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Structure of the Jovian magnetodisk current sheet: initial Galileo observations

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Abstract

The ten-degree tilt of the Jovian magnetic dipole causes the magnetic equator to move back and forth across Jupiter's rotational equator and the Galileo orbit that lies therein. Beyond about 24 Jovian radii, the equatorial current sheet thins and the magnetic structure changes from quasi-dipolar into magnetodisk-like with two regions of nearly radial but antiparallel magnetic field separated by a strong current layer. The magnetic field at the center of the current sheet is very weak in this region. Herein we examine the current sheet at radial distances from 24–55 Jovian radii. We find that the magnetic structure very much resembles the structure seen at planetary magnetopause and tail current sheet crossings. The magnetic field variation is mainly linear with little rotation of the field direction. At times there is almost no small-scale structure present and the normal component of the magnetic field is almost constant through the current sheet. At other times there are strong small-scale structures present in both the southward and northward directions. This small-scale structure appears to grow with radial distance and may provide the seeds for the explosive reconnection observed at even greater radial distances on the nightside. Beyond about 40 Jovian radii, the thin current sheet also appears to be almost constantly in oscillatory motion with periods of about 10 min. The amplitude of these oscillations also appears to grow with radial distance. The source of these fluctuations may be dynamical events in the more distant magnetodisk.

Keywords: Current sheet; Galileo; Jupiter; Reconnection

1. Introduction

Thin current sheets are ubiquitous in the solar system. There are thin current sheets imbedded in the solar wind; thin current sheets between the shocked solar wind and the magnetospheres of the planets; thin current sheets in the magnetotails of the planets, and specifically at Jupiter in the magnetodisk about 24 Jovian radii (R_J) from the planet's center. Some of these current sheets, such as the Jovian magnetodisk, lie between plasmas that are quite similar. Others, such as the magnetopause, lie between plasmas that are quite different in properties and origin. It is of some interest to determine if the processes in these two different current layers are similar or different.

Magnetized plasmas, with quite distinct origins, will remain separated unless some process disrupts the current in the layer separating the two plasmas. In a collisional medium, ordinary collisions supply the dissipation. In collisionless plasmas, the effective resistivity is provided by plasma instabilities that disrupt the current and alter the magnetic field connectivity across the current sheet. The magnetic structure of these sheets, in turn, provides diagnostic clues as to the nature of those instabilities and hence has been studied in some detail, especially at planetary magnetopauses (Russell, 1995; Huddleston et al., 1997). At the Earth's magnetopause there is evidence for 'steady-state' reconnection in which there is a quasi-steady normal component of the magnetic field and flow accelerated away from a 'neutral' line (Paschmann et al., 1979; Sonnerup et al. 1981). There is also transient or patchy reconnection in which short duration strong normal components and fast flows are seen (Russell and Elphic, 1978). Steady-state reconnection has been confirmed only at the terrestrial magnetopause but evidence for transient reconnection has been found at Mercury (Russell and Walker, 1985); Earth (Russell and Elphic, 1978) and Jupiter (Walker and Russell, 1985). Finally, there is apparently quiescent structure along the magnetopause normal that seems not to lead to any dynamical consequences. These structured, but apparently quiescent, normal components are seen at magnetopause crossings throughout the solar system (Huddleston et al., 1997).

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These three states of the magnetopause current layer (quiescent, transiently reconnecting and steady-state reconnecting) could be present at different times, corresponding to different solar wind conditions. However, these states could also represent three different stages of evolution of the magnetopause current layer, albeit with the rate of that evolution depending on external conditions. Thus they could be present simultaneously but at different locations on the magnetopause.

Jupiter provides us with a magnetic geometry that evolves with radial distance. Close to Jupiter the magnetic field is dipolar, but becomes less so with radial distance so that at about 24 R_J the field pattern is best described in terms of a magnetodisk. There is radial transport of mass outward in the Jovian magnetosphere from its source at Io, ultimately to be released down the tail. Evidence for this outflow in the middle magnetosphere in the form of a transported Europa plume or wake has been reported by Intriligator and Miller (1982) and by Russell et al. (1999). The eventual release of that material from the Jovian magnetosphere is believed to occur via a steady-state reconnection process that releases islands of magnetized material down the tail (Vasyliunas, 1983). Direct observations of this process have not yet been reported but transient reconnection has been observed by Russell et al. (1998a) who report the occurrence of patches of strong northward and southward magnetic field from 50–100 R_J near 0300 LT. In this paper we examine the structure of the current sheet interior to this region to determine if it has reconnection type structure imbedded within it. In this initial look at the structure of the current sheet within the inner magnetodisk we restrict our attention to the first two inbound passes of Galileo, the passes that later encountered Ganymede and hence are referred to as Ganymede 1 and Ganymede 2.

2. Observations

In this study we examine the magnetic field measured by the fluxgate magnetometer (Kivelson et al., 1992). Future work will extend this study to multi-instrument data sets but for our purposes we can learn much from the magnetometer data alone. The magnetometer samples the magnetic field 30 times per second with 12-bit resolution in one of three ranges ± 32 nT, ± 512 nT and $\pm 16{,}384$ nT. The 30 sample/s data is only available in snapshot samples of 200 vectors. At other times the 30 Hz data are filtered and resampled at a lower rate. The highest data rate available in significant volume is at 3 samples/s when tape recording is possible. When tape recording is not used, the data are sometimes transmitted in real time at a rate of the order of once per 24 s. This is called RTS data. Over some of the orbit even lower rate data, averaged over intervals of the order of 30 min long, are taken. This is referred to as memory-read-out data or MRO data. The RTS and MRO data are despun before transmission. The data are returned to Earth using 16 bits. Thus, in the 512 nT range used over much of the orbit studied in this paper, the resolution of the measurement is ± 8 pT and the digital noise level 10^{-3} nT^2/Hz.

To illustrate the range of behavior of the magnetodisk we select five examples of current sheet crossings: one representative of the region 24–40 R_J; two representative of the region 40–50 R_J and two representative of the region 50–55 R_J.

2.1. *5 September 1996, 1700 UT*, 26 R_J

The first example of a current sheet traversal is shown in Fig. 1 for the period 1345–1715 UT on 5 September 1996. The coordinate system is radial, southward, and tangential or corotational (rst). At this time Galileo was at a distance of 25.8 R_J and a local time of 0812, and makes a simple pass through the current sheet with no evidence for oscillatory motion of the current sheet about its mean position except for the 10-h periodicity associated with the tilt of the dipole axis and the rotation of the planet. Figure 1 and the following figures consist of four panels each. The upper left panel shows the data obtained in the rst coordinate system. The lower left panel shows the data rotated into a current sheet coordinate system abc in which the 'a' component is aligned with the projection of the change in field on to the current sheet; the 'b' component is along the component of the magnetic field crossing the current sheet; and 'c' is in the direction of the current. The two panels on the right-hand side show the measurements in the current sheet coordinate as a pair of hodograms. The lower panel is filtered with a low pass corner frequency of 1 mHz to show the variation of the field with the high frequency noise removed.

Because the magnetic variation through the current sheet is very linear, it is difficult to obtain robust estimates of the directions of the current sheet coordinate system from principal axis analysis of the variances. To obtain the current sheet coordinate system, we use what amounts to the coplanarity theorem that is often used to determine coordinate systems for the bow shock. First, find the change in the average direction of the field above and below the current sheet. The direction along the difference between these two fields is taken as the 'a' direction. This direction is roughly radially outward. The 'c' direction is along the cross product of these two vectors and roughly in the direction of corotation. Finally, the 'b' direction is along the cross product of the 'c' and 'a' directions and is approximately southward. If the current sheet is thin, this field component should be constant across the sheet.

The dip in magnetic field strength marks the entry into the current sheet. It is evident that this region of higher

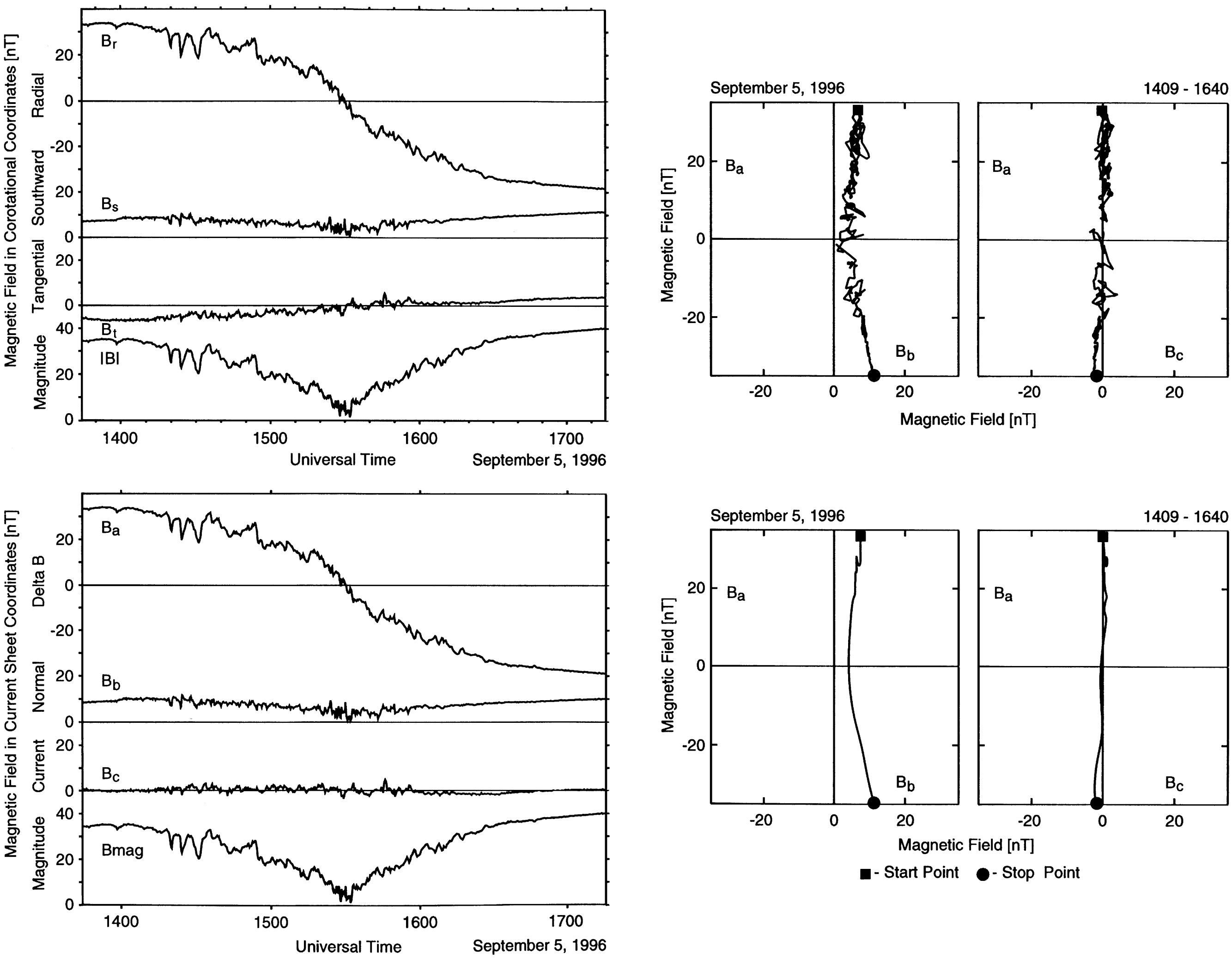

Fig. 1. Magnetic field measured by Galileo on 5 September 1996, from 1345–1715 UT at a radial distance of 25.8 R_J and a local time of 0812 at a rate of one sample every 24 s. Measurements in the upper left-hand panel are in the corotational coordinate system, *rst*, where *r* is radially outward, *s* is southward parallel to the rotational axis and *t* is tangential to the direction of corotation. The lower left-hand panel shows the same measurements rotated into a current sheet coordinate system, *abc*, where *a* is aligned with the change in the magnetic field from the northern lobe to the southern lobe, *b* is along the magnetic field component normal to the sheet, and *c* is in the direction of the current flow. The right-hand panels show hodograms of the magnetic field in the *a*, *b*, *c* coordinate system both unfiltered (top) and filtered (bottom) with a high frequency corner frequency of 1 mHz.

plasma energy density is also noisier than the lobe region above and below the current sheet. This noise is indigenous to the current sheet region. It is obvious from the left-hand panels but also on the lower left that the magnetic field component along the normal to the current sheet weakens in the center of the sheet. We attribute this to the relative thickness of the sheet at these lower radial distances. The noise in the current sheet is quite isotropic along the three directions. In this region it lowers the field strength close to zero at times but it seldom causes any reversals of the field. On the few times that such a reversal occurs it is very small and scarcely significant. The weakening of the field along the current sheet normal can be best seen in the lower left and upper right panels.

2.2. *24 June 1996, 1015 UT*, 41 R_J

Figure 2 shows the period from 0840–1140 UT on 24 June 1996, when Galileo was at a radial distance of 41.4 R_J and a local time of 0708 and crossing an oscillating current sheet under otherwise fairly quiet conditions. An oscillation of the location of the current sheet is the probable cause of the about 8-min periodicity in the total field as Galileo crosses the sheet. The 1 mHz filter removes much of the effect of the 8-min wave in the lower right-hand, showing that in this region of the current sheet the average field is quite constant along the current sheet normal. Again here the ‘noise’ is confined to the region of the current sheet. There is an oscillation in the normal

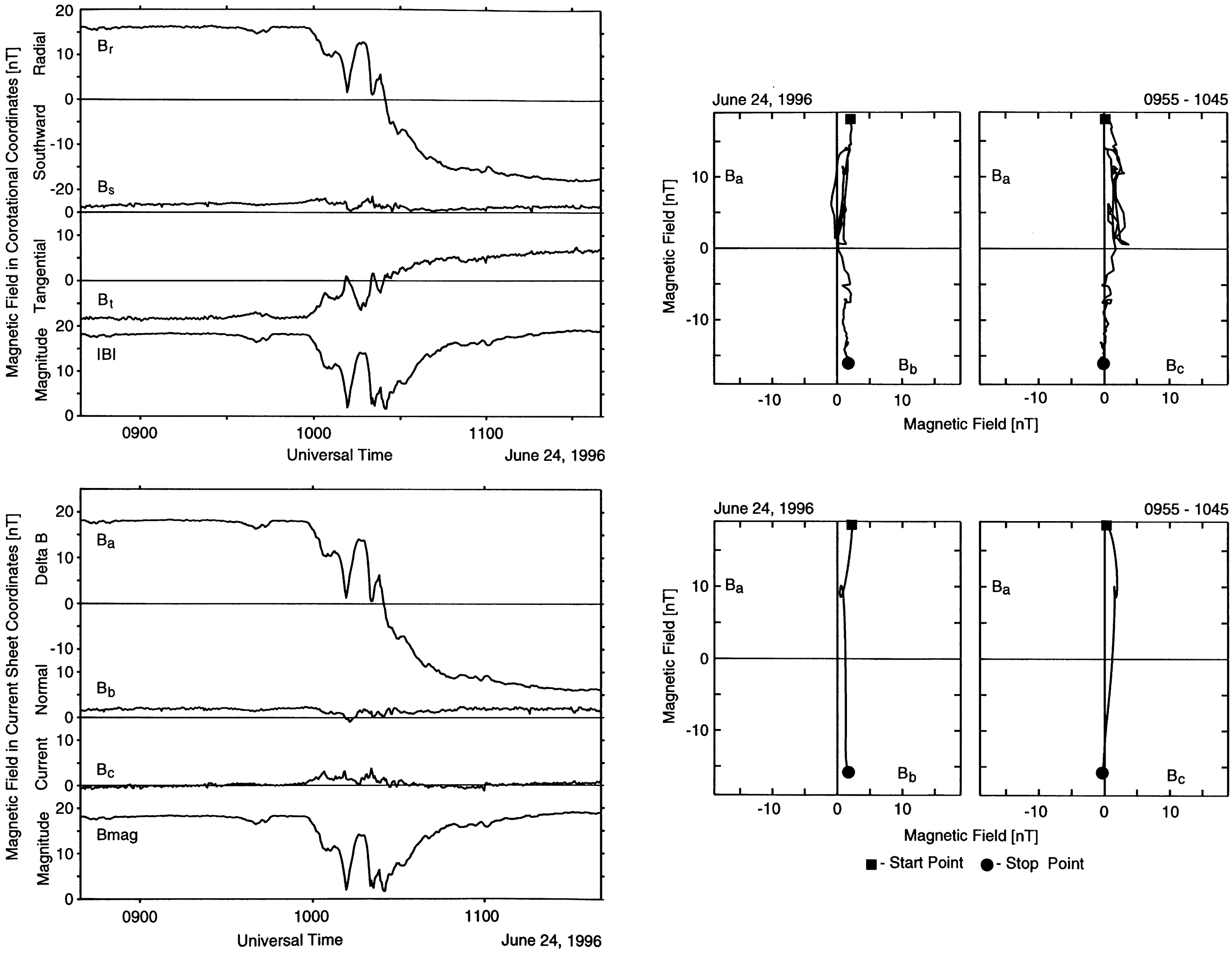

Fig. 2. Magnetic field measured by Galileo on 24 June 1996, from 0840–1140 UT at a radial distance of 41.4 R_J and a local time of 0708 at a rate of one sample every 24 s. Other comments in the caption to Fig. 1 apply.

component that reverses the normal component briefly. It is possible that this is due to an oscillation in the orientation of the current sheet but it is also possible that this structure is due to weak magnetic tearing.

2.3. 3 September 1996, 0330 UT, 46 R_J

Figure 3 shows the period from 0225–0430 UT on 3 September 1996, when Galileo was at a radial distance of 46.1 R_J and a local time of 0626. Again there is evidence of an oscillating current sheet with a period in the neighborhood of 10 min, but the motion is more irregular than periodic. Again the noise is strongest within the current sheet and again these are brief reversals of the magnetic field along the normal. With reversals this small it is possible that an orientation change caused the normal component to change sign but it is also possible that this is the signature of tearing islands.

2.4. 2 September 1996, 0700 UT, 52 R_J

Figure 4 shows a much more disturbed current sheet characteristic of the region beyond 50 R_J. Here Galileo is at a radial distance of 51.9 R_J and at 0607 LT. The multiple crossings of the current sheet can be most easily seen in the radial component of the magnetic field. The current sheet motion appears to be somewhat chaotic with a typical period near 10 min. The filtered hodograms show a normal component that is clearly responding to the oscillating orientation of the current sheet. At shorter periods, there appears to be much noise in the field, large enough to reverse the normal component several times. Moreover, now the amplitude of the reversal intervals is

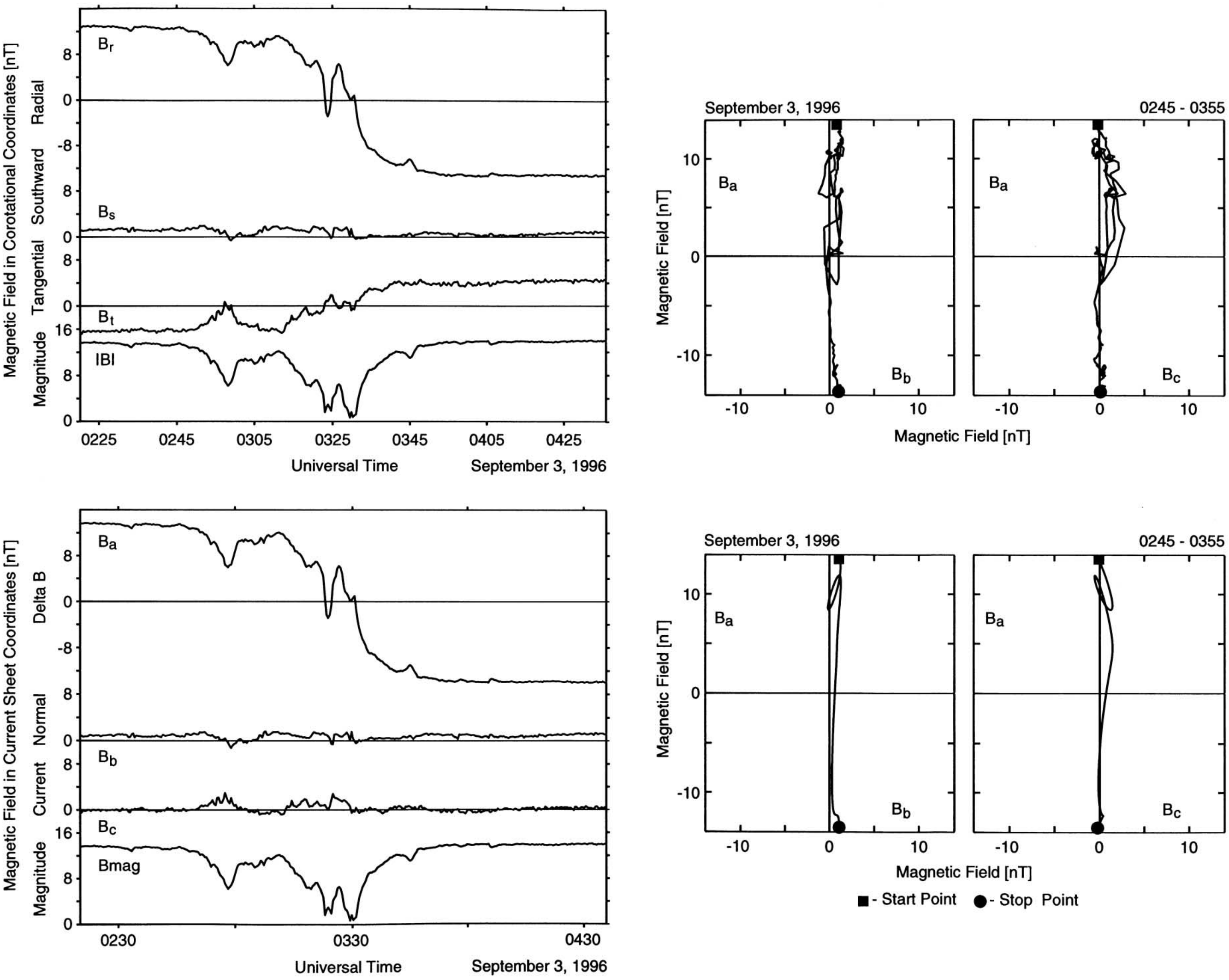

Fig. 3. Magnetic field measured by Galileo on 3 September 1996, from 0220–0435 UT at a radial distance of 46.1 R_J and a local time of 0626 at a rate of one sample every 24 s. Other comments in the caption to Fig. 1 apply.

as large as the normal polarity intervals. This is very suggestive of tearing of the current sheet.

2.5. *1 September 1996, 2110 UT*, 55 R_J

Figure 5 shows our final example of a chaotically moving current sheet from 1955 to 2205 UT on 1 September 1996, when Galileo was at a distance of 54.6 R_J and a local time of 0600. The normal component to the current sheet has become impulsive in both directions and begins to resemble the wormholes reported by Sonnerup and Guo (1996) in the Earth's magnetopause or the spikes reported for Earth by Russell (1995); and Uranus and Neptune by Huddleston et al. (1998). It appears from this brief tour of the magnetodisk current sheet that there is much evolution in the fine scale structure of the current with radial distance and of the oscillations of the position of the current sheet.

3. Radial variation of current sheet

We have performed similar calculations to those above for all of the current sheet crossings on the first two inbound passes. The results of this survey are given in Tables 1 and 2. These tables list the time of each current sheet crossing, its radial distance and local time, the sweepback angle, alpha, of the magnetic meridian and the twist angle, beta, of the current sheet normal around the radius vector, the component of the magnetic field normal to the current sheet, the standard deviation of the normal component normalized by the average normal component, the number of current sheet crossings during the interval and the number of times during which the field along the current sheet normal was opposite that of the dipole. The table begins inside the inner edge of the current sheet to show that the observed magnetic meridian is close to the expected magnetic meridian at the

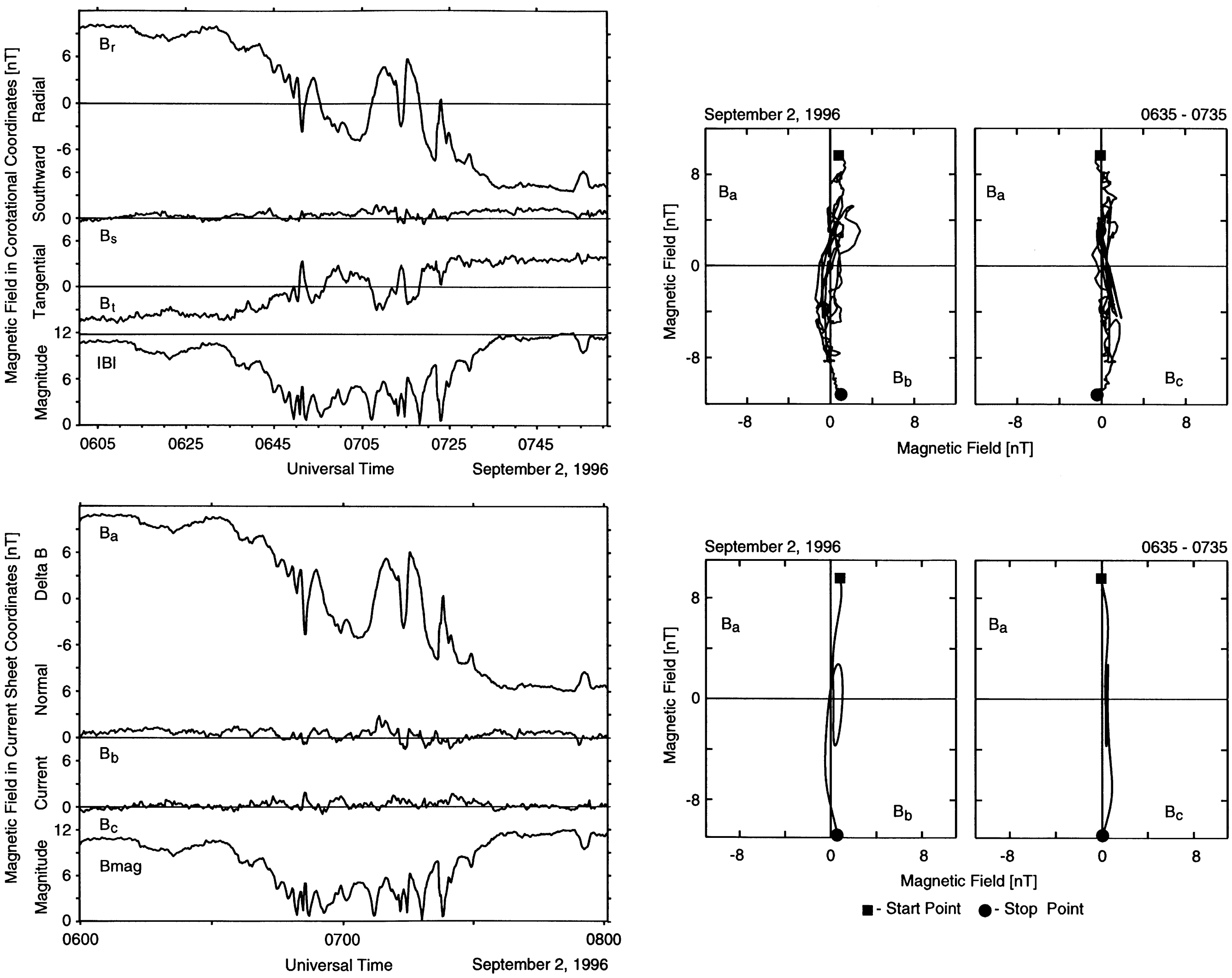

Fig. 4. Magnetic field measured by Galileo on 2 September 1996, from 0600–0800 UT at a radial distance of 51.9 R_J and a local time of 0607 at a rate of one sample every 12 s. Other comments in the caption to Fig. 1 apply.

inner edge of the magnetodisk and the magnetic field component across the current sheet is strong there. At greater radial distances the sweepback increases to about 30° at 45 R_J on the first pass and about 20° on the second pass. The normal component decreases to about 1 nT at these distances. This behavior is qualitatively similar to that observed on earlier missions (Khurana, 1997). The normal to the current sheet swings back and forth as expected when the current sheet is moving northward and then southward. However, the angle the sheet normal makes to the rotational axis is large and quite variable. We have examined the magnetic profile of every current sheet crossing on these two passes and find that the variation in the current sheet is mainly a linear variation and not a rotational one. Finally, we characterize each crossing by the activity in the normal component in two ways. First we show the standard deviation of the unfiltered normal component about the mean field as normalized by the mean normal component. Second, we list the number of reversals seen in the normal component. While there is some variation in the normal component at all radial distances, these variations are only large enough to reverse the normal component and hence be indicative of a torn or disturbed current sheet at the greatest radial extent of our study interval. The one exception to this on the Ganymede 1 pass at 31.6 R_J is a very small, short-lived event. Finally, there is some evidence for vertical motion of the current sheet during many crossings (see for example the oscillations in B_R in Fig. 1). These oscillations cause occasionally multiple crossings of the current sheet from 30–40 R_J but are much more prevalent beyond 40 R_J.

4. Discussion and conclusions

Our brief examination of the current sheet in the inner magnetodisk reveals that the current sheet is constantly

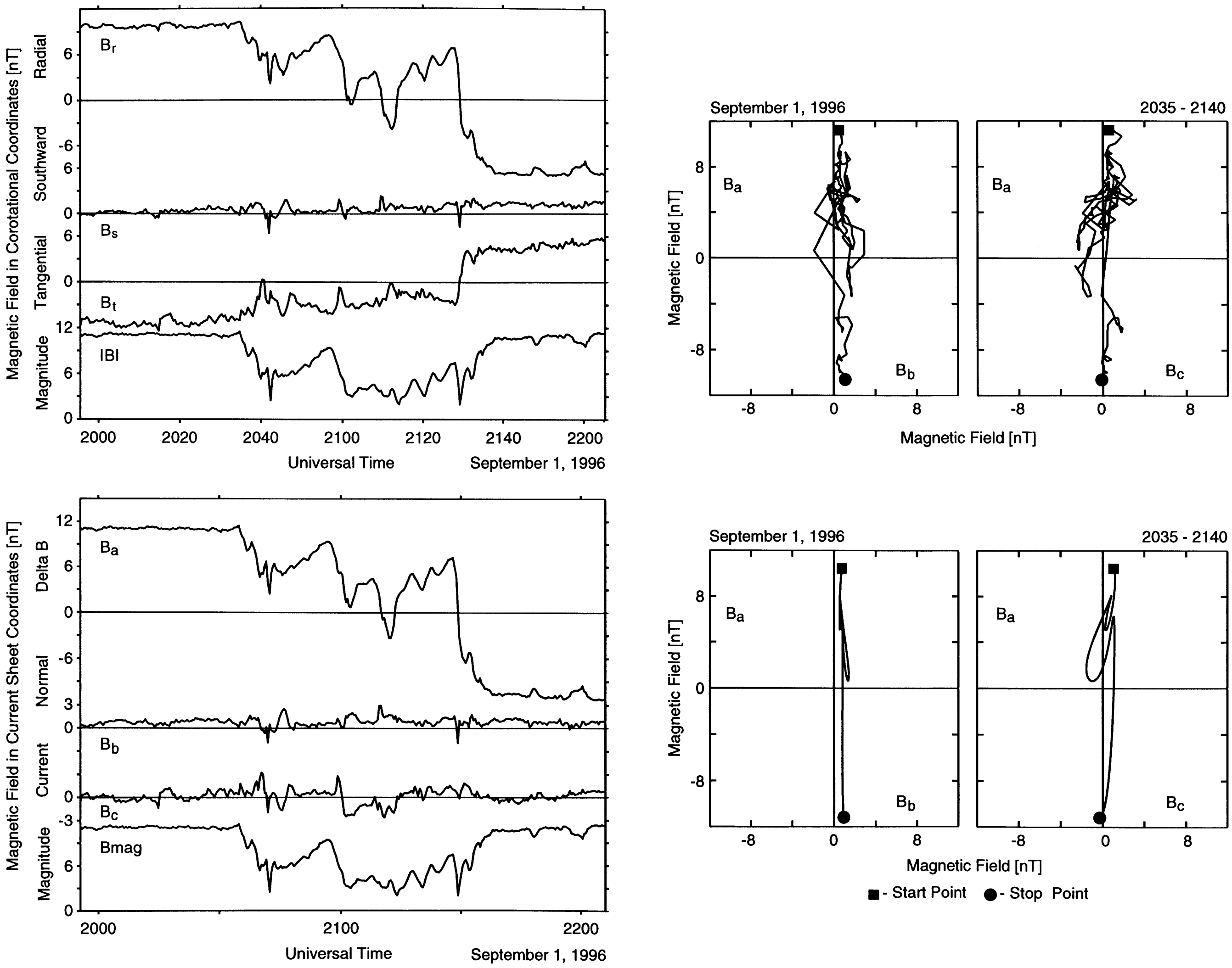

Fig. 5. Magnetic field measured by Galileo on 1 September 1996, from 1955–2205 UT at a radial distance of 54.6 R_J and a local time of 0600 at a rate of one sample every 24 s. Other comments in the caption to Fig. 1 apply.

Table 1
Ganymede 1 orbit current sheet properties[a]

Date	Time	$R[R_J]$	LT	Alpha	Beta	B_n[nT]	$\delta B_n/B_n$	Crossings	Reversals
26/6/96	0845	23.6	8.91	7.5	−10.7	6.4	0.27	1	0
	0225	26.2	8.52	9.3	26.2	3.7	0.34	1	0
25/6/96	2300	27.6	8.34	13.4	−3.4	3.9	0.41	1	0
	1620	30.4	8.02	15.6	27.7	2.9	0.34	3	0
	1300	31.6	7.90	16.1	−4.7	2.6	0.41	1	1
	0630	34.1	7.67	17.6	43.4	2.4	0.38	1	0
	0300	35.4	7.56	21.2	−5.1	1.8	0.32	1	0
24/6/96	2020	37.9	7.38	22.0	33.5	1.9	0.43	1	0
	1700	39.1	7.29	25.0	−1.8	1.7	0.49	1	0
	1030	41.4	7.14	23.4	36.2	1.2	0.53	1	1
	0030	44.9	6.94	30.7	74.2	0.3	2.91	3	2
23/6/96	2130	46.1	6.87	33.1	−26.0	1.8	1.30	7	4

[a] Local Time (LT) is given in decimal hours; alpha is the sweepback angle of the magnetic meridian, with 0° being a radial field; beta is the angle of twist of the current sheet about the radial direction with positive angles denoting the northward current sheet normal pointing in the direction of corotation; B_n is the average normal component across the current sheet obtained as described in the text; $\delta B_n/B_n$ is the normalized standard deviation of this component; the last two columns give the number of times the radial field reversed and the number of intervals of northward magnetic field respectively.

Table 2
Ganymede 2 orbit current sheet properties[a]

Date	Time	R	LT	Alpha	Beta	B_n	$\delta B_n/B_n$	Crossings	Reversals
5/9/96	2130	23.5	8.56	8.0°	−15.2°	11.5 nT	0.23	1	0
	1530	25.8	8.20	7.9	10.8	7.3	0.26	1	0
	1140	27.3	8.01	10.5	−15.4	4.7	0.19	1	0
	0525	29.6	7.73	11.2	1.0	3.7	0.29	1	0
	0145	30.9	7.58	13.1	−13.5	3.1	0.31	3	0
4/9/96	1910	33.3	7.36	15.2	9.5	2.3	0.22	1	0
	1545	34.5	7.25	14.5	−21.3	2.5	0.29	0	0
	0910	36.7	7.06	12.4	13.9	1.0	0.68	1	0
	0555	37.8	6.97	11.8	−42.4	2.3	0.41	1	1
3/9/96	2305	40.1	6.81	15.5	18.6	1.6	0.44	7	1
	2005	41.0	6.75	17.1	−37.6	1.8	0.34	1	0
	1315	43.2	6.61	14.6	15.9	0.8	0.52	1	1
	1000	44.2	6.55	16.2	−32.7	2.0	0.15	3	0
	0330	46.1	6.43	18.1	9.1	0.7	0.76	3	3
2/9/96	2350	47.2	6.37	19.2	−14.7	0.9	0.51	3	1
	1700	49.2	6.26	22.2	34.1	0.9	0.53	1	1
	1415	49.9	6.22	25.3	−3.9	1.2	0.40	1	2
	0700	51.9	6.12	21.0	25.1	0.4	1.55	9	9
	0440	52.6	6.10	24.5	−39.6	1.1	0.58	5	0
1/9/96	2110	54.6	6.00	28.1	15.3	0.9	0.65	3	2

[a] See notes at bottom of Table 1 for definitions of quantities in table.

in motion, not only at the 10-h rotation rate of the planet, but with a period close to 10 min about its 'warped' location. The amplitude of this motion varies from one current sheet encounter to the next. Within about 40 R_J on this pass, the amplitude of this surface wave was small enough that the spacecraft generally crossed the current sheet only once. The period of waves standing along field lines is much longer than 10 min in the Jovian magnetosphere (Khurana, 1993). The observed wave period, however, is close to that expected for a standing compressional wave confined to the current sheet. Such waves that represent macroscopic motion of the current sheet could be generated by transient reconnection at greater distances on the nightside of the magnetosphere (Russell et al., 1998a) and then be carried to the morning magnetosphere by the rapid rotation of the magnetosphere plasma. The events studied in that paper (beyond 50 R_J) appear to show evidence for transient structure of large enough magnitude to be responsible for dynamics of the current sheet.

As most evident in the filtered data in current sheet coordinates, the magnetic field reverses across the current sheet with a mainly linear variation in the field. Hodograms have very little curvature. The current sheet also contains a variable irregular field with a component along the current sheet normal. When their durations are compared to the duration of the current sheet crossing, these field reversing structures appear to be smaller and hence contained well within it. These structures are larger and more frequent with radial distance in the two sample passes we examined herein. Thus we do not expect these structures to remain in the current sheet; eventually they may be responsible for the dynamic events that trigger the current sheet positional oscillations and field restructuring that we see outside the current sheet.

This structure appears to be quite similar to that seen at the magnetopause of the Earth (Russell, 1995; Sonnerup and Guo, 1996) and the outer planets (Huddleston et al., 1997). In both the magnetopause and magnetodisk current systems, this structure might have similar causes and consequences. It appears to be associated with tearing or reconnection in the current sheet since it causes structure that appears along the current sheet normal. The larger negative normal component regions may be similar to the 'worm hole' reported by Sonnerup and Guo (1996). As long as such structures remain inside the current sheet, they should have no major consequences on the current sheet. However, if one grows to a size such that it extends outside the current sheet, it could expand much more rapidly in the low density lobe where the Alfven velocity is high. Thus as the plasma in the current sheet moves outward, we envision that eventually some of that structure excites rapid reconnection between the two magnetic lobes above and below the current sheet. In other words the mesoscale structure seen here may form the seeds for the explosive reconnection seen post midnight beyond 50 R_J (Russell et al., 1998a). Generalizing this hypothesis, we believe that similar structures in the magnetopause, the magnetotail and the heliospheric current sheet, could also cause large-scale disruptions of these current sheets once reconnection proceeds into low density regions. The magnetopause is asymmetric with a high density region on one side and a low density region on the other so that the analogy may be somewhat imperfect here, but the magnetotail current sheet is bounded by two low density regions and we might expect greater similarity in the behavior of the terrestrial magnetotail and the Jovian magnetodisk. In fact, the breakthrough of reconnection into the tail lobes has long been postulated to be responsible for the expansion phase of substorms (Russell and McPherron, 1973). In short, the magnetodisk current sheet very much resembles the other current sheets we have studied in the heliosphere, despite its rather different setting.

Acknowledgments

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