GALILEO AT JUPITER: CHANGING STATES OF THE MAGNETOSPHERE AND FIRST LOOKS AT IO AND GANYMEDE*


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ABSTRACT

Several investigations based on data from the magnetometer on the Galileo Orbiter are described. From Galileo’s initial inbound pass, we learn that the magnetosphere can experience large changes in its magnetic configuration. Between 50 and 30 R_J, the radial magnetic forces on the plasma were larger in 1995 than in 1973 when Pioneer 10 passed through the same region of the magnetosphere, implying that either external or internal plasma forces were also larger. Although there are several ways to interpret the change of the magnetic configuration, we suggest that the variations are governed principally by the solar wind dynamic pressure and that the dayside magnetosphere as far in as ~30 R_J may be more strongly affected by the solar wind than has previously been recognized. Minor effects of higher mass loading may also be present. Data from the flyby of 10 show a large magnetic perturbation; we argue that it is plausible that Io has an intrinsic magnetic field and that also contributions from plasma perturbations are significant. We find unexpected evidence that molecular ions are being picked up over a large spatial region in the vicinity of the moon. During the pass by Ganymede we observed a large magnetic perturbation consistent with an intrinsic dipole field. The multiple flybys of Ganymede scheduled for later portions of Galileo’s mission will allow us to test our understanding of the magnetic signature.

THE INBOUND PASS

The Galileo Orbiter, inbound towards insertion into orbit around Jupiter on December 8, 1995, acquired magnetic field data in the outer and middle magnetosphere near the dawn meridian. Galileo is the sixth spacecraft to have probed the jovian magnetosphere. All of the other spacecraft entered from near 10:00 LT. Exits were more dispersed as can be seen in Figure 1.

A prime mission objective of the Galileo Orbiter is to characterize the temporal variability of the magnetosphere on long time scales. In order to be sure that differences between two sets of measurements

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represent temporal changes, it is desirable to acquire data at different times in the same spatial region of the magnetosphere. Fortunately Galileo’s inbound pass occurred within one hour of local time of the path along which Pioneer 10 left the jovian magnetosphere just 22 years or 2 solar cycles earlier, and thus a comparison of the two data sets can shed light on questions of time variability. We will show that the magnetic structure observed on two passes through the same spatial region of the magnetosphere differed considerably, and we will discuss possible reasons for the changes.

The internal computer of the magnetometer (Kivelson et al., 1992) can be set to average the magnetic field at sampling rates from once per minute to once per 16 hours. The rate is selected to provide data

![Bowshock Crossings at Jupiter](image1)

![Galileo and Pioneer 10: JSE Coordinates](image2)

Fig. 1. Above: Schematic of the trajectories of Galileo, Voyager 1, Voyager 2, Pioneer 10 and Pioneer 11 in an equatorial plane projection with shock crossings marked by circles. Ulysses shock crossings are marked with squares. Pioneer 10 exited near dawn, Pioneer 11 just pre-noon, Voyager 1 near 0400 LT, Voyager 1 near 0200 LT, and Ulysses near dusk. Schematic shock surfaces illustrated represent possible forms for differing solar wind dynamic pressure and/or different internal plasma conditions. Below: The inbound Galileo trajectory and the outbound Pioneer 10 trajectory in a cylindrical system with \( \tau \) along the spin axis of Jupiter and \( \rho \) perpendicular to the spin axis. The Galileo and Pioneer 10 trajectories were inclined to the rotational equator by -6° and +10°, respectively.
continuity despite infrequent and intermittent interrogation from ground tracking stations. During several weeks before closest approach, 2 to 8 minute averages were acquired and these data are used here to identify shock crossings and study the large scale structure of the outer and middle magnetosphere.

Three pairs of shock crossings (inbound and outbound separated by roughly 2 hours) were followed by a final shock crossing into the magnetosheath. The shock locations between 214 $R_J$ and 156 $R_J$ are shown in Figure 1 (above) where the positions of shock crossings reported from previous flybys are also plotted. The full set of shock crossings is analyzed by Huddleston et al. (1997) who infer the global structure of the jovian shock surface.

On the flanks of the magnetosphere, the transition through the magnetopause is not always clear so we cannot specify its position precisely. However, the field within the magnetosphere is predictably southward-oriented with an amplitude of a few nT, and when a persistent southward field is observed, we argue that the spacecraft must have crossed the magnetopause. The crossing occurred on November 28 near 118 $R_J$. Thereafter the spacecraft remained within the magnetosphere, and near 105 $R_J$ clear periodic structure related to encounters with a tilted equatorial current disk developed.

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Figure 1 (below) shows that inbound Galileo and outbound Pioneer 10 trajectories were inclined at small angles to the rotational equator (−6° and +10°, respectively), with Galileo below the equator and Pioneer 10 above the equator. (Galileo moved radially about 10 $R_J$ per day. Pioneer 10 moved radially about 13 $R_J$ per day.) Symmetry arguments suggest that in a spherical coordinate system referenced to the planetary spin axis, the radial and azimuthal components of the magnetic field would be antisymmetric about the equator and the component along the polar angle would be symmetric. In Figure 2 we have plotted the Pioneer 10 outbound data as if they had also been acquired on a trajectory below the equator, assuming the proposed symmetry. A fit to the Pioneer 10 data (Khurana, 1997, referred to as Khurana-97) has also been plotted. Khurana’s model includes the internal field of Jupiter (the O6 model of Connerney (1992)) and a hinged and warped magnetodisk current system (without magnetopause currents). The model is applicable in regions where the field is little affected by the neglected magnetopause currents which includes much of the dawn-dusk and nightside low latitude magnetosphere and the inner magnetosphere at all local times. For appropriately selected parameters, it represents the outbound Pioneer 10 data out to ~90 $R_J$ in the dawn sector and the outbound Voyager 1 and Voyager 2 data at earlier local times. It is evident in Figure 2 that significant departures from the model occur only outside of ~90 $R_J$ where local magnetopause currents contribute important perturbations. Smith et al. (1976) refer to the outer region of fluctuating field with strong southward tilt where the magnetopause currents contribute significantly as the outer magnetosphere; such a region is observed on other inbound dayside passes. In the better-ordered region closer to Jupiter that Smith et al. refer to as the middle magnetosphere, the components $B_\perp$ and $B_\parallel$ dominate.

The Khurana-97 model can be sampled along other trajectories and, thus, provides a useful prediction of the field expected along Galileo’s orbit. In Figure 3, we show the Galileo data and compare it with the predictions along the Galileo trajectory from the field model. It is evident that the Galileo magnetic field data are highly disordered compared with both the model field and the field measured by Pioneer 10. The $B_\parallel$ component exceeds the model values almost everywhere inside of 90 $R_J$. Ten hour oscillations linked to planetary rotation are evident between 35 and 55 $R_J$ and between ~90 and 105 $R_J$. In these ordered regions, the magnitude of $B_\perp$ is close to the prediction with only slight phase shifts evident, but the magnitude of $B_\parallel$ exceeds the model values, particularly inside of 50 $R_J$.

As one cannot attribute the differences in the degree of order evident in Figures 2 and 3 to the locations of the passes within the magnetosphere, we think it likely that Galileo encountered the magnetosphere in a macroscopically different state than did Pioneer 10. Critical to our interpretation of those differences are data in the region between 30 and 50 $R_J$ where Galileo’s $B_\parallel$ values are enhanced by a factor of 2 relative to the model. As the azimuthal component of the current density $j_\phi$ was virtually the same for Galileo and Pioneer 10 outbound ($j_\phi$ is dominated by $\mathcal{E}_r/\mathcal{E}$ which changed little), the radial magnetic force,
Fig. 2. Magnetometer data from the outbound pass (December 1973) of Pioneer 10. From top to bottom: the magnitude and the azimuthal, polar, and radial components of the field. The coordinate system is a right-handed spherical coordinate system referenced to the spin axis of Jupiter. When $B_\theta > 0$, the field points southward. The signs of the radial and azimuthal components have been inverted to approximate the field components along a reflected southern hemisphere trajectory that would closely resemble the Galileo trajectory. The narrower, smoother line shows the model values of the field predicted from the Khurana (1997) Pioneer 10 magnetodisk model of the magnetic field. Beyond 130 Rj, the spacecraft was in the magnetosphere. The magnetopause moved inside the spacecraft, leaving it in the magnetosheath (shaded) between 98 and 130 Rj after which the magnetopause again moved out and Galileo returned to the magnetosphere. The 10 hour oscillations are clear.
Fig. 3. Magnetometer data from Galileo’s initial inbound pass (November 24, 1995 to December 6, 1995) plotted versus radial distance in Jupiter radii (Rj) as in Figure 2. The time resolution is 8 minutes, but between 73.2 and 73.8 Rj some data are plotted at 4 minute resolution. Beyond 130 Rj, the spacecraft was in the solar wind. Shading between ~120 and 130 Rj indicates an interval in the magnetosheath. The narrower, smoother line shows the model values of the field predicted from the Khurana (1997) magnetodisk model of the magnetic field along Galileo’s trajectory. Parameters that fit the Pioneer 10 outbound magnetic field data inside of ~90 Rj have been used. As in Figure 2, one sees a modulation corresponding to the ~10 hour period of planetary rotation, but a cycle covers a greater radial distance in the Pioneer 10 plot because of the greater speed along a flyby trajectory. (The Galileo inbound speed was deliberately low in order to allow capture into orbit.) Consequently, Pioneer 10 covered large distances in each planetary rotation and the oscillations of the field are spread out in a plot vs. radial distance.
was roughly a factor of 2 larger for Galileo than for Pioneer 10. The increased magnetic force must balance increased plasma force which can be imposed either internally or externally. There are no independent simultaneous measurements of the solar wind conditions or of the internal magnetospheric plasma properties (neither the Galileo plasma instrumentation (Frank et al., 1992) nor the Galileo plasma wave investigation (Gurnett et al., 1992) was operating during the inbound pass), which creates uncertainty. However, two possibilities can be suggested. Either, the magnetopause was located much closer to Jupiter than its average position during the final inbound portion of the Galileo flyby or the plasma content of the magnetosphere was higher than during the Pioneer 10 epoch. We shall consider each of these interpretations and show how they explain the observations.

Consider first the possibility that the differences were imposed by the solar wind. Galileo entered the magnetosphere at 118 RJ, an exceptionally large radial distance for the dawn magnetopause, early on November 28, 1995. Assuming solar wind control, the inflated magnetosphere would be attributed to an exceptionally low solar wind dynamic pressure. In the outer magnetosphere Galileo conditions differed little from those observed by Pioneer 10. Well inside the magnetopause, at ∼100 RJ, the southward component decreased to the value expected from the Khurana-1997 model and the radial and azimuthal components began to display the rotational periodicity of the middle magnetosphere. Four days later, early on December 1, 1995 with Galileo at ∼90 RJ, the field again took on the characteristics of the outer magnetosphere, i.e., increased $B_\theta$ and field magnitude, large fluctuations, and the absence of rotational periodicity, suggesting that the magnetopause had moved closer to Jupiter, possibly near 90 RJ. Again, assuming solar wind control, these features suggest that a fast (high dynamic pressure) stream reached Jupiter and pushed the magnetopause in. Taking account of the flared shape of the magnetopause with a typical ratio of dawn to noon distances of 1.5, an inward displacement of the dawn magnetopause to 90 RJ would correspond to previously observed dayside magnetopause encounters near 60 RJ (see for example Huddleston et al., 1997). Thus, a magnetopause at ∼90 RJ near dawn is not extreme. Comparison with other flybys reveals that the outer magnetosphere or boundary layer is likely to be 10-15 RJ thick (Kivelson et al., 1978). The persistence of large $B_\theta$ perturbations in to ∼60 RJ suggests that the magnetopause may have followed Galileo inward as far as ∼75 RJ. By ∼55 RJ, Galileo reentered the magnetodisk and periodic variations ($B_\theta$ and $B_r$) resumed. $B_\theta$ remained larger than in the model, consistent with magnetic flux compression into a smaller area when the magnetopause shifts inward (the total flux crossing the equatorial plane remains constant). Inward displacement from 118 RJ to 75 RJ increases the equatorial $B_\theta$ by a factor of ∼1.6, close to the ratio between the data and the model in the region inside of 55 RJ. Enhanced magnetopause currents, required for a compressed magnetosphere, would also increase the $\phi$ component. Compression of the plasma would tend to thicken (north-south) the plasma sheet and this could explain why the variations of $R_0$ with the 10 hour period of planetary rotation become large.

Although the Khurana 1997 model does not include magnetopause currents, it does model several internal contributions to the $B_\theta$ perturbations. The model applies in regions where plasma is moving outward from an internal source. In the absence of forces, outward-moving plasma conserves angular momentum and lags corotation. This causes the field to bend out of the meridian plane thus producing $B_\phi$ perturbations of the sense needed to accelerate the plasma to corotation speed. Consequently, the model predicts negative $B_\phi$ in the northern hemisphere as observed between 90 and 105 RJ. On the other hand, between 90 and ∼78 RJ, the $B_\phi$ perturbations in the data are almost out of phase with the predictions of the model. This is what one would expect if the flux tubes were bent out of the meridian plane in a configuration that leads corotation, which happens when plasma is displaced inward. The observed phase, out-of-phase with the model, is thus consistent with inward motion of the magnetospheric plasma in response to changes in the solar wind. If the magnetopause was moving in as the spacecraft moved from 90 to ∼78 RJ, its final position was somewhere between 90 RJ and 78 RJ, possibly close to the latter position. Correspondingly, the nose of the magnetopause was likely to have been near 50 RJ, roughly as close in as in any of the previous orbits. Magnetopause currents needed to stand off the solar wind at 50 RJ produce a southward
perturbation field inside the boundary of a few nT, possibly for the small but systematic discrepancy between the Galileo measurements and the model field developed for the Pioneer 10 pass with a more distant magnetopause. Thus, even inside of 50 R_J, the magnetic perturbations caused by increased solar wind dynamic pressure can explain the sign, the orientation, and the approximate magnitude of the departures from the model field.

Can the assumption of an increased plasma production rate and enhanced flux tube content account for the differences observed with equal success? The periodic changes of the field components over several planetary rotation periods between 35 and 55 R_J are quite systematic, so it is reasonable to assume steady state force balance. As plasma rotation produces a centrifugal force directed radially outward, an increase of plasma density on corotating flux tubes inside of 50 R_J must be balanced by an enhanced Lorentz force, directed radially inward, requiring a larger B_0 as observed. An increased plasma outflow rate would require larger radial currents to maintain approximate corotation and this would explain why the peak amplitude of B_4 in each rotation is markedly larger than predicted from the Pioneer 10 model. However, this interpretation fails to account for the recurrences of the outer-magnetosphere signatures (outside of 105 R_J and between 55 and 90 R_J) separated by an interval displaying magnetodisk signatures (90-105 R_J). We do not believe that enhanced plasma production alone can provide a satisfactory explanation of these features which still force us to invoke externally-driven magnetopause displacements.

Galileo and Pioneer 10 outbound are not the only examples of data sets taken in the same magnetospheric region but revealing different behavior. Pioneer 10 and 11 entered the magnetosphere at roughly the same latitude at ~09:30 local time with a separation of less than 1 hour, yet inside of 50 R_J, Pioneer 10 observed strong modulations of field latitude with planetary rotation, consistent with strong modulation of B_0 as expected for a thick current sheet, while Pioneer 11 found only weak modulation of field latitude consistent with a small, steady value of B_0 as expected for a thin current sheet. For Pioneer 10 (Pioneer 11) the closest magnetopause crossing occurred inside of 50 R_J (65R_J). Thus, just as different states of magnetospheric compression account for the different field configurations observed near dawn on the Galileo inbound and Pioneer 10 outbound passes, it seems likely that increased magnetospheric compression accounts for the presence in the local morning sector of a significant southward component on the inbound Pioneer 10 pass that was absent on the inbound Pioneer 11 pass.

We conclude that despite the great importance of internal sources in producing the structure of the Jovian magnetosphere, the outer boundary condition imposed by the solar wind modifies the magnetic configuration through much of the middle magnetosphere in important ways that must be considered in data interpretation even to distances as close as 35 R_J from Jupiter. Changes of plasma content may contribute to time dependent changes of the magnetic configuration, but we think that the differences observed between Pioneer 10 outbound and Galileo inbound are at most only slightly affected by changes in the plasma content of the magnetosphere. The later orbits of Galileo will provide more complete information on the temporal variations of both the magnetic field and the plasma properties of the magnetosphere. In interpreting time variations in the outer and middle magnetosphere, it will be important to recognize that these changes may have significant external causes.

THE MAGNETIC SIGNATURE OF THE IO FLYBY

During the close pass by Io (closest approach at 1745:58 UT on December 7, 1995), large magnetic perturbations were observed. In a paper (Kivelson et al., 1996a) based on the one minute averages returned in late December 1995, we reported that in Io’s wake the magnetic field magnitude decreased by almost 40% relative to the expected ~1835 nT magnitude of Jupiter’s field at Io’s position. We reviewed various possible sources of magnetic perturbations including currents flowing in the plasma and closing through Io or its ionosphere, currents or a diamagnetic effect produced by ions added to the flow by pickup or charge exchange, and an intrinsic magnetic field of Io. Using values of the plasma density and
temperature appropriate to the Voyager epoch, and assuming charge exchange rates consistent with expectations from ground-based observations, we were unable to understand a perturbation as large as that observed unless we included an internal magnetic field of Io or supposed that the ionosphere could carry current up at an altitude of 0.4 R\textsubscript{Io}. In order to carry a current, the ionosphere at 1.4 R\textsubscript{Io} must have an ion-neutral collision frequency \( f \) that satisfies \( f \lesssim \Omega_i \), where \( \Omega_i \) is the ion gyrofrequency. As this requires a neutral density large compared with that in most atmospheric models, we concluded that it is plausible to imagine that Io has an intrinsic magnetic field with a magnetic moment of order \( 10^{20} \) A\textperiodcentered m\textsuperscript{2}.

In late June, the full time resolution data that had been stored on the spacecraft tape recorder were returned. They reveal considerable structure within the large scale depression of the field magnitude (Figure 4). Details are provided elsewhere (Kivelson \textit{et al.}, 1996b), but here we summarize a few interesting features revealed by the high time resolution data. The new features are best identified by comparison with the signature expected in simple models of the interaction between the flowing plasma and Io. That comparison is presented in Figure 4 which shows traces of the field calculated along the Galileo trajectory in an MHD simulation on the same scale as the actual data (Linker \textit{et al.}, 1988, 1989, 1991; Linker, 1995, 1996). One model represents Io as a conducting sphere in the flowing jovian plasma. The second model represents Io as a magnetized sphere. The magnetic moment used in the simulation scales to a value of \( 10^{20} \) A\textperiodcentered m\textsuperscript{2} oriented approximately antiparallel to Jupiter's magnetic moment. Neither model includes pickup although such models are also being run. The models in Figure 4 show that the currents flowing from the plasma across a conducting Io (dotted curve) are insufficient to explain the observed amplitude of the perturbation signature. A magnetized Io (dashed curve) enhances the perturbation and explains the depression near the center of the wake, but it does not produce the \( \sim 1 \) minute time-scale features which must relate to plasma properties. In particular, the field depression is asymmetric about the center of the wake, with particularly large depressions near the flanks of the wake (i.e., near \( \pm 1 \) R\textsubscript{Io} away from the wake center). These regions contain plasma that has been accelerated to speeds higher than corotation speed as it flows around Io. As charge-exchange cross sections are velocity-dependent, the energy of pickup ions should peak near the flanks, thus accounting for the very large depression between 1743 and 1745 UT and the somewhat smaller depression between 1747 and 1748 UT. Between 1745 and 1748 UT, the field magnitude became stable (except for the large drop at \( \sim 1746 \) UT) with only very small fluctuations. This is characteristic of a low \( \beta \) (= thermal pressure/magnetic pressure) plasma. Possible plasma environments of low \( \beta \) are an extended ionosphere of Io or torus plasma so heavily loaded with pickup ions that the flow has stagnated and the plasma has cooled markedly. Measurements (Frank \textit{et al.}, 1996) of the plasma properties will allow fuller exploration of the details of the interaction.

The high time resolution data clearly shows that plasma contributions to the magnetic signature near Io are important at the 20 - 30\% level. However, it is likely that plasma contributions cannot by themselves account for the full magnetic depression near Io. A significant intrinsic field of Io still provides a plausible explanation of the magnetic signature, but analysis of the full data set from the Io flyby and more complete computer simulations of the interaction in the presence of pickup and charge-exchange are in progress to evaluate the situation fully.

Not only the localized field depressions near the flanks of the geometric wake of Io, but also the nearly monochromatic fluctuations on the scale of seconds seen on approach to Io give evidence of local pickup or charge exchange. From the distance of \( \sim 18 \) R\textsubscript{Io} outside of Io's orbit, fluctuating fields were present. The power peaks at or just above the gyrofrequency of SO\textsubscript{2}\textsuperscript{+} (Figure 5). The waves are strongly polarized with left-handed circular polarization. The spectra are consistent with the ion cyclotron instability generated by a strongly anisotropic distribution containing locally picked-up and/or charge exchanged molecular ions. In a plasma that is flowing only slowly along the field, the unstable frequency is expected to be close to the gyrofrequency of the newly picked-up particles. No power was present above
Data vs Dipole and Conducting MHD Models (plus Background)

Fig. 4. Full time resolution magnetometer data from the flyby of Io on December 7, 1995. Three component and the total field are plotted in nT. The $x$-direction is parallel to corotation (antiparallel to System 3 φ), $y$ is defined by $x \times B$ where $B$ is the local magnetic field of Jupiter at Io's orbital position. $B$ lies in the $x$-$z$ plane, mainly aligned with $z$. The additional curves show results from a magneto-hydrodynamic model of flow by a conducting Io (dotted curves) and a magnetized Io (dashed curves).

Fig. 5. Power spectrum of magnetometer data from 1735 to 1740 UT on December 7, 1995. The data have been rotated into a field-aligned coordinate frame with $z$ along the background field direction. Vertical lines show the gyrofrequency bands for mass per unit charge 64, 48, and 32, representing nominally $\text{SO}_2^+$, $\text{SO}^+$, and $\text{S}^+$. 
background at the gyrofrequencies of O$^+$ or S$^+$. This appears to us to be an important new result as it suggests that there is a rather large region around Io where newly-ionized molecules are significant in the pickup population.

Within the geometric wake of Io, the ion cyclotron waves disappeared but sharp decreases of field magnitude occurred intermittently. These drops have the character of mirror mode waves which can grow in amplitude when the temperature of the plasma is larger perpendicular to the field than parallel to the field. The plasma $\beta$ cannot be small, but as these drops appear near the edges of the apparent low $\beta$ region, it seems likely that they occur within the higher $\beta$ plasma that surrounds the center of the wake.

THE MAGNETIC SIGNATURE OF GANYMEDE

On June 27, 1996, Galileo had its second encounter with a moon of Jupiter. Closest approach to Ganymede was at ~0630 UT. The full data from the pass were returned in late July 1996 and are reported on elsewhere (Kivelson et al., 1996a). However, during this pass, the Magnetometer returned 24 s averages using a newly-developed capability of the spacecraft onboard computer. As Galileo flew by Ganymede, it recorded a change from a background jovian field of ~100 nT pointing southward and radially outward from Jupiter to a field of ~475 nT pointing towards Ganymede (Figure 6). Gurnett et al. (1996) report that they observed plasma wave signals consistent with Ganymede's having a miniature magnetosphere. Together these two results lead us to conclude that this moon has an intrinsic field with its magnetic moment antiparallel to Jupiter's. We know of no way that inductive fields can increase the field magnitude to such a large degree. Our estimate of the field strength at Ganymede's surface is in the range 600 to 800 nT and the magnetic moment is roughly antiparallel to Jupiter's tilted by ~10° relative to Ganymede's spin axis. We developed a preliminary model of the magnetic moment of Ganymede that was used successfully to predict the magnetic signature on the September 6, 1996 pass by Ganymede, a low altitude polar pass that confirmed the inferred intrinsic field. The strong interaction of this moon with its plasma environment challenges us to provide new models of its ionosphere, its surface, and interior that are consistent with the new Galileo results.

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Fig. 6. Twenty-four second averages of the magnetometer data for the Ganymede flyby on June 27, 1996. The spherical coordinate system, centered at Ganymede, is referenced to the spin axis with $\theta$ colatitude and $\phi$ azimuth in a right-handed system with $\phi = 0$ in the direction towards Jupiter. A simple model field for which a vacuum dipole is added to a model jovian field is shown as a dashed curve. The dipole is tilted by 10° relative to the spin axis and has a surface equatorial field strength of 800 nT. This is probably an overestimate as it is probable that part of the signature results from currents flowing through the plasma.


