Sheared magnetic field structure in Jupiter's dusk magnetosphere: Implications for return currents

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[1] The configuration of the magnetic field near 100 R_J in the dusk sector of the Jovian magnetosphere varies with distance from the equatorial current sheet. The changing twist out of meridian planes is consistent with flows that lag corotation near the equator but that may lead corotation at higher latitudes. Although a portion of the field perturbation may be produced by magnetopause currents, we argue that the observed sheared field structure requires field-aligned current flowing toward Jupiter's ionosphere inside the magnetopause but beyond ~100 R_J. This current must include a portion of the return current of the system that enforces partial corotation of outward moving magnetospheric plasma and may also be fed by boundary layer currents of the region 1 type. We estimate the total current into the auroral ionosphere as ~6 MA, and this current would flow into a narrow band of latitude (<2°) poleward of the main auroral oval. *INDEX TERMS:* 5737 Planetology: Fluid Planets: Magnetospheres (2756); 2756 Magnetospheric Physics: Planetary magnetospheres (5443, 5737, 6030); 2740 Magnetospheric Physics: Magnetospheric configuration and dynamics; 2731 Magnetospheric Physics: Magnetosphere—outer; *KEYWORDS:* planetary magnetosphere, Jupiter's magnetosphere, field-aligned currents, magnetospheric configuration

1. Introduction

[2] In Jupiter's rapidly rotating magnetosphere the internal plasma produced at and near Io at a rate generally estimated as 1 ton s^{-1} must, on average, move outward so that losses balance sources. In a rotating magnetosphere the conservation of angular momentum dictates that outward motion be accompanied by a decrease of angular velocity. The tendency to lag corotation as the plasma moves outward through the plasma sheet produces an azimuthal magnetic field perturbation that twists the field out of meridian planes as it approaches the equator. The field perturbations imply radial currents that flow outward through the equatorial current sheet. The radial current fed by field-aligned current linking to Jupiter's ionosphere is referred to as the corotation enforcement current (CEC). It has been described theoretically [*Hill*, 1979, 1983, 2001; *Hill et al.*, 1983] and characterized from spacecraft observations [*Khurana and Kivelson*, 1993; *Vasyliunas*, 1983; *Bunce and Cowley*, 2001a; *Khurana*, 2001]. Both observations and theory are generally consistent with a current system that couples the equatorial plane to the Jovian ionosphere through field-aligned currents (FACs) that flow toward the equator in the inner magnetosphere (within ~30 R_J) in the region where the plasma motion begins to depart systematically from corotation speed [*Kane et al.*, 1992, 1999], couple to radially outward currents near the equator, return to the ionosphere through FACs flowing away from the equator in the outer magnetosphere, and close through equatorward currents in the resistive high-latitude Jovian ionosphere. The outward radial currents are systematically observed in the night and morning sectors of the near equatorial magnetosphere outside of 15–20 R_J. The equatorward field-aligned current system that feeds the radial current sheet has been inferred from the divergence of the cross-field current [*Bunce and Cowley*, 2001b; *Khurana*, 2001]. It has been suggested that in the dusk sector the radial currents carried in the plasma sheet become weak. The field in the regions well above and below the current sheet no longer deviates from meridional planes (illustrated in Figure 8 of *Khurana* [2001]). This local time dependence also appears in magnetohydrodynamic (MHD) simulations [e.g., *Ogino et al.*, 1998, Figure 3]. Here we will examine field properties in the dusk sector more closely and remark on the structure of the field as a function of distance from the equatorial current sheet.

2. Observations

[3] Over most of the morning magnetosphere beyond 20 R_J, the field is well ordered and near the equator it twists in a clockwise sense (viewed from north of the equator) out of meridian planes, a configuration referred to as a "corotation lag." The configuration is revealed by the appearance of an azimuthal field component that varies in antiphase with the radial field component as the current sheet moves up and down over a near-equatorial spacecraft. The field variation described is seen clearly in Figure 1, which provides an example of Galileo magnetometer data [*Kivelson et al.*, 1992] acquired on the G2 orbit between 54 and 32 R_J near the dawn meridian. The top panel shows the radial and azimuthal components of the magnetic field. The trace of the radial component (B_r) resembles square waves

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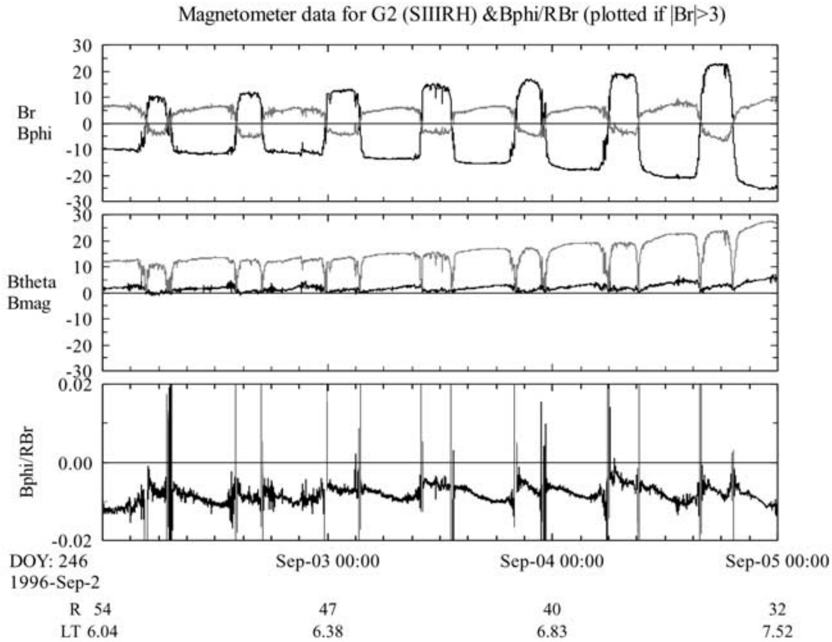

Figure 1. Magnetic field components in a right-handed System III coordinate system from Galileo's inbound G2 pass (near dawn from 54 to 32 R_J): (top) antiphase variations of B_R (black) and $B\varphi$ (gray); (middle) B_θ(black) and $|B|$ (gray), confirming that B_θ is a minor component throughout the plasma sheet on the dawnside; (bottom) $B\varphi /RB_R$, the tangent of the angle between the field direction and the meridian plane divided by radial distance from Jupiter. Intervals close to the current sheet crossing during which $|B_r| < 3$ nT are removed in the bottom panel. Except for short-duration spikes near the current sheet where small fluctuations produce large changes in the angle, the ratio is negative showing that the flux tube lags corotation. Radial distance in R_J and local time (LT) are given at the bottom of the plot.

with flat tops corresponding to the nearly constant field encountered when the spacecraft passes through the "lobes", i.e., the low plasma density regions that surround the plasma sheet. Because Galileo's G2 orbit lay somewhat south of the jovigraphic equator, the intervals in the southern lobe lasted longer than those in the northern lobe. The rapid transition between the northern lobe ($B_r > 0$) and the southern lobe ($B_r < 0$) implies that the plasma sheet was of order 1–2 R_J in thickness. The antiphase relation between B_r and B_φ implies that the field is twisted as expected if the plasma lags corotation. The middle panel shows the θ component (positive for southward orientation) and the magnitude of the field. Throughout the dayside plasma sheet, the θ component is a small fraction of the total field (typically between 1/4 and 1/3), consistent with strong curvature of the field in the equatorial region. In the bottom panel the ratio $\tan \alpha /R = B_\varphi/RB_r$ is plotted. Here α is equivalent to the spiral angle used to describe the orientation of the solar wind magnetic field. It is the angle that (B_r, B_φ, 0) makes with the radial direction. As in the solar wind analogue, this angle increases approximately linearly with the radial distance from Jupiter, so it is convenient to compensate for its amplitude variation by dividing by R. In the bottom panel, data gaps have been introduced in regions close to the current sheet crossing using the criterion -3 nT < B_r < 3 nT. In those regions the estimation of the angle α is undependable. Elsewhere it is clear that α is negative except close to the excised intervals.

[4] The variation of tan α within an interval in either lobe appears slightly U-shaped in the plot. This feature is readily understood by noting that during each planetary rotation a spacecraft at approximately fixed distance R_o from Jupiter encounters the equatorial current sheet twice, say at magnetic latitudes $\pm\lambda_o$. As $|\lambda - \lambda_o|$ increases, the spacecraft crosses field lines that close through the current sheet at increasing $R > R_o$. With α an increasing function of radial distance the field lines encountered away from the current sheet must twist more than the field lines that cross the current sheet locally near the equator crossing. This leads to periodic modulation of the bendback angle and explains the trend of the observations presented in Figure 1.

[5] *Khurana*'s [2001] survey of the lobe magnetic field and the *Ogino et al.* [1998] simulation show that the field orientation varies with local time across the magnetotail. In post dusk sector, bendback is smaller than in the morning sector. From ~2100 LT to midnight the field orientation is nearly radial beyond 50 R_J. Near the dusk meridian, at large radial distances, there is evidence from both data and simulations that the field bends out of meridian planes toward the magnetotail, i.e., in the sense of corotation lead rather than corotation lag. In the Khurana study the data from the outer portions of the dusk sector were obtained from Ulysses measurements. On its outbound pass near dusk at southern latitude ~35°, Ulysses systematically detected "corotation lead" field orientation beyond 30 R_J [*Balogh et al.*, 1992; *Dougherty et al.*, 1993] with the average lead angle increasing as it moved outward. The twist out of meridian planes became as large as 45° even within 60 R_J and remained close to that value everywhere beyond 70 R_J. The field lines encountered at the high

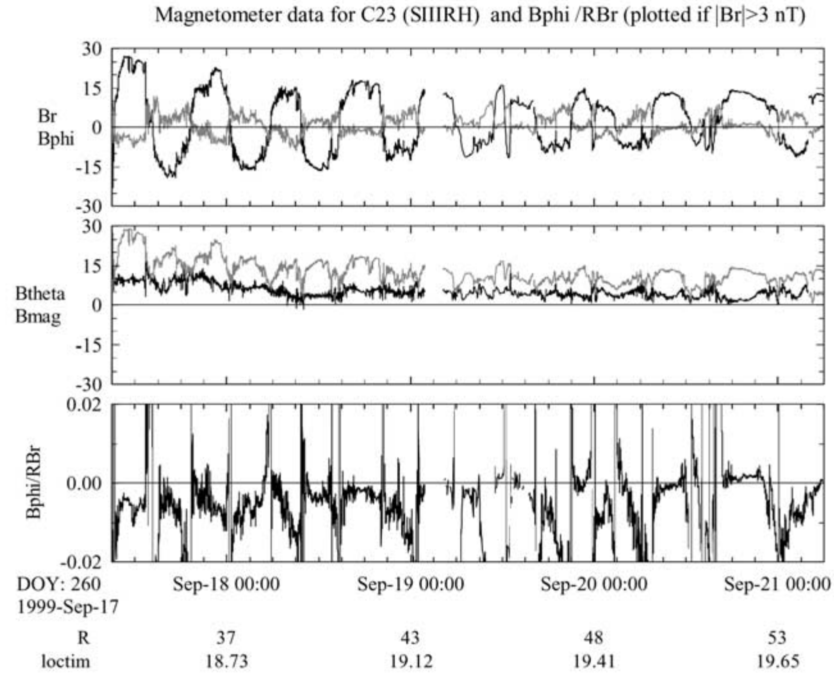

Figure 2. As for Figure 1, but for Galileo's outbound C23 pass (near dusk from 32 to 54 R_J). Despite field fluctuations, B_R (top, black) and $B\varphi$ (top, gray) vary predominantly in antiphase. The middle panel shows that B_θ (black) contributes significantly to the total field (Bmag in gray). $B\varphi/RB_R$ in the bottom panel is predominantly negative outside of intervals close to the current sheet crossings ($|B_r| < 3$ nT) for which data are not plotted. Although the structure is not stable in this sector, there is a tendency for the ratio to be more negative close to the current sheet than away from current sheet crossings.

latitude of this pass must have crossed the plasma sheet much beyond the Ulysses location. Even field lines encountered by Ulysses at 30 R_J may have mapped to regions near the magnetopause. The outbound magnetopause crossing occurred near 82 R_J [*Balogh et al.*, 1992] where strong boundary currents changed the tangential magnetic field by $\sim$10 nT. It is not clear if the tailward twist of the magnetic field was imposed by supercorotational flow or if it was dominantly the effect of boundary currents flowing on the magnetopause.

[6] Although Ulysses acquired the first duskside data on its high-latitude outbound pass, recent Galileo orbits also provide dusk sector data, in this case from regions near the equatorial plane. Figure 2 contains magnetic field observations from a segment of the C23 orbit in the dusk sector covering approximately the same radial range as that shown for the dawn sector in Figure 1. The plasma sheet is thicker at dusk than at dawn as has been noted both in magnetohydrodynamic (MHD) simulations [*Ogino et al.*, 1998] and in data from Ulysses [*Bame et al.*, 1992; *Lanzerotti et al.*, 1993] and Galileo [*Kivelson and Khurana*, 2002]. The thickening of the plasma sheet can be inferred from Figure 2 by noting that the variation of the radial component over a rotation period is no longer flat topped but is almost sinusoidal and fluctuations remain quite large even at times when Galileo is farthest from the current sheet. This implies that Galileo did not exit the plasma sheet. Near the current sheet crossings, $B_\theta \approx \frac{1}{2}|\mathbf{B}|$, implying that in the dusk sector the curvature of the field through the plasma sheet is much reduced relative to its curvature near dawn. As in Figure 1, data have been removed in the bottom panel in regions close to the current sheet crossing where the estimation of the angle α is undependable. Through most of the interval plotted, tan α is negative, implying that near the equator, the field retains its "bendback" orientation.

[7] The inconsistency between the Ulysses evidence for corotation lead and the Galileo evidence for corotation lag in the same local time sector could be attributed to temporal effects. We will argue, however, that a latitude-dependent shear in the field is present in the absence of temporal variations and that this accounts for the difference between the two sets of observations.

[8] Figure 2 provides a hint of the latitude dependence of the angle α in the dusk sector. The variations display considerable temporal variability but some features recur and appear to be systematic. On several rotations tan $\alpha /R = B_\phi/RB_r$ becomes most negative near the current sheet encounters. This suggests that in the absence of time variations the bendback is greatest near the current sheet and decreases with distance above the current sheet. The form of the variation is consistent with the possibility that at higher latitudes above and below the current sheet, the field bends toward the tail as observed by Ulysses. Indeed, Galileo measurements reveal a tailward bend on field lines that cross the current sheet well beyond 50 R_J. An example is shown in Figure 3 from the inbound G28 pass near 100 R_J at $\sim$1950 LT where eight of the eleven half-rotation periods include intervals with positive tan α, implying that the field is swept toward the tail and in the sense leading corotation. Thus the dusk sector data are consistent

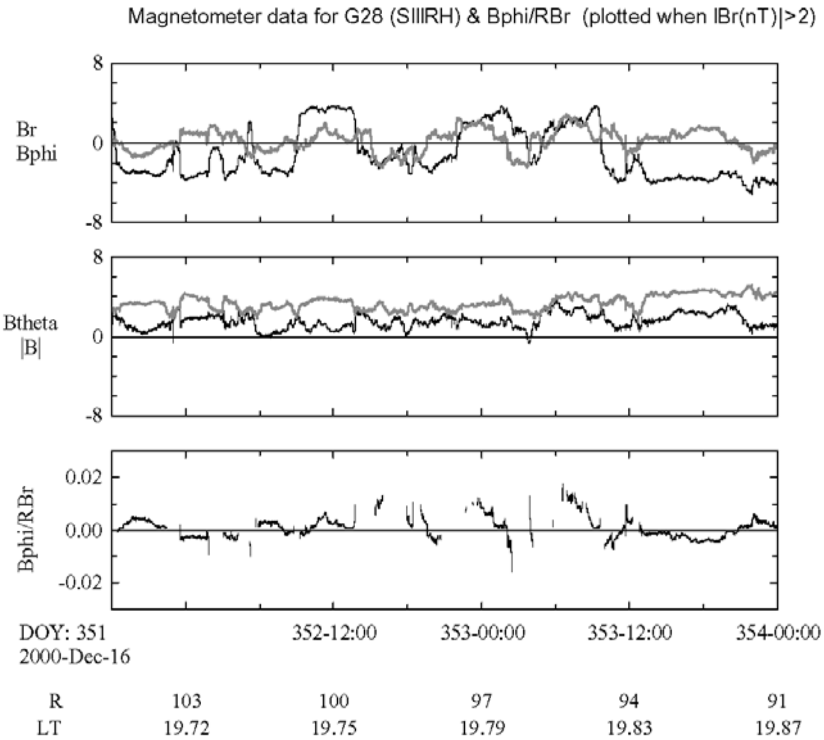

Figure 3. As for Figure 1, but for the inbound G28 pass near 100 R_J and local times near 1950. In the bottom panel, regions in which $|B_r| < 2$ nT have not been plotted. Positive values of tan α are present in several cycles producing an omega-shaped variation between current sheet crossings in several of the well-ordered rotations.

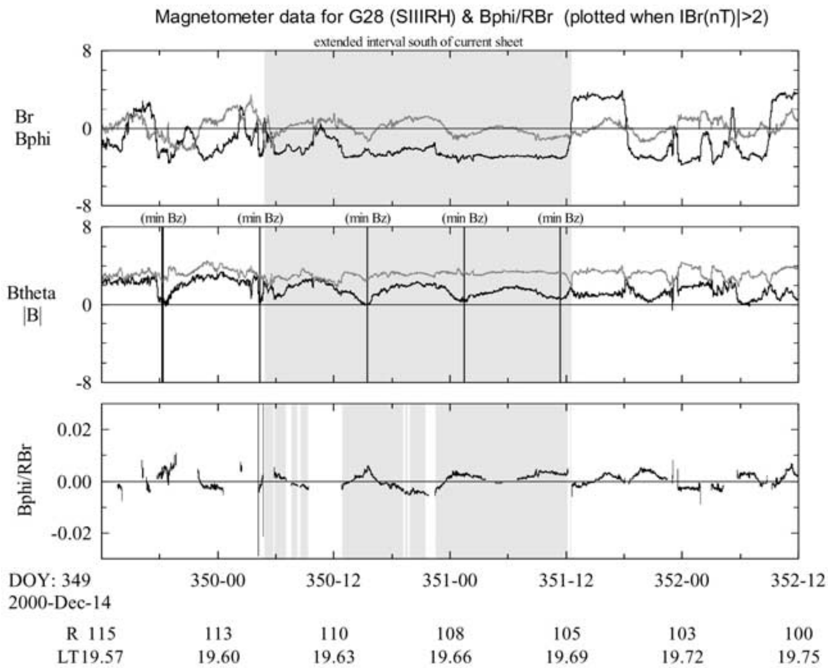

Figure 4. As in Figure 1 for an interval in the dusk sector near 110 R_J. Shading identifies an interval of ~30 hours during which Galileo remained south of the current sheet or barely crossed it. Times of local minima in B_θ, marked in the middle panel, are separated by 8–12 hours. Data are plotted in the lowest panel only where $|B_r| > 2$ nT. Between 350-06 and 351-12, the pattern of the B_φ/RB_r is consistent with bendback of field lines near the current sheet and bend forward of field lines well south of the current sheet.

with the assumption that on average tan α increases with latitude at a fixed radial distance, corresponding to an increase with distance near the equatorial current sheet.

[9] Fortunately, a brief and somewhat anomalous interval on the G28 pass provides clear evidence that latitude-dependent field shear can be present in the dusk sector in the absence of temporal variations over at least several Jovian rotation periods, with the field bent back near the current sheet and bent tailward at higher latitude. Figure 4 shows the anomalous interval. The data are from G28 inbound near 110 R_J and 1930 LT. For more than 30 hours the current sheet appears to have been displaced northward of its normal position. The typical rotational modulation of the B_r is absent and B_r remains roughly constant, especially during the latter half of the interval, although modulation of B_φ persists. This is consistent with upward displacement of the plasma sheet sufficient to leave Galileo in the region that we have referred to as the southern lobe. The θ component displays an exceptional signature with a clear ∼10 hour modulation, very different from the unmodulated form seen in Figures 2 and 3. This variation is consistent with the changing field orientation in the region between the outer edge of the plasma sheet and the lobe as illustrated schematically in Figure 5. The angle α undergoes a systematic variation being negative near the current sheet (at the maxima of B_θ) and positive away from the current sheet. The changing field twists are illustrated schematically in Figure 6.

[10] Simulations of the Jovian magnetosphere show that the orientation of the magnetic field relative to meridian planes varies with the radial distance to the equatorial crossing point [*Ogino et al.*, 1998, Figure 3] and in meridian planes, the distance to the equatorial crossing point increases with latitude away from the current sheet [e.g., *Ogino et al.*, 1998, Plate 4]. We have associated the latitude dependence of the field twist with the distance to the location where the field line crosses the current sheet. Flux tubes that extend to regions near the magnetopause in the dusk sector are twisted tailward both by magnetopause currents and by boundary layer flows as shown in Figure 7. The effect should be present on the dawnside as well as the duskside, but currents linking to the magnetopause oppose the return current of the corotation enforcement system. Thus the outer magnetospheric flux tubes near the dawn meridian continue to bend back. The effect appears weakly in Figure 1, where, as noted above, tan α follows a slightly U-shaped curve between current sheet crossings. This type of structure is more clearly observed on other morningside passes such as G1 inbound (125–120 R_J at ∼0340 LT). The largest negative values occur when the spacecraft is farthest from the current sheet on field lines that close at distances far outside Galileo's position. In the dawn sector as in the dusk sector, various effects may produce a distance-dependent twist. Boundary phenomena (both flows and magnetopause currents) twist the flux tubes toward the tail, adding to a corotation lag effect. In addition, the highest-latitude flux tubes, which extend farthest down the tail, are expected to experience increased corotation lag as they convect across the tail, thus increasing the bendback at large distances.

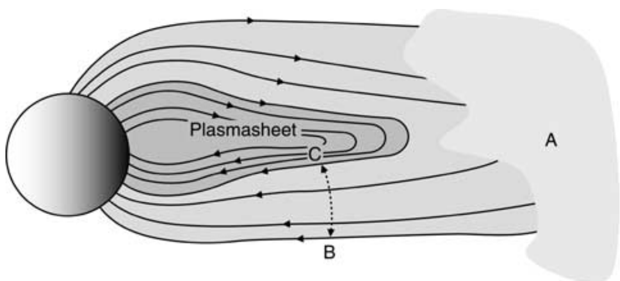

Figure 5. Schematic illustration of the field lines encountered by Galileo during the anomalous interval on G28 shaded in Figure 4. The double arrow indicates the motion of Galileo relative to the plasma sheet. At *C* the field points radially in and is tilted southward. At *B* the southward component of the field vanishes. The field line encountered at *C* crosses the current sheet in the nearby region of the magnetosphere. The field line encountered at *B* crosses the plasma sheet in the distant magnetosphere, a region indicated by *A*.

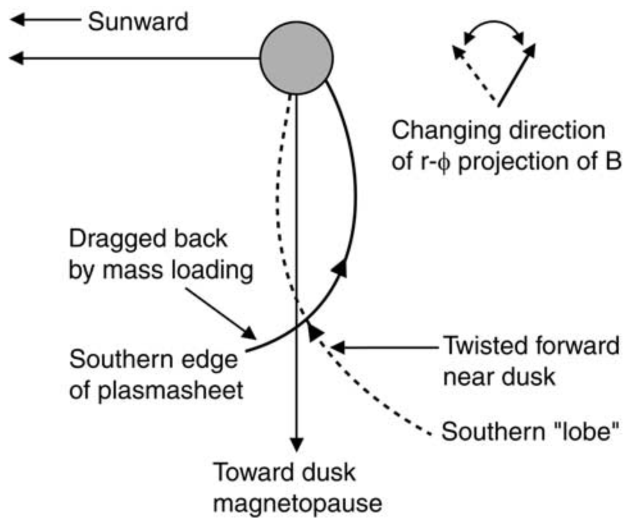

Figure 6. Schematic view from above of the field lines encountered during the interval shown in Figure 4. Field lines near the southern edge of the plasma sheet (spotted black) are twisted in the direction of corotation lag. Field lines encountered farther from the current sheet in the southern lobe (gray dotted) twist forward in the direction leading corotation.

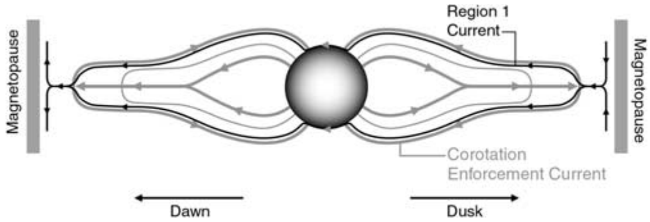

Figure 7. Schematic representation of the currents described as the source of the field-aligned currents observed on Galileo's G28 orbit near the duskside magnetosphere.

3. Interpretation

[11] The event of 15–16 December 2000 illustrated in Figure 4 occurred shortly after Galileo's last inbound magnetopause crossing (at 122 R_J in hour 5 of 13 December 2000). It is possible that the magnetopause remained nearby, but this cannot be confirmed. Magnetopause currents cause the magnetospheric field to rotate out of meridian planes. These currents produce solenoidal (curl-free) field perturbations inside the boundary. We can estimate what fraction of the field shear is likely to arise from the magnetopause currents and find it to be of order 1/3 of the azimuthal perturbation. This follows from the assumption that during the rotations shown in Figure 4, Galileo's motion relative to the plasma sheet was north-south as indicated by the double arrow in Figure 5. Let us call the north-south coordinate z and estimate that at 100 R_J, the most extreme displacement below the current sheet in the interval of interest is $\sim$100 tan(20°) $R_J \approx 36\ R_J$. The range of B_ϕ in each rotation period is roughly 2 nT, so $\partial B_\phi/\partial z \approx 0.055$ nT/R_J. If the field is solenoidal, these changes with z must be balanced by changes in B_z with ϕ. However, azimuthal changes of B_z are small. *Kivelson and Khurana* [2002] plot averages of B_z in the current sheet as a function of radial distance and local time in the magnetotail. Their distribution near 100 R_J in the dusk sector gives $(1/r)\ \partial B_z/\partial\phi \approx 0.016$ nT/R_J. This estimate suggests that $\sim$30% of the changing B_ϕ can be attributed to distant currents and the remainder of the change arises through field-aligned currents flowing locally.

[12] The portion of the field shear attributed to local currents requires a sheet of field-aligned current directed inward to Jupiter on flux tubes that cross the current sheet between Galileo's location near 110 R_J and the magnetopause. This is the sense of the current that closes the CEC as described by *Hill* [1983, 2001] and others. It is also the sense of FACs that link the boundary layer to the ionosphere, the Jovian equivalent of region 1 currents [*Iijima and Potemra*, 1976], so the FAC in the dusk sector may have two sources. The current structure is illustrated schematically in Figure 7.

[13] Field-aligned currents are usually identified from the divergence of the perpendicular current [*Khurana*, 2001; *Bunce and Cowley*, 2001b]. However, in the outer magnetosphere the field is of small amplitude and is often disturbed; the divergence of the perpendicular current may not be measurable. We are fortunate in this event to be able to estimate the FAC directly because the interval shown in Figure 4 was unusually quiet. The quiescence of the solar wind is confirmed by magnetometer data from Cassini, which was $\sim$230 R_J upstream of Jupiter near noon. Those data show that during the interval of interest the interplanetary magnetic field amplitude was only a few tenths of a nanotesla with small fluctuations (M. Dougherty and David Southwood, personal communications, 2001). Thus the data of Figure 4 provide a unique opportunity to observe the latitudinal structure of the magnetic field at a fixed radial distance without interference from fluctuating external conditions.

[14] Our dusk sector data show that tan α is negative near current sheet crossings as anticipated if outflow of plasma slows the rotation rate of the plasma sheet plasma at large distances from Jupiter. Away from the current sheet on field lines that extend well beyond the location of Galileo and possibly come very close to the magnetopause where tailward perturbations dominate, tan α is positive. Thus this duskside data provides an example of field orientations arising from corotation lag close to the current sheet and the opposed effects of boundary perturbations [*Dougherty et al.*, 1993] away from the current sheet. On the dawnside the effects are additive and although the field shears, tan α does not change sign.

[15] MHD simulations reveal similar structure of the field configurations, with the dawn sector structure showing the twist associated with corotation lag, whereas in the dusk sector the twist direction reverses for field lines that reach the near vicinity of the magnetopause [*Ogino et al.*, 1998]. This type of structure is present independent of interplanetary magnetic field (IMF) direction and of solar wind dynamic pressure. There is no supercorotation in this region [*Walker et al.*, 2001].

[16] We have noted that the FAC has the sense expected for Jovian region 1 currents [*Iijima and Potemra*, 1976]. One must note, however, that field-aligned region 1 current is fed by a near equatorial current with a component radially inward from the magnetopause (see Figure 7); yet the azimuthal component of the observed field near the equator remains consistent with radially outward current. Thus the field-aligned current that we have identified must be at least partially fed by the CEC system [*Hill*, 2001]. In the dawn sector, where the region 1 current opposes the CEC return current (in Figure 7, the two FACS flow in opposite directions), the net reduction in the strength of the FAC will make it difficult to identify the return currents of the CEC system.

[17] It is possible to estimate the total field-aligned current from the data of Figure 3. Let us assume that the current is flowing in field-aligned sheets of finite thickness. The total current I flowing in the sheet is given by

$$I = {}^2/_3[\max(B_\varphi) - \min(B_\varphi)]/\mu_o, \qquad (1)$$

where we have assumed that 1/3 of the variation of B_ϕ with z is balanced by the variation of B_z ($\sim B_\theta$) with ϕ and the sheet is considered azimuthally symmetrical. In the interval of interest, B_ϕ varies from ~ -1 to 1 nT. Thus the current density of the sheet is $I \approx 1$ mA/m or 0.07 MA/R_J, comparable with the radial current densities near 100 R_J reported by *Khurana* [2001]. If the current sheet extends over 3 hours of local time near 100 R_J the total current is $\sim$6 MA. It is possible that Galileo did not traverse the entire current-carrying region as it moved away from the current sheet, so these values may be underestimates. Khurana estimates the total current into the inner portion of the equatorial current sheet as 60–100 MA so the current feeding into a 3-hour segment is of order $\sim$7.5–12.5 MA. These estimates are very approximate, but they suggest that the field-aligned current flowing into the equatorial current sheet inside of 30 R_J is of the order of the outward field-aligned current that we have identified in the region outside of 100 R_J. However, the uncertainties in these estimates are large, and it is likely that region 1 currents also may contribute a portion of the field-aligned current.

[18] One can estimate the width of the ionospheric region into which the currents flow (colatitude range $\Delta\theta$ assumed to flow near 25° colatitude) by noting that the magnetic flux crossing the current sheet is the product of B_θ, which is ~2 nT, and the area through which the current flows (say between 100 and 150 R_J over a longitude range $\Delta\varphi$). Thus with an ionospheric magnetic field B_i of order 1×10^{-3} T, the latitude range into which the return current flows is approximately

$$\Delta\theta = 125 \times 50 B_z / B_i \sin\theta < 2^\circ. \qquad (2)$$

4. Summary

[19] For roughly 30 hours in December 2000 during an interval of quiescent solar wind the Jovian plasma sheet was displaced northward of its normal near-equatorial position, leaving Galileo in the duskside southern magnetic hemisphere for several planetary rotations. During this fortuitous event the orientation of the field varied systematically in a way that enabled us to describe how the magnetic structure varies with distance from the current sheet and to identify the currents required to complete the current system that imposes partial corotation on the plasma sheet. The analysis accounts for the differing field orientations reported from the Galileo observations near the equatorial plane and those reported at higher latitudes from Ulysses. The shear in the azimuthal field component was found to be consistent with the presence of ~6 MA field-aligned currents flowing from the current sheet into less than 2° of latitude in the Jovian ionosphere poleward of the zone of equatorward current flow associated with the main oval.

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