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Trapped electrons in Ganymede's magnetic field

D. J. Williams, B. Mauk, and R. W. McEntire

The Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland

Abstract. The NASA Galileo satellite encountered the Jovian moon Ganymede on 7 May 1997. The Energetic Particles Detector (EPD) measured energetic electron pitch angle distributions characteristic of closed magnetic field lines. Significantly different from distributions observed during other encounters with Ganymede, they displayed loss cone features near both 0° and 180° pitch angles and an additional minimum near 90° pitch angle. These double loss cone, butterfly distributions are characteristic signatures of particles drifting in a distorted magnetic field configuration. Distortions due to the flow of Jovian plasma past Ganymede qualitatively could account for the observed distributions. Electron injection could then occur either through the equatorial downstream hemisphere or at low Ganymede altitudes on high-latitude Ganymede–Jovian field lines adjacent to the closed field line region. The data indicate maximum injection efficiences of 1–10%.

Introduction

We present evidence for particle trapping in Ganymede's magnetic field obtained from Energetic Particles Detector (EPD) observations during the 7 May 1997 Ganymede encounter (designated G8 because the encounter occurred on Galileo's eighth orbit around Jupiter). The EPD measures the spectral and angular distributions of all ions above 20 keV, electrons above 15 keV, and elemental species from protons through iron above approximately 10 keV/nucleon [*Williams et al.*, 1992]. The EPD's two bidirectional detector heads are mounted on a stepper motor platform and when combined with the satellite spin provide a three-dimensional angular sampling of up to a full 4π steradians. EPD data have been received from the Ganymede encounters that occurred on 6 September 1996 (G2), 5 April 1997 (G7), and 7 May 1997 (G8). No EPD data were recovered from the 27 June 1996 (G1) encounter due to a software problem that was subsequently fixed. To set the background for the G8 observations we briefly review the EPD results from the G2 encounter [*Frank et al.*, 1997; *Kivelson et al.*, 1997; *Williams et al.*, 1997].

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 in Galileo's (or effectively Ganymede's) frame of reference, a magnitude ~85% of full corotation. Within Ganymede's magnetosphere, anisotropies were very small, and upper limits to the energetic ion 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 (Gurnett, personnal communication).

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]. All species and energy channels showed empty loss cones when EPD looked along the magnetic field towards Ganymede. All ion channels also displayed full loss cones when EPD viewed in the anti-moon direction. Also in the anti-moon direction, electrons were observed to have nearly full loss cones at low energies that evolved to empty loss cones at high energies. Noting that energetic electron bounce times between Ganymede and the near-Jupiter mirror point are much smaller than the drift times across the Ganymede system, *Williams and Mauk* [1997] determined the amount of pitch angle scattering occuring during one bounce, and from that determination estimated the magnitude of the energy-dependent pitch angle diffusion coefficient on these Ganymede–Jupiter field lines. EPD observations from the G7 encounter, a pass through the wake created by Jovian plasma flow past Ganymede, are similar to the results described for the G2 encounter.

Of the Ganymede encounters for which EPD data are available, the G8 encounter presents the most promising possibility for intersecting Ganymede closed field lines, according to the present model field [*Kivelson et al.*, 1996, 1997]. The Galileo G2 trajectory was over the polar cap at a closest approach altitude of ~260 km and sampled field lines connecting Ganymede and Jupiter. At G7 Galileo flew through the wake at high latitudes and at a closest approach distance of ~3000 km, well away from the expected region of closed field lines. At G8 Galileo crossed the upstream hemisphere of the moon at a closest approach altitude of 1596 km, coming the closest to the expected closed field line region for these three encounters (see Figure 1).

G8 Data

Figure 1 shows the geometry of the G8 encounter with respect to a model of Ganymede's magnetic field superimposed on the ambient Jovian magnetic field [*Kivelson et al.*, 1996; J. Warnecke, personal communication]. The view is from the wake region towards the moon (the direction of corotation is normal to and out of the plane of the figure), and Galileo passes on the upstream side of the moon at an altitude of 1596 km. Simultaneous with the change in B_z, the B_x component (not shown) becomes the dominant magnetic field component. These changes are consistent with Galileo entering a region of closed field lines (Kivelson et al., Genymede's magnetosphere: Magnetometer overview, submitted to *J. Geophys. Res.*, 1997).

For the purpose of this study we utilize EPD electron channels to minimize gyroradii effects. Electron gyroradii for the energies

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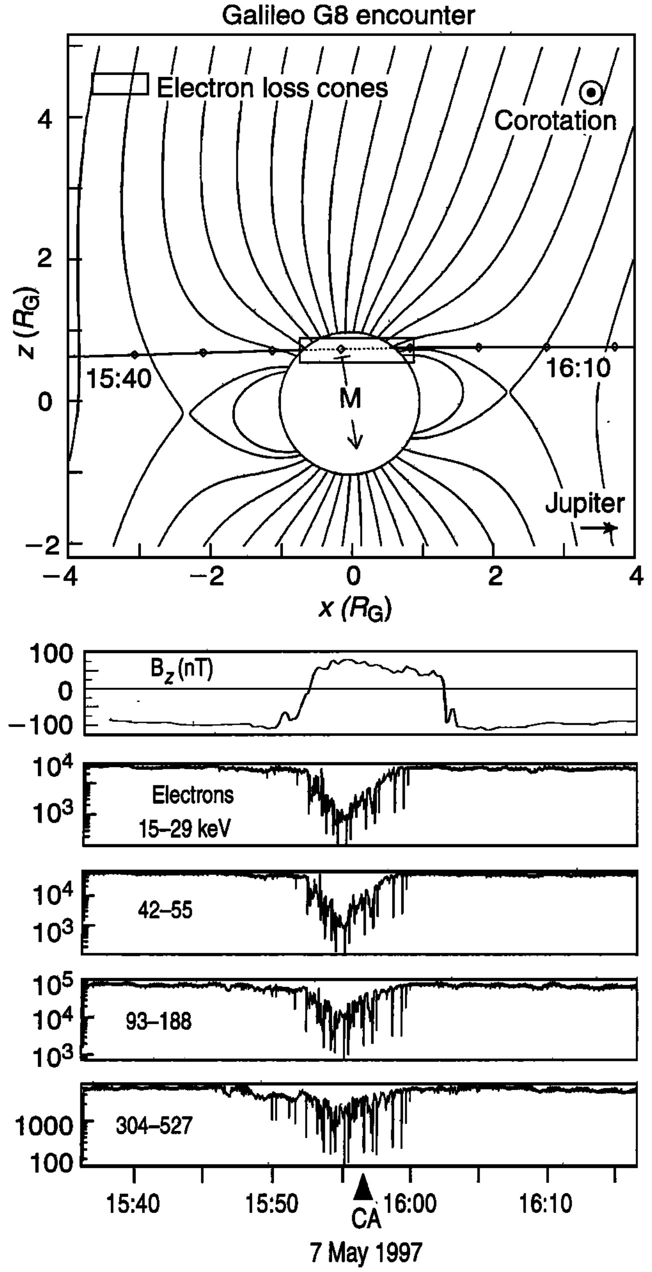

Figure 1. Galileo trajectory and EPD electron measurements through the 7 May 1997 Ganymede encounter, G8. The top panel shows the geometry of the Galileo trajectory through the Ganymede model magnetic field [*Kivelson et al.*, 1996]. The z axis is aligned with Ganymede's spin axis, the x axis points towards Jupiter, and the y axis points in the direction of corotation. The region where loss cones were observed in the electron pitch angle distributions is indicated on the trajectory. The next panel shows the response of the z component of the magnetic field through the encounter (Kivelson, personal communication). The remaining panels show the response of EPD's electron channels. The spikey decreases seen within the general intensity decrease are due to viewing in the electron loss cone.

shown in Figure 1 are <~25 km for the ~200 nT fields measured during the G8 encounter, a magnitude small compared to the flyby distance. Because of these small gyroradii, electrons provide an excellent fine-scale probe of Ganymede's magnetic field configuration. Energetic ions have gyroradii that are a large fraction of, or are larger than, the moon's radius and will require detailed trajectory calculations to account for finite gyroradius effects.

All electron channels show a broad decrease in the vicinity of Ganymede closest approach. The sharp spike-like decreases are loss cone signatures measured when EPD viewed in either direction along the field line. The region where EPD observed the loss cone signatures is indicated in the trajectory panel at the top of Figure 1. This loss cone region coincides with the interval

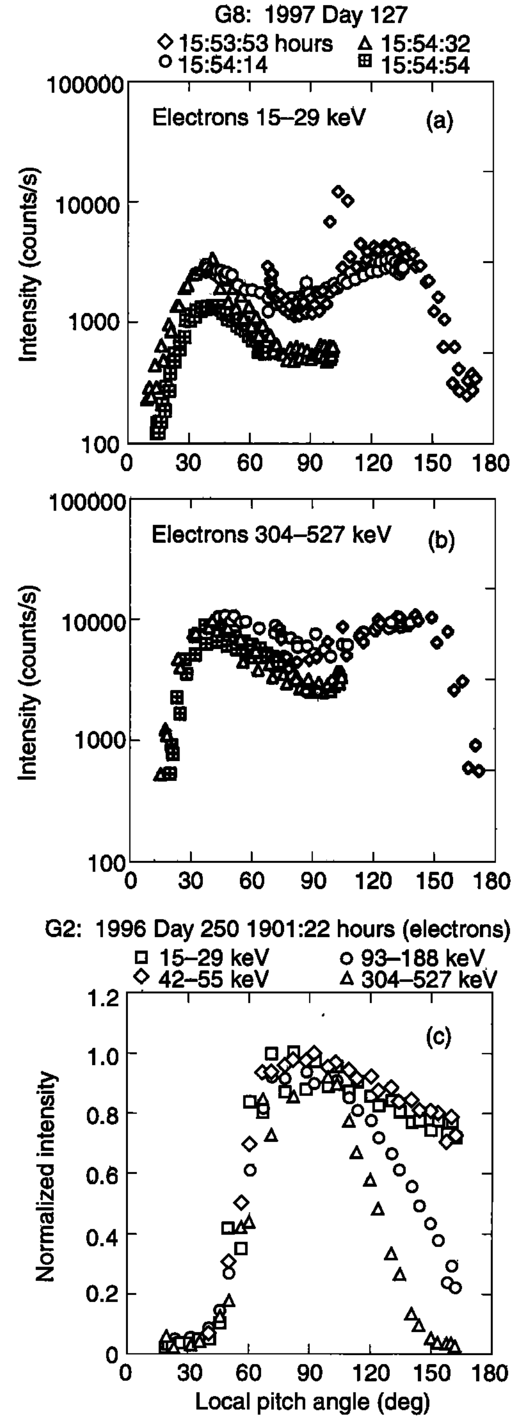

Figure 2. Panels (a) and (b) are pitch angle distributions measured just prior to G8 closest approach. Because EPD was in its full stepping mode during this encounter, it was necessary to use several consecutive spins (in this case four spins totaling ~80 s) to develop a full pitch angle distribution. Panel (c) shows typical distributions observed over Ganymede's polar cap during the 6 September 1996 encounter, G2. Electron pitch angle distributions from the 5 April 1997 Ganymede encounter, G7, were similar to those seen during G2. See text for discussion.

where B_z reverses sign and B_x becomes (and remains) the dominant component.

The first indication that the EPD G8 encounter differs from previous EPD Ganymede encounters is the magnitude of the broad electron intensity decrease near closest approach: a factor of ~40 at ~20 keV, as compared with factors of ~5 and ~2 seen at G2 and G7 respectively. This difference occurs despite the fact that the G2 encounter was substantially closer to Ganymede (~261 km) than that of G8 (1596 km).

To avoid missing the field line direction, EPD was operated in its full stepping mode, obtaining a full 4π steradian angular sample once every ~140 s. Because of the limited pitch angle coverage of individual step positions, it was necessary to combine several sequential steps to obtain a complete pitch angle distribution. From the intensity variations shown in Figure 1 it is apparent that space/time aliasing occurs in the resulting distributions. Nevertheless it is possible to obtain a measure of the main features of the distributions well enough to compare them with the loss cone structures observed during earlier Ganymede encounters.

Figure 2 shows pitch angle distributions constructed as described in the preceding paragraph for two energies representing the low and high energies measured by EPD. Distributions measured during the G2 encounter are shown for comparison. Two general characteristics stand out at the energies shown (and hold for all EPD electron channels): (1) intensities decrease sharply when viewing along the field line in either direction, indicating particle loss cones at pitch angles near 0° and 180°; and (2) the distributions also display decreased intensities around 90° pitch angle, resulting in "butterfly" distributions characteristic of magnetospheric shell-splitting effects. These features are in contrast to the observations of the G2 (and G7) encounter, where, as can be seen in the G2 panel of Figure 2, nearly full loss cones were observed in the anti-moon viewing direction at low energies, and no minima at 90° pitch angles were seen. The distributions measured during the G2 encounter were interpreted as electrons trapped on Jovian field lines intersecting Ganymede [*Williams et al.*, 1997]. These electrons bounce several times between their Ganymede and Jupiter mirror points during their drift across the Ganymede system. The clear loss cone seen when viewing toward Ganymede is due to electrons impacting the moon and is re-established each bounce. The evolution of the anti-moon loss cone from nearly full at low energies to empty at high energies was explained as being due to energy-dependent pitch angle scattering taking place during the electron's travel from Ganymede to its near-Jupiter mirror point and back [*Williams and Mauk*, 1997]. We note that only Ganymede is able to create loss cones of the magnitude measured by EPD (tens of degrees) during these close encounters with the moon; Jovian atmospheric loss cones are <~1° at Ganymede's altitude and are not resolved by the EPD.

The pitch angle distributions measured during the G8 encounter, having loss cones observed in either direction along the field line and additional minima around 90° at all energies, are consistent with trapping on closed Ganymede field lines. Double loss cone structures are established by closed field line geometries, and intensity minima near 90° pitch angle may be due to gradient and curvature drift in a distorted magnetic field or through other specialized source or loss geometries.

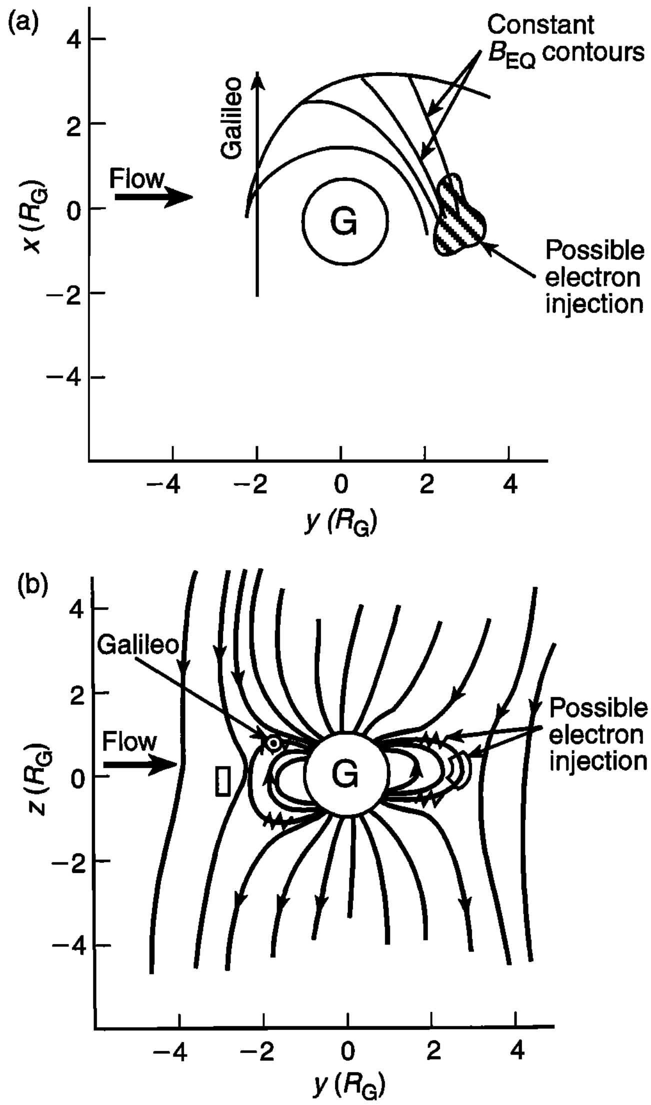

Figure 3. Illustrative schematic showing the development of butterfly distributions in a possible Ganymede magnetospheric configuration. Panel (a) shows an equatorial cross section and a possible electron injection region in the downsteam hemisphere. Electrons are injected at all pitch angles. Panel (b) shows a meridional cross section. A guide to Galileo's position during the G8 encounter is shown by the line in panel (a) and the circle in panel (b). See text for discussion.

Discussion

There are no absolute measures of the "closedness" of magnetic field lines and whether or not particles are trapped on such field lines. However in the absence of other plausible explanations for these observed distributions, we conclude that the energetic electron data presented provide strong evidence for the trapping of electrons on closed Ganymede magnetic field lines. This stems from a combination of facts: (1) the measured pitch angle distributions at all electron energies measured by EPD are characteristic of magnetospherically trapped distributions—double loss cones and butterfly distributions [see, for example, *Sibeck et al.*, 1987, and references therein]; (2) they differ significantly from the distributions measured during the G2 and G7 encounters, distributions that were interpreted as being on field lines connecting Ganymede to Jupiter; (3) electron intensities decreased substantially more at the G8 encounter than at the G2 and G7 encounters, suggesting a greater insulation from the ambient environment; (4) during the interval through which the EPD loss cone structures were observed, the magnetic field orientation changed to being consistent with a Ganymede closed field line geometry; and (5) based on Ganymede's magnetic field model geometry, the possibility of Galileo intersecting closed field lines is greater for the G8 encounter than for either G2 or G7.

The present model for Ganymede's magnetic field environment is a simple intrinsic dipole superimposed on the ambient Jovian field [*Kivelson et al.*, 1996]. The resulting configuration is azimuthally symmetric. As plasma effects and currents are not taken into account, it is surprising that this simple guideline model does so well in predicting the overall geometry of the Ganymede magnetosphere, e.g., the location of the boundary between Jovian field lines and field lines connecting Ganymede to Jupiter [*Gurnett et al.*, 1996; *Williams et al.*, 1997]. However it is expected that the corotating Jovian plasma will compress and flatten the upstream hemisphere while extending (at least relatively) the downstream hemisphere, similar to solar wind flow shaping the Earth's magnetosphere.

In their drift in a magnetic field under conservation of the adiabatic invariants, particles trapped at equatorial pitch angles near 90° will follow contours of constant equatorial magnetic field magnitude. Those at small equatorial pitch angles will tend to preserve the length of the field lines between mirror points [see for example, *Roederer*, 1967, 1969; *Lyons and Williams*, 1984]. One consequence resulting from distortions in the magnetic field geometry is the removal of azimuthal symmetries in the particles' drift through the magnetic field. Magnetic shell-splitting effects, whereby particles injected on a given field line will drift to different field lines according to their pitch angle, are common in extended magnetospheric configurations such as the Earth's.

Figure 3 is a qualitative sketch of a possible Ganymede magnetosphere that could support the distributions shown earlier. An equatorial projection and a meridional cross section aligned with the corotational flow are shown. Contours of constant equatorial field magnitude are shown in the equatorial projection. With this diagram we hypothesize that electrons diffuse into or are injected into Ganymede's magnetosphere at a near-equatorial downstream region. They appear at all pitch angles on the field line. Electrons injected at near-90° equatorial pitch angles will follow the constant field magnitude contours and impact the boundary separating Jovian field lines from those connecting Ganymede and Jupiter. They are lost to the Ganymede system at this boundary and thus are not able to complete their drift to the upstream hemisphere sampled by Galileo. The meridional projection illustrates the effects of shell-splitting on electrons along the entire field line. Again, electrons from the injection region near 90° pitch angle would drift to a point outside the boundary, i.e., they impact the boundary before they reach Galileo's upstream location. Electrons at small pitch angles, however, conserving field line length between mirror points, are able to drift to the upstream hemisphere. This source location requires significant electron drift through Ganymede's magnetosphere.

Trapped electrons injected at the upstream boundary will not develop butterfly distributions at that boundary via gradient and curvature drift. This rules out significant energetic electron injection at low latitudes in the upstream stagnation region. However at high latitudes on Jovian field lines intersecting the moon, only electrons with small pitch angles enter the high-field region of Ganymede. A fraction of these electrons could be scattered onto adjacent closed field lines, forming butterfly distributions at Galileo's location. This source location requires a minimum of drift motion through Ganymede's magnetosphere.

From Figure 1 we see that the energetic electron intensities in Ganymede's magnetic field drop to a factor of 10–100 below that of the electron intensities on nearby Jovian field lines, indicating a maximum direct injection efficiency of ~1–10%. The relation and reaction of energetic ions to Ganymede's magnetic field, while similar in some respects to energetic electrons, is more complex because of finite gyroradius effects. Detailed trajectory calculations are being implemented to follow the ions through their interaction with the Ganymede system.

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D. J. Williams, B. Mauk, and R. W. McEntire, The Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723. (e-mail: Don.Williams@jhuapl.edu; Barry.Mauk@jhuapl.edu; Richard.McEntire @jhuapl.edu)

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