropized in one bounce cycle, whereas high-energy electrons (304–527 keV) were scattered much less. The bounce period of 15–29 keV electrons is ~21 s (1/2 the full bounce period in the absence of Ganymede). If we assume that the Ganymedian flux tube has a diameter 3 times the diameter of Ganymede at positions close to Ganymede but where the Jovian magnetic field dominates (see Figure 5 of *Kivelson et al.* [1996]), the bounce-averaged flow velocity expressed in the form of its near-Ganymede value is ~8000 km/(7 × 21 s) = ~54 km/s. Thus the bounce-averaged flow velocity of the Ganymedian flux tube is a factor of ~3 smaller than the ambient (nearly corotational) flow velocity. Since this value is similar to the local flow velocity obtained within Ganymede's magnetosphere [*Williams et al.*, 1997a], we conclude the flow depression within the Ganymedian flux tube extends along the flux tube for several Jovian radii away from Ganymede, essentially to the mirror points of the observed particles.

Qualitatively, the smaller losses away from the region of closest approach result from the encounter geometry as sketched in Plate 2b. The drift time (distance) from the external medium to the Galileo satellite is smaller away from the G2 closest approach region (over the polar cap) and allows fewer bounce cycles, resulting in lower losses.

The depression in the intensities of the higher-energy electrons is similarly explained, however the parameters are less solid. The higher-energy electrons are not fully isotropized during their transits between Ganymede and Jupiter, and substantially less than the ~22% of the observed intensities are lost for each bounce cycle. However, that situation is compensated by the fact that the higher-energy electrons bounce up to a factor of ~3 more times during the flux tube occupation period. Our equation now becomes

$$I/I_0 = \exp[-0.22fm], \qquad (2)$$

where f is now the fraction of the loss cone that becomes filled during a single bounce period. Unfortunately, we do not have a reliable way of estimating f. If we make the heuristic assumption that the average f scales according to the pitch angle diffusion coefficient of the electrons, we can use the results of *Williams and Mauk* [1997, Figure 6] to estimate an average f of ~0.2 for 304–527 keV electrons (Figure 1). From the depression in intensities for 304–527 keV electrons of ~4 and a Ganymede-to-Jupiter bounce period of ~7 s, equation (2) gives a value of m ~ 31. The bounce-averaged flow velocity is ~8000 km/(31 × 7 s) = ~39 km/s. Although this calculation is far less reliable than the calculation performed for 15–29 keV electrons, the results still indicate that the ion flow velocity depression within the Ganymedian flux tube extends along the flux tube many Jovian radii away from Ganymede, essentially to the mirror points of the observed particles.

6. Summary

The EPD returned data for three of the four close encounters of Ganymede performed by the Galileo satellite. Measurements of energetic particle intensities and angular distributions have provided new information about Ganymede including the following: (1) the significant slowing down of ambient Jovian corotation speeds within the Ganymede environment; (2) an indication that the slower convective speeds are in place for several Jovian radii along the Jupiter-Ganymede field lines; (3) a measure of Ganymede's surface magnetic field; (4) verification of Ganymede's intrinsic magnetic field; (5) a direct measure of the energy dependent electron pitch angle diffusion coefficient and scattering lifetimes on Jupiter-Ganymede field lines; (6) evidence that similar scattering magnitudes exist throughout the Ganymede L shell; (7) stability of the observed characteristics of Ganymede's environment over at least the several month interval between encounters; (8) measurement of electrons trapped on closed Ganymede magnetic field lines; (9) agreement of magnetopause locations as identified by the magnetometer, plasma wave detector, and EPD; and (10) conclusion that Ganymede has a magnetosphere and a resident trapped particle population.

Items 1, 3, 4, and 9 have been discussed by *Williams et al.* [1997a]. Item 5 was reported by *Williams and Mauk* (1997). Items 8, 9, and 10 have been discussed by *Williams et al.* [1997b]. Items 2, 6, and 7 are new to this report.

Figure 7 shows an old and popular schematic of the known solar system magnetospheres, to which we have added the magnetosphere of Ganymede. The scaling in the figure clearly shows Ganymede's magnetosphere to be larger than that of Mercury. Note however that all of the planetary magnetospheres are shown in a meridional plane projection whereas Ganymede's magnetosphere is shown in the plane separating the upstream and downstream hemispheres. The impinging plasma flow is out of the figure in the Ganymede panel and from left to right in all other panels. This highlights some of the differences between Ganymede's magnetosphere and those of the planets. Not only is Ganymede's magnetosphere imbedded within the Jovian magnetosphere, it is formed by a sub-Alfvénic plasma flow containing a substantial heavy ion population. Within several R_G (a few tenths of R_J) of the moon along the Ganymede fluxtube, magnetic field lines resume their Jovian character (with the exception of corotation effects) and ultimately intersect the Jovian ionosphere. They do not fold back behind the moon and form a magnetic tail. In short, we do not know how to sketch the Ganymede magnetosphere in a meridional plane equivalent. The observations of trapped electrons indicate that the closed field line portion of Ganymede's field is compressed on the upstream hemisphere and extended (relatively) on the downstream hemisphere. However, we do not yet have a measure of or a model of the Ganymede magnetospheric current system. A full determination of the Ganymede system requires the use of all the Galileo particles and fields data.

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