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Energetic particle signatures at Ganymede: Implications for Ganymede's magnetic field

D. J. Williams,[1] B. H. Mauk,[1] R. W. McEntire,[1] E. C. Roelof,[1] T. P. Armstrong,[2] B. Wilken,[3] J. G. Roederer,[4] S. M. Krimigis,[1] T. A. Fritz,[5] L. J. Lanzerotti,[6] and N. Murphy[7]

Abstract. The second encounter of the Galileo satellite with the Galilean moon Ganymede provided energetic particle measurements showing effects due to the presence of that moon. Jovian corotation signatures, present on approach to and departure from the Ganymede system, suddenly become much smaller when Galileo enters what has been termed Ganymede's magnetosphere. The location of these transitions agrees with magnetopause crossings identified by the magnetometer and plasma wave instruments. In Ganymede's magnetosphere, energetic ion and electron distributions display loss cone signatures whenever the Energetic Particles Detector (EPD) views along the magnetic field line. The loss cone measurements are used to estimate Ganymede's surface magnetic field along the satellite track. The results agree with model projections to Ganymede's polar cap and support the existence of a Ganymede-intrinsic magnetic field. An evolution from single to double loss cone also occurs with increasing electron energy.

Introduction

After injection into orbit around Jupiter, the Galileo satellite's first encounters with a Galilean moon were with Ganymede on 27 June (G1) and 6 September (G2) 1996. Due to an onboard software problem, the EPD did not operate during the G1 encounter. The problem was resolved in time for the G2 encounter, a pass over Ganymede's polar cap at a minimum altitude of 261 km. Ganymede, with a radius of 2634 km, orbits Jupiter at a radial distance of 1,070,000 km (~15 Jupiter radii) and during the G2 encounter was embedded in Jupiter's plasma sheet.

The EPD measures spectral and angular distributions of all ions above 20 keV, electrons above 15 keV, and elemental species from protons through iron above about 10 keV/nucleon [*Williams et al.*, 1992]. Its two bidirectional detector heads are mounted on a stepper motor platform, and when combined with the satellite spin, provide a three-dimensional angular sampling up to a full 4π steradians. The angular sampling used for the G2 encounter was guided by the magnetometer measurements made during the G1 encounter [*Kivelson et al.*, 1996].

[1]The Johns Hopkins University Applied Physics Laboratory, Laurel, MD
[2]University of Kansas, Lawrence, KS
[3]MPAe, Katlenburg-Lindau, Germany
[4]University of Alaska, Fairbanks, AK
[5]Boston University, Boston, MA
[6]Lucent Technologies, Murray Hill, NJ
[7]Jet Propulsion Laboratory, Pasadena, CA

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Data

Figure 1 shows raw data from three selected EPD channels as a function of spacecraft event time (SCET) during the encounter. (All times hereinafter are SCET.) These channels were selected to display the main energetic particle characteristics seen during the G2 encounter. The remaining energy and species measurements show the same features, albeit with varying sensitivity and clarity. The locations of Ganymede's magnetopause at entry and exit are shown as identified by the magnetometer [*Kivelson et al.*, 1997] and plasma wave instruments (Gurnett, personal communication).

All ion channels show spin-modulated anisotropies outside of Ganymede's magnetosphere as determined by the magnetopause locations shown in Figure 1. The magnitude of the anisotropy in any given EPD channel depends on the species and energy of the ions being measured. An analysis of the anisotropies yields an energetic ion convective flow speed of ~152 km/s, about 80% of the expected full corotation speed (~190 km/s). The anisotropies change markedly at or near the magnetopause, becoming much smaller and nearly vanishing inside Ganymede's magnetosphere. Upper limits to the flow speeds within the Ganymede system are ~25–45 km/s, as inferred from EPD ion anisotropies.

The sharp intensity drop-out features of Figure 1 are loss cone signatures resulting from the loss of particles impacting the moon. To display these effects more clearly, we show plots of pitch angles sampled (as determined from magnetometer measurements) in Plate 1, together with electron intensities in two energy channels and the total ion intensity in our lowest-energy ion channel. The distinct pattern in the pitch angle display is due to the stepping sequence used for EPD observations during the encounter. Within the Ganymede system, a marked decrease in intensitiy (the loss cone) is seen whenever the EPD views nearly along the magnetic field line in the direction of the moon. Loss cones were not observed between ~1850 and ~1854 UT because the EPD stepping sequence did not sample small enough pitch angles to determine the presence of a loss cone. All ion channels show a single loss cone, observed when looking along the field line toward the moon. No loss cone is seen when looking along the field away from the moon. Low-energy electrons (15–29 keV panel) show a pronounced loss cone when viewing in Ganymede's direction and a greatly diminished effect when viewing away from the moon. High-energy electrons, however (304–527 keV panel), show pronounced loss cone features in both directions along the field line. *Frank et al.* [1997] present observations of electron signatures at energies ≤4.5 keV.

EPD low-energy electrons and ions display intensity variations as Galileo nears closest approach to Ganymede (Figure 1). We analyzed all loss cone signatures not compromised by these

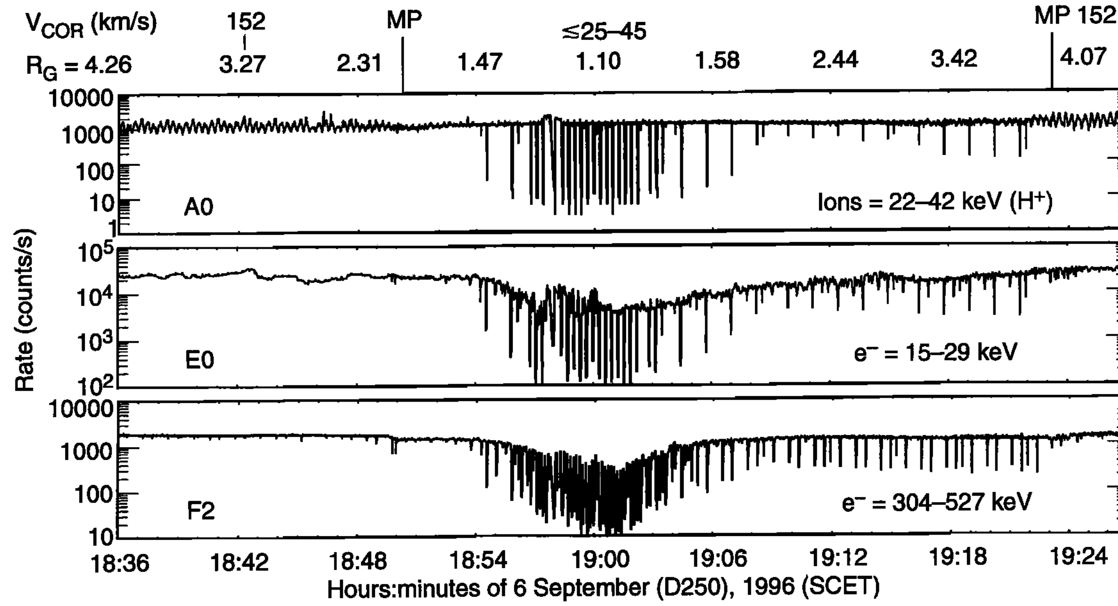

Figure 1. Count rates from three EPD channels for the second Galileo flyby of Ganymede, the G2 encounter. Closest approach occurred at ~19:00 hours. MP indicates locations of Ganymede's magnetopause as determined by the magnetometer and plasma wave instruments. Scales at the top are distance and corotation speed.

variations and used these loss cone measurements to estimate the magnitude of Ganymede's surface field. Although all species and energies display qualitatively similar loss cone signatures, we use electron channels in the present analysis to minimize gyroradii effects (50-keV electrons have gyroradii ranging from 0.6 to 8 km in the 100- to 1200-nT fields observed through the G2 pass). Figure 2 shows three pitch angle distributions for 29–42 keV electrons; two (19.0064 and 19.0453 hours) occur soon after closest approach, and the third (19.229 hours) occurs close to exit from the Ganymede system (see Figure 1 and Plate 1). The 19.0064 and 19.0453 distributions are typical of those observed through closest approach and show a diminishing loss cone as the magnetic field decreases, qualitatively consistent with expectations. The distribution measured at 19.229 hours typifies those seen after ~19.5 hours, displaying a much more diffuse character than those observed closer to the moon. This difference is partly due to the changing portion of the ambient Jovian electron pitch angle distributions sampled by EPD through the Ganymede pass. Using, for example, 100 nT as the local Jovian equatorial field strength, the distributions shown in Figure 2 at 19.0064, 19.0453, and 19.229 hours sample the ambient Jovian electron distributions at equatorial pitch angles <17°, <21°, and <60° respectively.

Discussion

Conservation of the first adiabatic invariant ($E \sin^2(\alpha)/B$ = constant, where E = energy, B = magnetic field strength, and α = pitch angle) states that for two points on an equipotential field line, $\sin^2(\alpha_1)/B_1 = \sin^2(\alpha_2)/B_2$. For an absorber on the field line at a point G in a region of field strength B_G greater than that of the observation point B_1, a loss cone is established at the observation point whose size is given by $\sin^2(\alpha_{LC}) = B_1/B_G$. Combining EPD measurements of the loss cone size with the simultaneously measured magnetic field strength provides an estimate of Ganymede's surface magnetic field intensity B_G and its variation along the Galileo field line footprint track. The fact that the observed loss cones over Ganymede's polar cap do not extend to $\alpha = 90°$ (the observed maximum loss cone angle is ~60°—see Figure 2) shows that the magnetic field strength increases significantly between Galileo and the moon's surface.

We fitted the EPD pitch angle distributions just outside the loss cone with the functional form $h(\alpha) = \sin^n(\alpha)$ for $\alpha > \alpha_{LC}$ and $h(\alpha) = 0$ for $\alpha < \alpha_{LC}$. Values of n ranged from 0.5 to 1.0 through the Ganymede encounter. The values of n for the pitch angle distributions in Figure 2 were, from earlier to later times, 1.0, 0.58, and 0.54. We then use α_{LC}, extracted from the analysis, to estimate Ganymede's surface field strength B_G at the Galileo field line footprint. The fitting procedure deconvolutes the finite detector view cone (15° full width). Due to the changing shape of the pitch angle distributions away from clos-

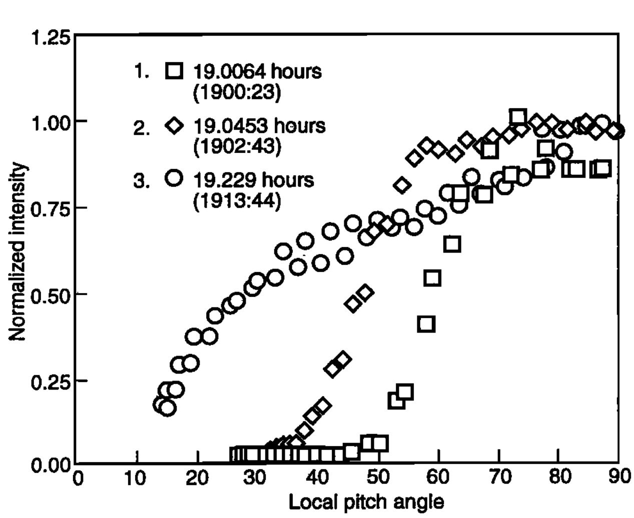

Figure 2. Sample measured local pitch angle distributions during the G2 encounter. Well-defined loss cones are observed near the polar cap (19.0064 and 19.0453 hours; field strength at Galileo was 1133 and 800 nT, respectively). Less well-defined loss cones are well away from the polar cap (19.229 hours; field strength at Galileo was 134 nT).

est approach and the sensitivity of the $\sin^2\alpha$ term at small angles, this technique becomes unreliable at times after ~19.05 hours (19 h 3 min). Therefore we also used a technique whereby a straight line segment is fitted to the small pitch angle portion of the distribution. The point at which this fit breaks away from the higher pitch angle portion of the distribution allows an additional determination of the edge of the loss cone α_{LC}. Finally, the single loss cone structure observed at low electron energies and the shape of the pitch angle distributions measured after 19.05 hours indicate that pitch angle scattering effects may be affecting our loss cone estimates at those times. Consequently we also used the preceding procedure with a higher-energy electron channel (304–527 keV), where a strong double loss cone is seen and scattering effects ought to be less of a problem than at lower energies.

Figure 3 shows the results of these analyses. All techniques gave essentially the same results prior to 19.05 hours. The results diverge after this time. The least reliable estimate after 19.05 hours is that labeled e1sin. The spread between the e1line and f2line estimates represents a good measure of the uncertainty in our estimates. The magnetic field measured at Galileo and the predicted surface field from the Ganymede model field are shown for comparison. By mutual agreement the predicted surface field was made available by the magnetometer team (Kivelson, personal communication) only after the final estimates were obtained from the loss cone measurements.

Through closest approach and before ~19.05 hours, the analyses yield Ganymede surface magnetic field magnitudes that agree with the projections of a simple dipole field model [*Kivelson et al.*, 1996]. After ~19.05 hours, our estimates of the surface field

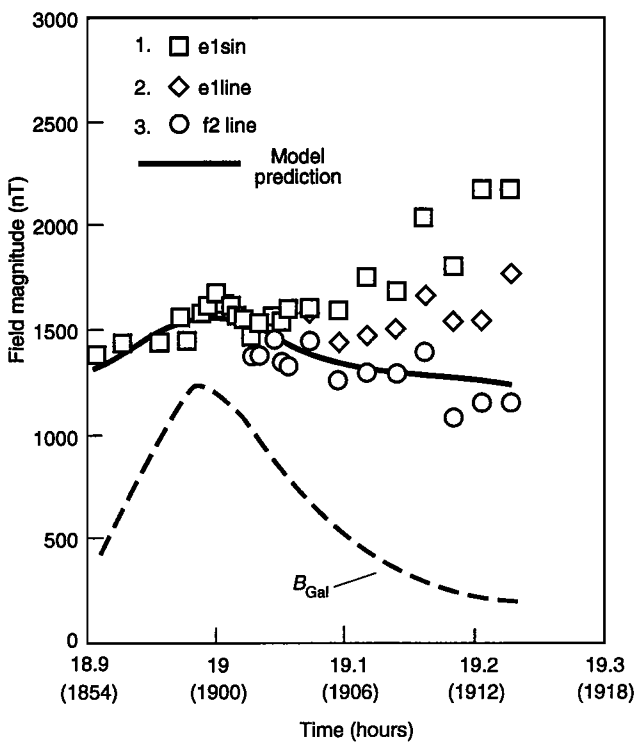

Figure 3. Comparison of estimates of Ganymede's surface field at the Galileo field line footprint obtained from EPD loss cone measurements with the surface field expected from the existing Ganymede magnetic field model [*Kivelson et al.*, 1996]. Measured magnetic filed strength at Galileo is also shown. See text for details.

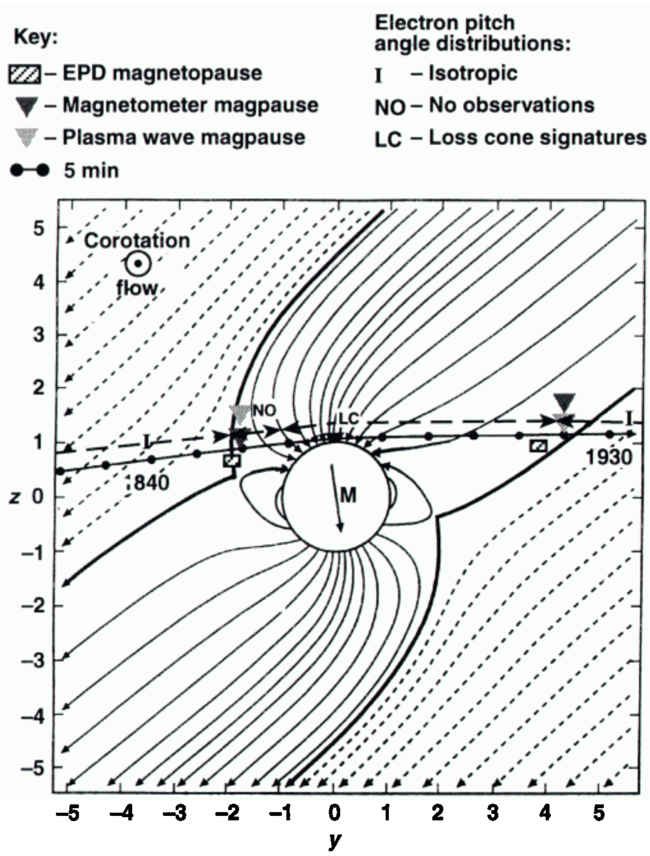

Figure 4. Superposition of the G2 flyby, an EPD loss cone summary, and EPD, magnetometer, and plasma wave determinations of G2 magnetopause locations on the model field developed from the first Ganymede flyby [*Kivelson et al.*, 1996]. Direction of corotational flow is shown.

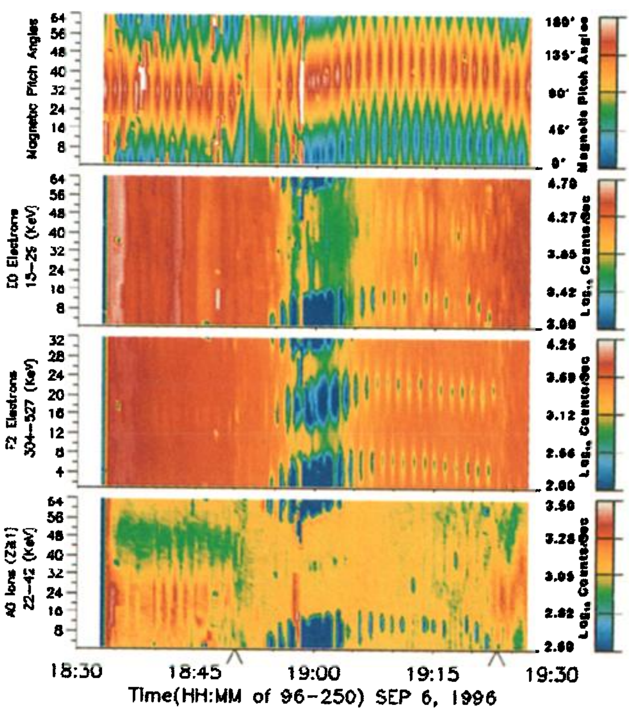

Plate 1. All data are displayed in a spin sector versus time grid for the G2 encounter. Shown from top to bottom are pitch angles sampled, 15-29 keV electron intensities (64 samples/spin), and 304-527 keV electron intensities and 22-42 keV ion intensities (32samples/spin). Loss cones show as dark regions whenever pitch angle sampling approaches 0° or 180°. Marks at ~18:50 and 19:23 along the bottom axis are times of magnetopause crossing as determined by the magnetometer and plasma wave instruments.

are much more uncertain because of the difficulties noted above in accurately measuring the loss cone at small pitch angles with a 15° detector aperture. However, the predicted surface field strength lies within the range of values obtained from the loss cone analysis. We conclude that these measurements agree with and support the intrinsic magnetic field postulated for Ganymede [*Gurnett et al.*, 1996; *Kivelson et al.*, 1996].

Figure 4 places these observations within the perspective of the present Ganymede model field [*Kivelson et al.*, 1996]. Corotating particles flow perpendicular to and out of the plane of the figure. The positions where EPD experiences a marked change in measured corotation signatures are indicated as "EPD magnetopause." Note that the EPD observed well-defined loss cones from ~1854 SCET until exit from the Ganymede magnetosphere at ~1923 SCET. Loss cones measurements were not available from magnetosphere entry at ~1850 SCET until ~1854 SCET because EPD did not sample small pitch angles (Plate 1). Electron angular distributions were nearly isotropic in the ambient Jovian environment, whereas ion distributions displayed a convective flow signature indicating a flow velocity of ~152 km/s. Figure 4 also shows magnetopause determinations by the magnetometer [*Kivelson et al.*, 1997] and the plasma wave instrument (Gurnett, personal communication). The EPD measurements agree with this model of Ganymede's magnetic field—a surprising result given that Figure 4 represents a vacuum superposition of a dipole field with the ambient Jovian field. Nevertheless the EPD results shown in Figures 3 and 4 provide support for a Ganymede-intrinsic magnetic field.

The possibility remains that the EPD observations after 19.05 hours actually do indicate a loss cone smaller than (or equivalently, as shown in Figure 3, a surface field larger than) that expected for the existing Ganymede magnetic field model. In this case several explanations are possible, some requiring detailed calculations of particle trajectories through the Ganymede system. One possibility, for example, is that the field lines crossed by Galileo in Figure 4 after 19.05 hours map back to an anomalously strong region of magnetic field on Ganymede's surface. Modeling such an effect is needed to test whether or not the Galileo magnetic field observations for all Ganymede flybys still can be reproduced.

A second and related explanation is that the field line geometry and corresponding electron trajectories may be far more complex than indicated in Figure 4. This could lead to gradient/curvature drifts and scattering effects that could modify the particle pitch angle distributions.

A third explanation, the possibility that the field lines sampled after 19.05 hours do not intercept Ganymede, appears to be ruled out by the observation of ion loss cones when viewing towards Ganymede throughout this period. If the field lines did not intercept the moon, this loss cone would be filled by ions streaming past the moon from the opposite hemisphere.

While the first two possibilities are not ruled out, the evidence of Figures 3 and 4 strongly supports a Ganymede-intrinsic field. However, many other aspects of the plasma interactions occurring in this environment remain to be studied and understood. Particularly for EPD observations, the question of why electrons show an evolution to a pronounced double loss cone with increasing energy remains open. Maintaining a full particle distribution in the anti-moon hemisphere for ions can be understood in terms of the ion half bounce period (tens of minutes) and the time for particle drift across the Ganymede system (a few minutes). On the other hand, the electron half-bounce periods are 30 s or less for all EPD electron channels. We suggest that the nearly full, anti-moon loss cones observed in the lower-energy electron channels may be caused by pitch angle scattering as the electrons travel toward Jupiter along the field line and return. It remains to be seen whether there is sufficient power at appropriate frequencies, as measured by the plasma wave instrument, to account for this evolution with wave–particle interactions.

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S. M. Krimigis, B. H. Mauk, R. W. McEntire, E. C. Roelof, and D. J. Williams, The Johns Hopkins University Applied Physics Laboratory, Johns Hopkins Road, Laurel, MD 20723-6099 (e-mail: tom.krimigis@jhuapl.edu; barry.mauk@jhuapl.edu; dick.mcentire@jhuapl.edu; ed.roelof@jhuapl.edu; don.williams@jhuapl.edu)

T. P. Armstrong, Department of Physics and Astronomy, University of Kansas, Lawrence, KS 66045 (e-mail: armstrong@kuphsx.phsx.ukans.edu)

T. A. Fritz, Center for Space Physics, Boston University, 725 Commonwealth Avenue, Boston, MA 02215 (e-mail: fritz@bu.edu)

L. J. Lanzerotti, Lucent Technologies, Bell Lab Innovations, 600 Mountain Avenue, Murray Hill, NJ 07974-0636 (e-mail:ljl@physics.att.com)

N. Murphy, Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91103 (e-mail: nmurphy@gllsvc.jpl.nasa.gov)

J. G. Roederer, Geophysical Institute, University of Alaska, 903 Koyukuk Drive, Fairbanks, AK 99775 (e-mail: jgr@geewiz.gi.alaska.edu)

B. Wilkin, Postfach 20, MPAe, 37189 Katlenburg-Lindau, Germany (e-mail: wilken@linmpi.mpae.gwdg.de)

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