GEOPHYSICAL RESEARCH LETTERS, VOL. 24, NO. 17, PAGES 2155-2158, SEPTEMBER 1, 1997

The magnetic field and magnetosphere of Ganymede

M. G. Kivelson[1,2], K. K. Khurana[1], F. V. Coroniti[3], S. Joy[1], C. T. Russell[1,2], R. J. Walker[1], J. Warnecke[1], L. Bennett[1], and C. Polanskey[4]

Abstract. Within Jupiter's magnetosphere, Ganymede's magnetic field creates a mini-magnetosphere. We show that the magnetic field measured during Galileo's second pass by Ganymede, with closest approach at low altitude almost directly over the moon's polar cap, can be understood to a large measure in terms of the structure of a vacuum superposition model of a uniform field and a Ganymede-centered dipole field. Departures from the simple model can be attributed principally to magnetopause currents. We show that the orientation of the observed magnetopause normal is qualitatively consistent with expectations from the vacuum superposition model. The magnetopause currents inferred from the inbound boundary crossing are closely related to expected values, and the magnetic structure of the boundary is similar to that observed at the magnetopause of Earth. We use the vacuum magnetic field model to infer the magnetic field near Ganymede's surface, and thereby predict the particle loss cones that should be present along the spacecraft trajectory. By mapping a fraction of the corotation electric field into the polar cap, we determine expected flow velocities near closest approach to Ganymede as a function of reconnection efficiency. We conclude by discussing prospects for measurements on Galileo's remaining passes by Ganymede.

Introduction

Galileo's first two passes by Ganymede revealed the existence of an internal magnetic field strong enough to carve out a magnetosphere within Jupiter's magnetosphere [*Kivelson et al.*, 1996; *Gurnett et al.*, 1996]. The implications of an internal field for models of Ganymede's internal structure and for our understanding of planetary dynamos have been discussed elsewhere [*Kivelson et al.*, 1996; *Schubert et al.*, 1996]. Here we focus on some of the features of that magnetosphere and consider the implications for currents and flows within and around it.

Both passes occurred near noon at locations well northward of the magnetospheric current sheet in locations where the magnetospheric field of Jupiter was oriented radially outward and southward with a magnitude near 100 nT. The flow speed was 152 km/s km/s (below the corotation speed of ~190 km/s) [*Williams et al.*, 1997]. Other plasma conditions near Ganymede's orbit can be inferred from Voyager reports. The density ranges from ~1 cm^{-3} to 10 cm^{-3} [*Belcher*, 1983]. Thermal pressure is dominated by 10s of keV particle contributions; near the center of the current sheet, the pressure is ~15 nPa [*Mauk et al.*, 1996] but this pressure drops considerably with height above the current sheet and well above the current sheet, it is small compared with the magnetic pressure of ~8 nPa. The dynamic pressure well above the current sheet is ~1 nPa and the Alfvén Mach number is ~0.3. In Figure 1, we show the magnetic field measurements (components: B_x, B_y, B_z and magnitude B) for the second pass at a time resolution of 0.33 s. The data are given in a Ganymede-centered coordinate system with $\hat{\mathbf{x}}$ along the direction of corotation, $\hat{\mathbf{z}}$ parallel to Jupiter's spin axis, and $\hat{\mathbf{y}}$ radially inward to Jupiter. In an earlier publication [*Kivelson et al.*, 1996], we showed 1 minute averaged data read directly from the magnetometer memory [*Kivelson et al.*, 1992] before the higher resolution data stored on the spacecraft tape recorder were available. Despite the improvement of more than two orders of magnitude in time resolution, the two data sets differ little except in two localized regions which we discuss below.

In Figure 1, we also plot a model field obtained as a vacuum superposition of a Ganymede-centered dipole [*Kivelson et al.*, 1996] and a model of the magnetic field of Jupiter's magnetosphere [*Khurana*, 1997]. The model is a lowest order approximation that does not incorporate the plasma interactions but has proved extremely useful in organizing many of the features of the observations. We explore some of the inferences that we can draw from the model and also comment on some

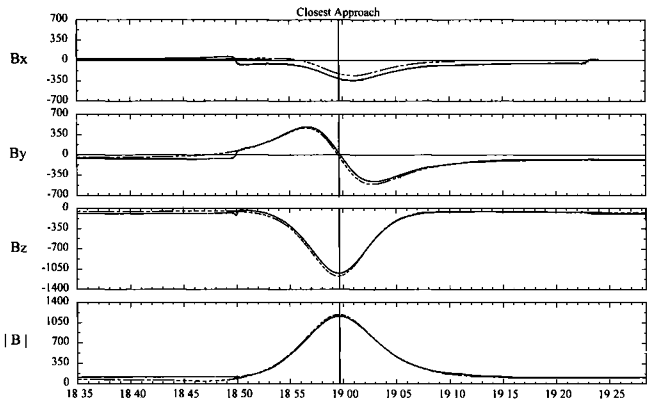

Figure 1. The three components of the magnetic field B_x, B_y, B_z and its magnitude B in a Ganymede-centered coordinate system with x along the direction of corotation, y radial and positive inward towards Jupiter, and z aligned with Jupiter's spin axis. Both magnetometer data (solid line) and a model described in the text (dashed line) are plotted from 18:35 UT to 19:35 UT on September 6, 1996. Trajectory information is given beneath the panels. Data are 0.33 s averages. Closest approach is marked.

[1]Institute of Geophysics and Planetary Physics, University of California, Los Angeles, Los Angeles, CA. (e-mail: mkivelson@igpp.ucla.edu; kkhurana@igpp.ucla.edu; sjoy@igpp.ucla.edu; ctrussell@igpp.ucla.edu; rwalker@igpp.ucla.edu; joerg@igpp.ucla.edu; lbennett@igpp.ucla.edu)
[2]Department of Earth and Space Sciences, University of California, Los Angeles, Los Angeles, CA.
[3]Department of Physics University of California, Los Angeles Los Angeles, CA. (e-mail: coroniti@physics.ucla.edu)
[4]The Jet Propulsion Laboratory, 4800 Oak Grove Avenue, Pasadena, CA. (e-mail: cpolanskey@gllsvc.jpl.nasa.gov)

Paper number 97GL02201.
0094-8534/97/97GL-02201$05.00

elements of the measurements that are not well-represented by simple vacuum superposition.

Features of the Data

The background magnetic field of Jupiter at Ganymede's location ($\mathbf{B}_o$) was dominated by the radial and southward components with $\mathbf{B}_o$ = (17, -67, -88) nT and B_o = 113 nT. As Galileo passed over the polar cap at an altitude of 0.1 R_G (R_G, Ganymede radius = 2634 km), the field magnitude reached 1167 nT, an order of magnitude larger than the ambient field, and rotated to point towards Ganymede's magnetic north pole which is tilted 10° from the spin axis towards 200° Ganymede east longitude [*Kivelson et al.*, 1996]. (Ganymede's field is northward-oriented at the equator where its surface magnitude is 750 nT.) The field varied extremely smoothly through most of the interval near closest approach (with the largest fluctuations of order 5-6 nT) except for two clear and relatively abrupt rotations at 18:49:53 to 18:50:23 UT and ~19:22:27 to 19:24:03 UT that we have interpreted as magnetopause crossings. We have rotated the data through the inbound magnetopause crossing into a boundary normal coordinate system [*Russell and Elphic*, 1978] which we plot in Figure 2. The rotation appropriately places the full change across the boundary in the L direction and gives a nearly constant value in the N direction. The M component shows a small rotation within the magnetopause boundary of the type often noted in crossings of the terrestrial magnetopause. The boundary normal direction is (0.659, 0.748, -0.074), meaning that the projection into the y-z plane is nearly aligned along the y direction.

The general structure of the Ganymede magnetosphere can be understood by considering the field lines in the schematic of the vacuum superposition model illustrated in Figure 3 in a jovian meridian plane that passes through Ganymede's center. The parameters for the model were selected for analysis of the first pass by Ganymede on 27 June 1996. The background field of Jupiter near the Ganymede encounter was taken as a uniform field of 120 nT pointed away from Jupiter at an angle of ~125° to the spin axis and lying in the meridian plane. The Ganymede dipole was also modeled as lying in the plane, with its north pole tilted by 10° away from Jupiter. At the surface magnetic equator, the dipole field points north with a magnitude of 750 nT. Although $\mathbf{B}_o$ differed slightly from the values selected for the schematic illustration during the second pass, the qualitative features of the field geometry remain approximately unchanged. The trajectories for the two first passes by Ganymede are shown, also projected into the meridian plane. The dashed field lines in this schematic link to Jupiter's ionosphere at both ends. Solid field lines link to Ganymede at one or both ends. The heavy curves represent the separatrix surface that encloses Ganymede-linked field lines. In our simple representation, this separatrix plays the role of the magnetopause in a conventional magnetosphere and it encloses a region of diameter ~ 4 R_G (radius of Ganymede = 2,631 km). Despite the simplifications of the field geometry that we have imposed, the inbound crossing of the separatrix in the model occurs at 18:48 UT, within ~2 minutes of the actual magnetopause crossing and the boundary normal has the orientation inferred from the data The outbound crossing of the separatrix occurs at 19:26 UT, a bit more than 2 minutes after the observed exit. In both cases, the field magnitude does not change across the magnetopause which is consistent with our expectations that the thermal pressure and the normal component of the dynamic pressure of the ambient plasma are small compared with magnetic pressure at the locations of the boundary crossings.

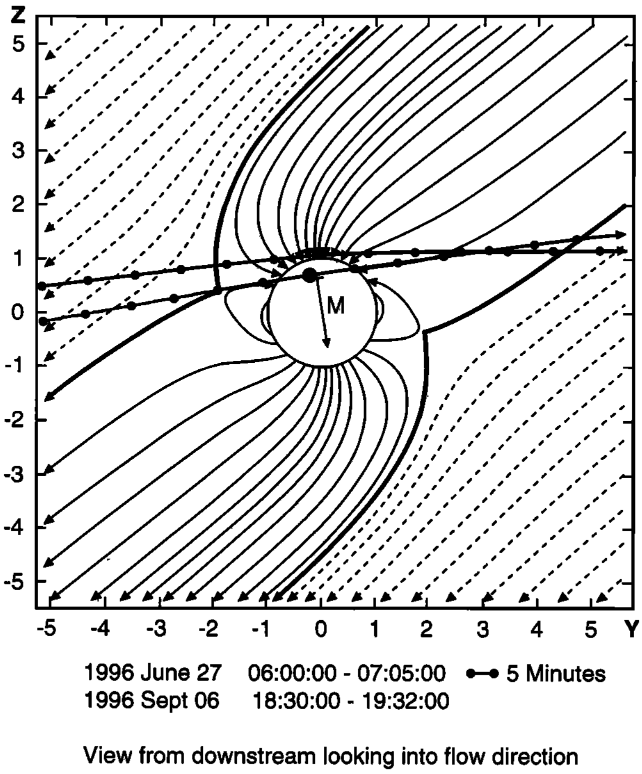

Figure 3. A schematic representation of the field geometry in a jovian meridian plane cutting through Ganymede's spin axis. the view is from positive x towards Ganymede. Ganymede's magnetic moment is labeled **M**. Dashed lines are used to represent field lines that do not link to Ganymede. Solid lines represent field lines that link at least once to Ganymede. The separatrix surface that bounds the latter type of field lines is shown with a heavy line. Crossing the field lines are curves showing the trajectories of the Ganymede flybys on June 27, 1996 (identified by the large black circle) and on September 6, 1996 projected into the plane of the schematic. Small black circles are placed at 5 minute intervals on the trajectory starting at 06:00 UT for the June 27 case and at 18:30 UT for the September 6 case.

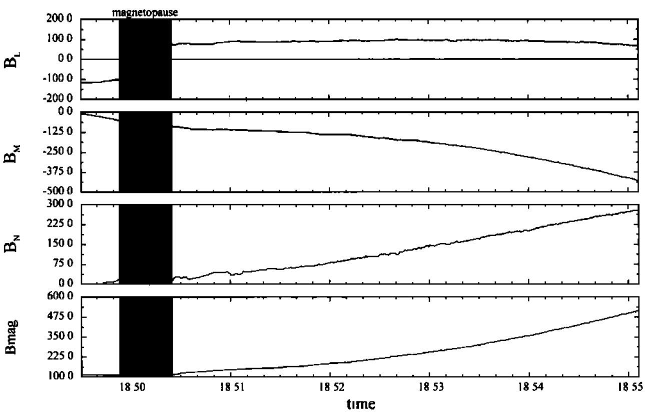

Figure 2. Data for the inbound Ganymede magnetopause crossing on September 6, 1996 in a minimum variance coordinate system with L along the direction of maximum change and N along the direction of minimum change.

The vacuum superposition model omits effects of currents external to Ganymede, yet such currents are certainly present. We believe that the primary differences between the data and the model in Figure 1 can be interpreted in terms of expected plasma currents. For example, before the inbound magnetopause crossing, a slow increase in B_x is just what would occur if the plasma flow around the Ganymede-obstacle slowed more near the equator than at higher Ganymede-latitudes, with the importance of that slowing increasing on approach to the magnetopause.

Neubauer [1980] developed the theory of the interaction of the flowing plasma of Jupiter's magnetosphere with Io, an obstacle in the flow. In the case of Ganymede, the obstacle is the magnetosphere, but the analysis differs little. The magnetopause is a current-carrying boundary, in this case part of the Alfvén wing current system that closes through Ganymede or its ionosphere. This current system adds a negative B_x perturbation over the northern polar cap. Indeed, in the interval between the two magnetopause crossings, the principal difference between the measured field, **B** and the modeled one, $\mathbf{B}_M$ is a nearly constant difference in the x-component: $\delta B_x = B_x - B_{Mx} \approx 100$ nT. *Neubauer's* [1980] upper limit to the current, I, flowing in each Alfvén wing can be written

$$I = 2\ell M_A B_o / \mu_0 \approx 0.5 M_A \qquad (1)$$

where M_A is the Alfvén Mach number of the unperturbed flow, which near Ganymede is ~0.3, B_o is the background field ≈ 100 nT, and ℓ is the diameter of the obstacle which we take as 4 R_G. The rotation of the field at the first magnetopause crossing (where the tangential field changed by ~200 nT in 1 minute) provides an independent estimate of the current carried in the Alfvén wings. If the Alfvén wing current is carried in sheets of length ℓ along the flow direction, then the total current flowing in the Alfvén wings is

$$I = \kappa \ell \delta B / \mu_0 \approx 1.6\, \kappa MA \qquad (2)$$

where we have included a factor κ of order 1 to account for the geometry. The two estimates agree for $\kappa = 0.3$.

Model Estimates of Field and Plasma Parameters

The magnetometer measurements determine the properties of the field along the spacecraft trajectory, but particle measurements can be used to probe field properties at remote locations. For example, measurements of the loss cone angle along the trajectory can be used to determine the magnitude of the surface field at the intersections of the field lines with Ganymede's surface. We have used the vacuum superposition model plotted in Figure 1 to predict the changing angles of particle loss cones in fluxes of northward-traveling charged particles as a function of time. In Figure 4 we show the magnitude of B in the field model sampled along the trajectories for the first two passes by Ganymede. We trace the field lines from the trajectory to their intersection with Ganymede's surface and also show the magnitude of that surface field, B_s, at each point along the trajectory. The loss cone angle, α_{lc}, satisfies $\sin^2 \alpha_{lc} = B / B_s$ and represents the range of angles about the direction of the local magnetic field that is devoid of upward-moving particles because of losses into Ganymede's surface or atmosphere. The loss cone becomes quite small and difficult to detect as the trajectory approaches the magnetopause. Data on particle loss cones for the second Ganymede flyby are reported by *Williams et al.* [1997]

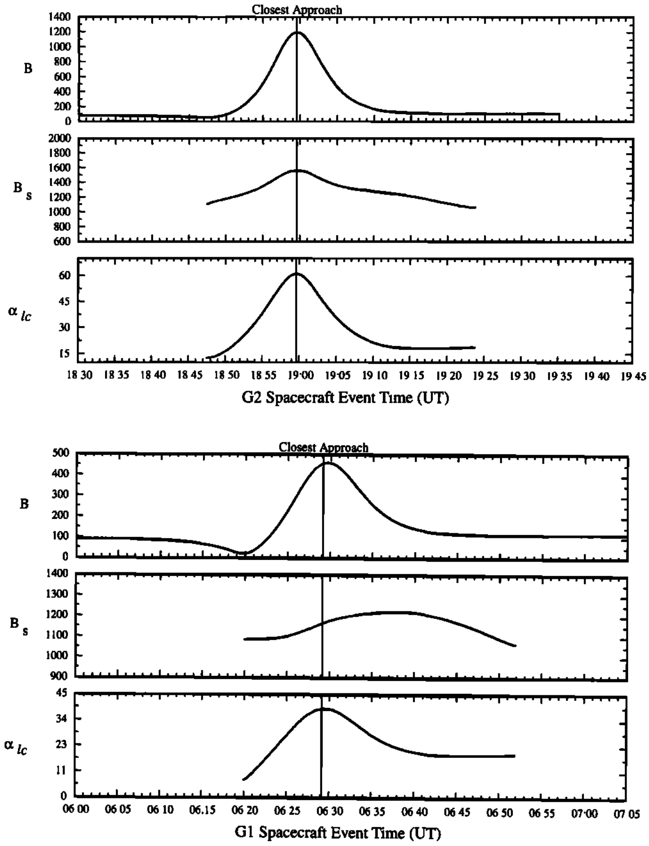

Figure 4. The magnitude B of the model field (see text for the description of the model field used in Figure 1) along the trajectory, the field magnitude B_o at the foot of the field line at Ganymede's surface, and the loss cone angle α_{lc} along the trajectory for (a) the polar pass of September 6, 1996 and (b) for the lower latitude pass of June 27, 1996.

and *Frank et al.* [1997] for energetic particles and thermal plasma, respectively. The loss cones observed by the energetic particle detector are in good quantitative agreement with the predictions of the model.

There is an interesting link between flow speeds over Ganymede's polar cap and reconnection efficiency at the nose of its magnetopause. This follows from the fact that the voltage drop across the magnetosphere is a fraction of the voltage drop across the same distance in the corotating flow upstream. Thus, the convection electric field within the magnetosphere of Ganymede is a fraction of the corotation electric field determined by the efficiency of reconnection. The model allows us to estimate the convective flow speeds of plasma over the polar cap if the reconnection efficiency is known, and conversely allows us to estimate the reconnection efficiency if the flow speed over the polar cap is known. We assume that the magnetospheric plasma upstream of the magnetopause is corotating at a velocity $\mathbf{v}_{cr} = \mathbf{E}_{cr} \times \mathbf{B}_o / B_o^2$ where $\mathbf{E}_{cr}$ is the corotation electric field. Much as in Earth's magnetotail, the electric field E_L in the lobes (at high altitudes well away from the surface where the field is approximately uniform and $\approx B_o$) is a fraction ε of the corotation field, with ε the efficiency of reconnection on the upstream boundary. Thus, at high altitudes within the lobes of Ganymede's magnetosphere, the convective flow speed v_L is

$$v_L = E_L / B_o = \varepsilon E_{cr} / B_o \qquad (3)$$

However, we are interested in estimating v, the flow speed at the low altitude of the second Ganymede pass. We must map the electric and magnetic fields from the lobe down to the trajectory of Galileo at low altitude above the polar cap. We assume that the convecting flux tubes are at constant potential (although parallel electric fields may well be present in some regions, particularly near the polar cap boundary). As one follows a flux tube from the lobe towards the polar cap, the magnetic field increases from B_o to B which was $\leq 10\ B_o$ for the second Ganymede pass. Because the width of the flux tube decreases approximately like $(B_o/B)^{1/2}$, the electric field increases from E_L to E where $E \approx E_L(B/B_o)^{1/2}$. Thus, along the trajectory of Galileo, the flow is approximately

$$v = (E_L/B)(B/B_o)^{1/2} = \varepsilon v_{cr}(B_o/B)^{1/2} \quad (4)$$

For $\varepsilon = 1$, i.e., 100% reconnection efficiency, equation (4) provides an upper limit for the flow speed near the center of the polar cap (where $B \approx 10\ B_o$) of ≈ 60 km/s (assuming $v_{cr} \approx 180$ km/s). As the upstream fields are quite skewed from an antiparallel orientation with the dipole field lines near the low Ganymede latitude upstream magnetopause, such high efficiency seems improbable. A more likely value of ε is probably between 0.1 and 0.3. At 18:55 UT and 19:03 UT, the field is ~600 nT and the flow speed is $v \approx 0.4\ \varepsilon\ v_{cr} \approx 73\ \varepsilon$ km/s. This values agrees with the *Williams et al.* [1997] estimate of 25-45 km/s for reasonable values of ε. Further comparisons will establish more accurately the reconnection efficiency in Ganymede's magnetosphere.

Future Passes

In Galileo's remaining passes by Ganymede, there will be an opportunity to approach closely or even encounter field lines of Ganymede's magnetosphere that link to Ganymede at both ends, the equivalent of closed field lines in the terrestrial magnetosphere. One would expect that this will allow us to investigate the return flow which is required to conserve flux in a convecting magnetosphere. We will also have a chance to investigate more fully the processes whereby flux tubes reconnect in the downstream region.

Summary

The magnetosphere of Ganymede provides an opportunity to study a magnetosphere in a plasma regime never previously investigated, with sub-Alfvénic upstream flow and a large and predictable orientation of the upstream magnetic field. The scale lengths are small, but still large enough for magnetohydrodynamic arguments to apply to many of the features observed. Here we have merely touched on some of the phenomena of physical importance that will require deeper investigation in the future.

Acknowledgments. We appreciate the capable assistance of A. Fredericks and D. Wolkovitch at UCLA and of D. Bindschadler and Y. Mei at the Jet Propulsion Laboratory. Work was supported by the Jet Propulsion Laboratory under contract # 958694.

References

Belcher, J. W., Low-energy plasma in the jovian magnetosphere, *Physics of the Jovian Magnetosphere*, A. J. Dessler, Ed., Cambridge Univ. Press, N.Y., 1983.

Frank, L. A., et al., *Geophys. Res. Lett.*, this issue, 1997.

Gurnett, D. A., W. S. Kurth, A. Roux, S. J. Bolton, and C. F. Kennel., Evidence for a magnetosphere at Ganymede from plasma-wave observations by the Galileo spacecraft, *Nature*, *384*, 535, 1996.

Khurana, K. K., Euler potential models of Jupiter's magnetospheric field, *J. Geophys. Res.*, *102*, 11,295, (1997).

Kivelson, M. G., K. K. Khurana, C. T. Russell, R. J. Walker, J. Warnecke, F. V. Coroniti, C. Polanskey, D. J. Southwood, and G. Schubert, Discovery of Ganymede's magnetic field by the Galileo spacecraft, *Nature*,.*384*, 537, 1996.

Kivelson, M. G., K. K. Khurana, J. D. Means, C. T. Russell & R. C. Snare, , The Galileo Magnetic Field Investigation, *Space Science Rev.*, *60*, 357 (1992).

Mauk, B. H., S. A. Gary, M. Kane, E. P. Keath, and S. M. Krimigis, Hot plasma parameters of Jupiter's inner magnetosphere, *J. Geophys. Res.*, *101*, 7685, 1996.

Neubauer, F. M., *J. Geophys. Res. 85*, 1171, 1980.

Russell, C. T., and R. C. Elphic, Initial ISEE magnetometer results: Magnetopause observations, *Space Science Rev. 22*, 681, 1978.

Schubert, G., K. Zhang, M.G. Kivelson, and J.D. Anderson, The magnetic field and internal structure of Io and Ganymede, *Nature, 384*, 544, 1996

Williams, D. J., B. H. Mauk, R. W. McEntire, E. C. Roelof, T. P. Armstrong, B. Wilken, J. G. Roederer, S. M. Krimigis, T. A. Fritz, L. J. Lanzerotti, and N. Murphy, Energetic particle signatures at Ganymede: Implications for Ganymede's magnetic field, *Geophys. Res. Lett.*, this issue, 1997.

(Received: March 17, 1997; revised: July 8, 1997;
accepted: July 11, 1997.)