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Low–energy electron measurements at Ganymede with the Galileo spacecraft: Probes of the magnetic topology

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Abstract. During the close flyby of Ganymede by the Galileo spacecraft on 6 September 1996 a plasma analyzer was used to obtain comprehensive measurements of the thermal electron plasmas in the vicinity of this moon. Our initial analyses are directed toward the character of energy influxes into Ganymede's polar caps and the pitch angle distributions for warm electrons in the energy range of 70 eV to 4.5 keV. The source of these electrons is Jupiter's plasma sheet within which Ganymede was embedded during the flyby. These electrons were present along the entire trajectory and provide the opportunity to use their pitch angle distributions with respect to the magnetic field in order to investigate the magnetic field topology at Ganymede. Observations of the loss cones for these pitch angle distributions are a simple means of determining whether or not a given magnetic field line intersects the moon's surface. It is found that the observed pitch angle distributions are inconsistent with the current magnetostatic model for the magnetic fields in the vicinity of Ganymede. Thus a major revision of this model is required that accounts for the contributions of the plasma dynamical interaction in order to achieve a more accurate assessment of an intrinsic magnetic moment in the interior of this moon. In addition, the electron energy fluxes into the polar cap at the time of flyby were measured to be about 1 erg/cm^2-s, or a total of approximately 5×10^{16} ergs/s over each polar cap available for excitation and ionization of any atmosphere near the moon's surface.

Introduction

At 1859:35 UT on 6 September 1996 the Galileo spacecraft achieved its closest approach altitude of a remarkable 261 km as it sped over the north polar cap of Ganymede. A plasma analyzer (PLS), which was specially designed for the comprehensive measurements of low–energy ions and electrons in Jupiter's fascinating magnetosphere, acquired high-resolution measurements via the spacecraft's tape recorder. The energy/charge (E/Q) range of the plasma analyzer is 0.9 V to 52 kV. A description of this instrumentation is given by *Frank et al.* [1992]. The results of an initial analysis of the ion observations, including the detection of a supersonic outflow of cold hydrogen ions from this moon, are published in a companion paper [*Frank et al.*, 1997]. Recently, data from the first two flybys of Ganymede as gained with the magnetometer on the Galileo spacecraft were used to conclude that this moon's interior is intrinsically magnetized. The model was constructed with a dipole magnetic field of Ganymede superposed upon an approximation of Jupiter's magnetic fields at the location of the moon [*Kivelson et al.*, 1996]. This model of Ganymede's magnetic field provides definite predictions as to whether or not a magnetic field line at the spacecraft will intersect the moon's surface. Thus, if the field line intersects the surface, a prominent "loss cone" of greatly diminished electron intensities arriving back to the spacecraft will be observed because of their absorption at the surface. The observations of the loss cone, or its absence, provide a simple, direct probe of the magnetic field topology. Because of the combination of the multi–sensor fields–of–view of the PLS and the rotation of the spacecraft, decisive observations of the pitch angle distributions of the electrons were achieved. We present these measurements here.

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Observations

The trajectory of the Galileo spacecraft during its close flyby past Ganymede is shown in Figure 1. The radius of Ganymede is 2634 km. The coordinates are X in the direction of rigid corotation of the Jovian plasma sheet, Z directed perpendicular to Ganymede's orbital plane, and Y for a right–handed coordinate system (generally toward Jupiter). A summary of the qualitative character of the electron pitch angle distributions is also shown in Figure 1. The small and large solid dots indicate the availability of measurements. The character of these distributions as the Galileo spacecraft passes through the region of interaction of Ganymede with Jupiter's plasma sheet is the principal topic of this paper.

The pitch angle distributions of electrons for a selected, but representative subset of available data are shown in Figure 2. The phase space densities are color coded according to the color bar in the upper left–hand corner and are plotted as functions of their speeds parallel ($V_{||}$) and perpendicular ($V_\perp$) to the ambient magnetic field as determined with the onboard magnetometer. The range of electron speeds for the present observations is $0.4–4 \times 10^4$ km/s. Positive $V_{||}$ is generally directed southward relative to Jupiter's equatorial plane.

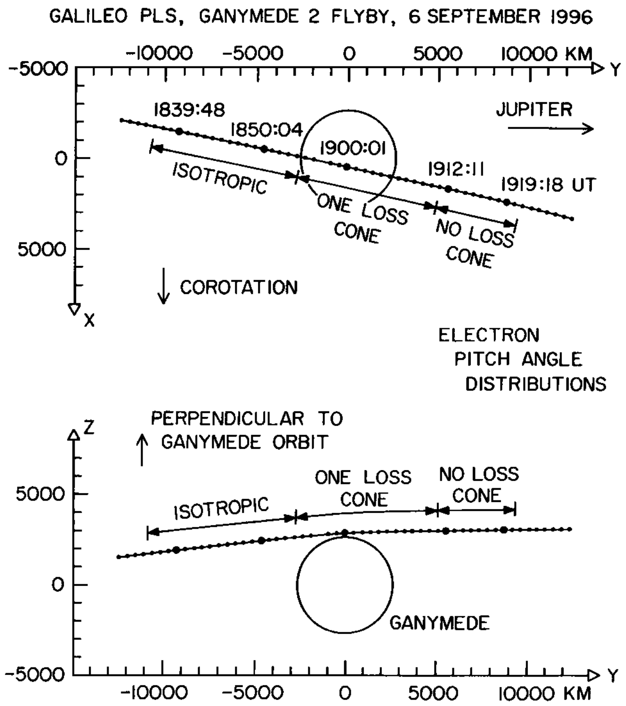

Figure 1. The trajectory of the Galileo spacecraft during its close flyby of Ganymede on 6 September 1996. The types of pitch angle distributions of electrons that were observed along the trajectory are summarized. The source of the electrons is Jupiter's plasma sheet.

Because the spacecraft passed over Ganymede's northern polar regions at closest approach, the absorption of electrons by the moon's surface would cause a large decrease in electron intensities observed with the plasma instrument along the $-V_{||}$ axis. This intensity decrease due to absorption of electrons by the surface of the moon will occur for all electron speeds and over the same range of pitch angles. This is the definition of "loss cone" used in this paper.

Examination of Figure 2 finds that the electron velocity distributions are isotropic during 1847 to 1854 UT, i.e., no loss cone. At 1854 UT there is a suggestion of a loss cone. For the interval 1855 to 1911 UT there is a well-defined loss cone for each pitch angle distribution. The magnetic field lines sampled along the spacecraft trajectory during this interval clearly intersect the surface of Ganymede. At closest approach at about 1900 UT the loss cone is greatest, approximately 60° for the angular dimension from the $-V_{||}$ axis to the edge of the decrease in phase space densities. During the period 1912 to 1920 UT the pitch angle distributions of the lower speed electrons are isotropic. During the overlapping interval of 1906 to 1915 UT the higher speed electrons exhibit intensity decreases along the $V_{||}$ and $-V_{||}$ axes. The pitch-angle distributions for electrons with higher speeds than reported here are discussed by *Williams et al.* [1997]. The above features are the principal characteristics of the electron pitch-angle distributions during the Ganymede flyby.

According to the model of Ganymede's intrinsic dipole field as deduced from magnetic field measurements [*Kivelson et al.*, 1996] the Galileo spacecraft enters this moon's magnetosphere at 1850 UT. The magnetic field lines in the model intersect Ganymede's surface and there must be a loss cone. Because there are no loss cones observed during the interval 1850–1854 UT the present magnetic model fails to provide an accurate description of the global topology of the magnetic fields (see Figures 1 and 2). In fact the dimensions of the loss cones, as computed with the model magnetic field, were 18° at 1850 UT, 27° at 1854 UT, 63° at 1900 UT, 35° at 1905 UT, and 18° at 1912 UT. Loss cones with dimensions $\gtrsim 10°$ are readily detectable with the plasma analyzers during the interval 1840–1920 UT, if present.

The pitch angle distributions during 1855–1905 UT display a well-defined single loss cone at all speeds as expected because the spacecraft is passing directly over the polar region of Ganymede (see upper panel of Figure 1). The following time interval of 1906–1915 UT exhibits another notable feature. At high speeds there are two intensity minima, i.e., one each along the $+V_{||}$ and $-V_{||}$ axes. There are at least two possible interpretations of this feature. The first is that one minimum is due to the intersection of the magnetic field with Ganymede, i.e., a loss cone, and the other minimum is due to the fact that the magnetic flux tube has been emptied of electrons with these pitch angles. This is certainly possible because an electron with speed of 40,000 km/s can travel to Jupiter and return in about 60 s. The second possibility is that the flux tube was emptied of electrons with these

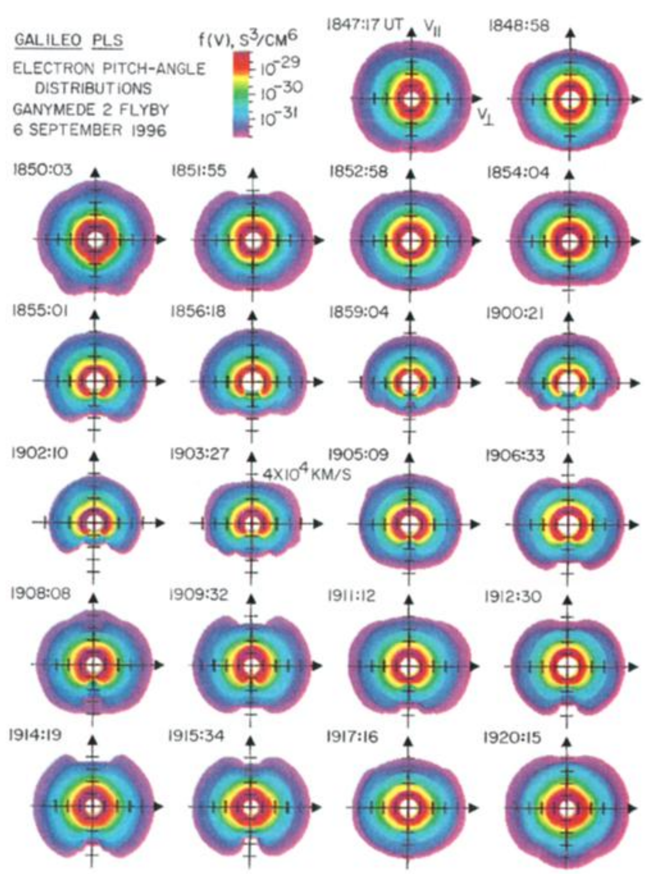

Figure 2. A summary of the pitch angle distributions of electrons which were observed during the Ganymede flyby. All of the samples of these distributions are not shown, but those taken near the major boundaries are included. The color scale for the phase space densities is shown in the upper left-hand corner.

pitch angles at earlier times when the field intersected Ganymede and this field line subsequently convected away from the moon to the spacecraft's position.

The above interpretive ambiguity in the intensity minima at higher speeds can be resolved with examination of the low-speed electrons during 1906–1915 UT. During 1906–1911 UT the low-speed electrons exhibit a loss cone. These magnetic field lines intersect Ganymede's surface. Also during this interval the two minima in high-speed electron intensities along $+V_{||}$ and $-V_{||}$ axes are due to the depletion of the electron intensities at these pitch angles along the entire Jovian magnetic field line. During 1911–1915 UT there is no loss cone in the pitch angle distributions of the low-speed electrons. Then, for this interval, the two field-aligned minima for the high-speed electrons are the signature of the initial loss of the entire electron population at these pitch angles by absorption on the surface of Ganymede and subsequent convection of this flux tube such that it no longer intersects this moon. The speeds of the low energy electrons are too slow to allow similar depletion for the entire flux tube because of the fast convection of these plasmas, 50 km/s [*Frank et al.*, 1997]. The travel time of the low-speed electrons is about 200 to 300 s and the field lines are transported out of the region of interest in less than 200 s. The spacecraft reenters the Jovian plasma sheet at about 1917 UT as shown by the last two pitch angle distributions in Figure 2. No loss cones or well-defined, field-aligned intensity minima are found in this region.

Examples of the electron pitch-angle distributions at constant speeds are shown in Figure 3. The phase space densities are plotted for bins of 20 degrees in pitch angle. With Figures 1 and 2 as guides, the distributions are: at 1848:58 UT in Jupiter's plasma sheet prior to Ganymede encounter, at 1852:58 UT in the region of increased magnetic fields inside the "magnetopause", at 1900:21 UT near closest approach, at 1909:32 UT downstream in the moon's interaction region, and at 1917:16 UT for the return to Jupiter's plasma sheet. The pitch angle coverage is sufficiently comprehensive such that a significant loss cone cannot avoid detection.

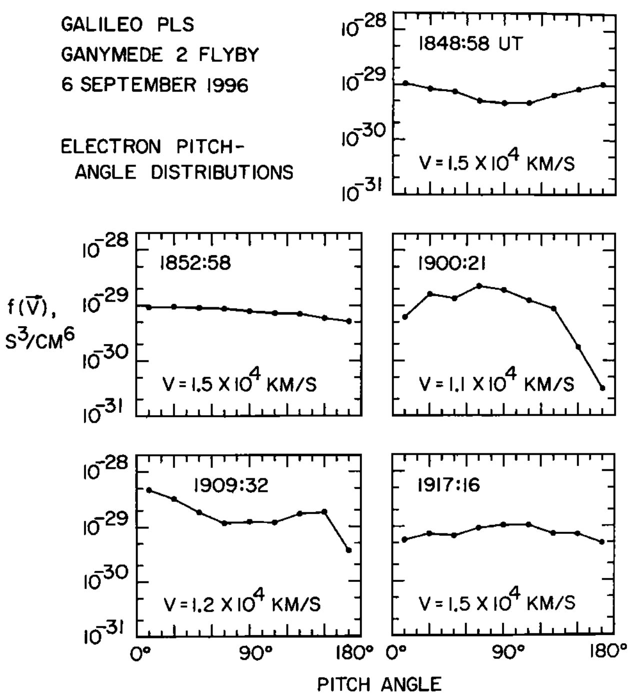

Figure 3. Plots of the pitch angle distributions at the specified speeds for a selected set from Figure 2.

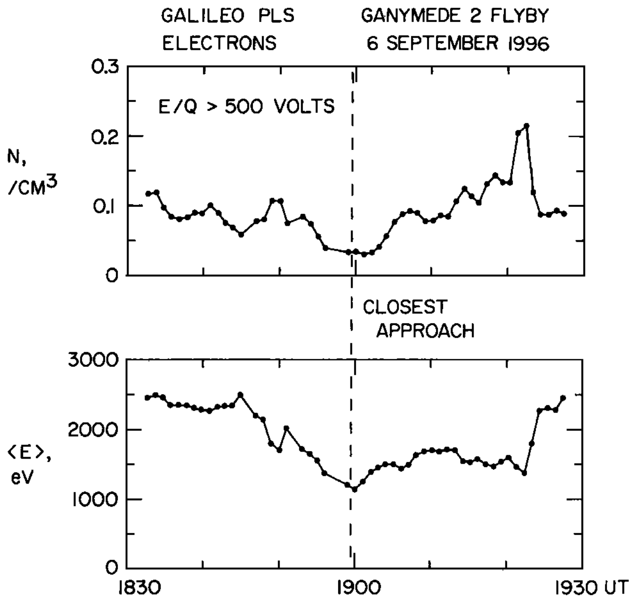

Figure 4. The average densities and average energies for warm electrons during the flyby of Ganymede.

The densities and temperatures of the warm electrons during the flyby of Ganymede are shown in Figure 4. These warm Jovian electrons were present throughout the flyby. In the Jovian plasma sheet the densities of the warm electrons account for approximately 10% of the total electron number density. The cold electrons provide the remaining significant densities. The warm electron densities and temperatures, and the total densities [*Frank et al.*, 1997], at this position in the Jovian plasma sheet are similar to those observed with the plasma instrumentation on Voyager [*Belcher*, 1983]. The energy influx into Ganymede's north polar cap during the flyby as evidenced by the loss cones during 1855 to 1905 UT in Figure 2 is about 1 erg/cm^2–s.

Discussion

We report the pitch angle distributions of electrons within the energy range 70 eV to 4.5 keV as observed during the close flyby over Ganymede's northern polar cap by the Galileo spacecraft. These electrons are those of Jupiter's plasma sheet which were present in the vicinity of Ganymede throughout the flyby. According to the analysis of the magnetic field measurements during this close flyby there is an intrinsic dipole field in Ganymede's interior [*Kivelson et al.*, 1996]. These researchers claim that there was a crossing of the "magnetopause" of this moon's magnetosphere at 1850 UT. This "magnetopause" is more accurately described as a separatrix between Jovian magnetic field lines and those field lines with one end intersecting Ganymede's surface and the other end mapping into Jupiter's atmosphere. It is useful to refer to Figure 1 at this point. The spacecraft subsequently passed over Ganymede's polar cap and remained in this moon's magnetosphere until about 1923 UT according to the interpretation of the magnetometer records [*Kivelson et al.*, 1997]. The magnetospheric model of *Kivelson et al.* [1996] employed the simple magnetostatic superposition of Ganymede's dipolar field onto a uniform field for the Jovian plasma sheet. There was no consideration of a substantial dynamical interaction with the flowing plasmas of the Jovian plasma sheet.

The magnetic model of *Kivelson et al.* [1996] requires that each field line intersects Ganymede's surface during the interval 1850 to 1923 UT. The presence or absence of loss cones in the electron pitch-angle distributions is used to test this prediction. Indeed well-defined loss cones due to the absorption of electrons by impact with the moon's surface were observed during 1854 to 1911 UT. However, no loss cones were present during the intervals at 1850–1854 UT (inbound to Ganymede) and 1912–1923 UT (outbound). These observations are incompatible with the present magnetostatic model for Ganymede's magnetic field [*Kivelson et al.*, 1996] and suggest that the interior dipole moment may be considerably weaker. The plasma dynamical interaction of Ganymede with the Jovian plasma sheet is strong [*Frank et al.*, 1997] and should be investigated with adequate three-dimensional numerical simulations in order to obtain an accurate assessment of the intrinsic dipole moment in Ganymede's interior.

There is a possible interpretation of the absence of a loss cone during the two above critical intervals in terms of an electric field parallel to the magnetic field and positioned between the spacecraft and Ganymede's surface. The direction of the electric field would be such that the electrons are reflected before reaching the moon's surface. Because no field-aligned intensity minima are observed for electrons with $E \lesssim 10$ keV this potential drop must be 10 kV or more. Examination of the trajectory in Figure 1 and the smoothly varying densities of hot electrons in Figure 4 shows that this electric field is severely constrained by being present and absent at sharp transition boundaries at about 1854 UT and 1911 UT with no corresponding substantial change in the electron parameters. Thus the existence of such electric fields is considered to be unlikely.

A principal source of particle precipitation into the polar caps of Ganymede are electrons with average energies of about 0.5 to 3 keV from the Jovian plasma sheet. The energy influx during the Ganymede flyby is about 1 erg/cm^2–s. For a polar cap with a reasonable diameter of 3000 km, the total energy influx available for ionization and excitation phenomena is about 5×10^{16} ergs/s. A second source of electron energy influxes are the low-energy electrons with $E \lesssim 15$ eV. The number densities of the above warm electrons with energies in the range of 0.5 to 3 keV are only a fraction, $\sim 5 \times 10^{-3}$, of the total densities of ~100 /cm^3 [*Frank et al.*, 1997]. The determination of the temperatures of the low-energy electrons is subject to a final analysis of the spacecraft potential but, with an assumed average energy of ~10 eV, the corresponding energy fluxes into the polar caps are ~0.5 ergs/cm^2–s and comparable to the energy influxes from the warmer electrons.

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