dihedral angle. Previous work has shown that, in similar systems, dihedral angle decreases with increasing temperature (*2*, *20*). At the same time, increasing pressure may increase dihedral angle (*3*, *4*). Melt composition also has an influence (*2*, *3*). The profile of dihedral angle throughout the lower mantle then will depend on the interaction of all of these factors as the pressure and temperature increase. Better constraints on the effects of pressure, temperature, and composition are needed before the percolative ability of the lower mantle can be completely assessed; however, the ~35° decrease in dihedral angle due to the mineralogy change at the upper-lower mantle boundary suggests percolation in the lower mantle may be a feasible core segregation mechanism.

For the early Earth, these results are most relevant to models of core formation. Core formation by percolation in the entire mantle is not feasible because of the large dihedral angle in matrices formed at lower pressures. Some melting of the silicates, diapiric instability, or a nonequilibrium process such as shearing may have been required to mobilize the melt downward at lower pressures. However, the decrease in dihedral angle in lower mantle assemblages suggests that percolation in the deep Earth may be possible under some conditions. If so, then core formation could have proceeded by rainfall through melted silicates at lower pressures (<25 to 30 GPa) (*21*) and by percolation at greater pressures. If percolation is not enough enhanced by the decrease in dihedral angle to allow complete segregation of core material, then other mechanisms to mobilize the melt such as partial melting of silicates or shearing are needed to complete core formation.

These data also have ramifications for Earth now. The ability of core material to infiltrate the lower mantle at the core-mantle boundary is also characterized, in part, by the dihedral angle. An angle on the order of 71° means that core melt could percolate upward, by capillary action, some distance into the base of the lower mantle. The density contrast between mantle and core may allow only a thin zone of metal capillary infiltration. If molten iron is entrained in D″, then it will tend to percolate back to the core along grain boundary pathways. The amount of melt present and the distance of infiltration will provide important constraints on models of the formation of D″, interactions at the core mantle boundary, and mantle dynamics (*22*).

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Localized Reconnection in the Near Jovian Magnetotail

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The oppositely directed magnetic field in the jovian magnetic tail is expected eventually to reconnect across the current sheet, allowing plasma produced deep inside the magnetosphere near Io's orbit to escape in the antisolar direction down the tail. The Galileo spacecraft found localized regions of strong northward and southward field components beyond about 50 jovian radii in the postmidnight, predawn sector of the jovian magnetosphere. These pockets of vertical magnetic fields can be stronger than the surrounding magnetotail and magnetodisk fields. They may result from episodic reconnection of patches of the near jovian magnetotail.

The Galileo spacecraft has, since insertion on 7 December 1995, operated at Jupiter in a series of orbits whose line of apsides has rotated from a position behind the dawn terminator to close to midnight. The eighth of these orbits had sufficient telemetry bandwidth that nearly continuous measurements could be obtained through the apojove region and telemetered to Earth. This allowed us to study the temporal stability of the magnetodisk and near magnetotail with the data from the magnetometer (*1*) from midnight to 3 AM local time and at distances from 50 to 100 jovian radii (R_J) from the planet (Fig. 1A). On the basis of previous observations by Pioneer 10 and 11 (*2*), Voyager 1 and 2 (*3*), and Ulysses (*4*), we expected the magnetospheric field to be radially directed through most of this region except near the current sheet. The tilt of the magnetic dipole axis controls the current sheet location so that the current sheet is, in general, displaced from the rotational equator in which Galileo orbits so that it can fly by the four Galilean moons (Fig. 1B). The rotation of Jupiter carries the current sheet back and forth across Galileo every 10 hours.

The volcanic moon Io supplies up to a ton of ions per second to the jovian magnetosphere. This material is transported radially outward to ultimately be lost down the tail in the antisolar direction (*5*, *6*). In a perfectly electrically conducting fluid, the

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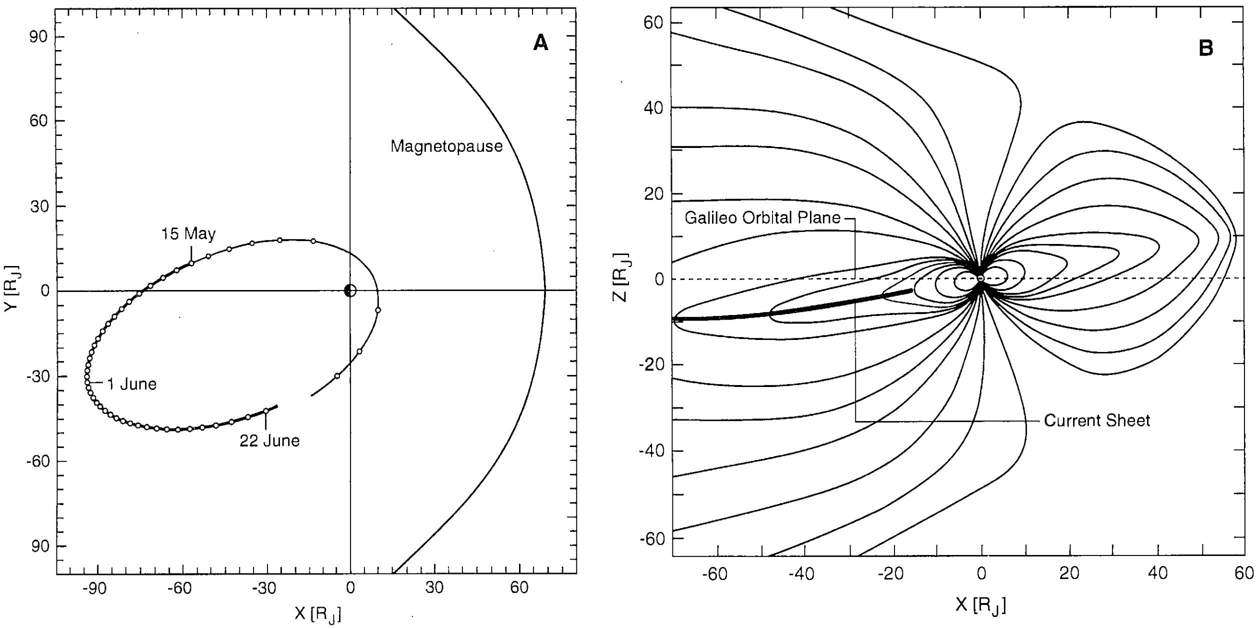
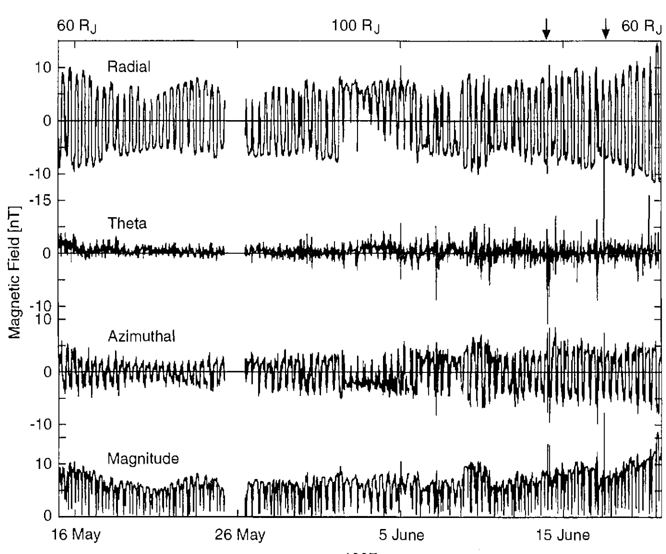


Fig. 1. Orbit of the Galileo spacecraft in the jovian magnetosphere. The orbit remains within 1° of the rotational equator throughout its trajectory. (**A**) The eighth orbit projected in the equatorial plane. The data examined herein were obtained between 15 May and 22 June. The average location of the magnetopause in this plane is shown (*11*). (**B**) The magnetic field lines in the noon-midnight meridian at a time when the northern magnetic dipole axis is tilted away from the sun and the current sheet is below the Galileo orbit.

fluid elements carry the magnetic field with them. Because the magnetic flux in the jovian magnetosphere is controlled not by Io but by currents in the interior of Jupiter, this transport process cannot result in a net loss of magnetic flux by the planet. Thus, we expect that, at some distance from Jupiter in the midnight sector, the current sheet associated with the radial field configuration will pinch off, allowing the magnetic field to reconnect across a portion of the current disk and releasing an "island" of magnetized plasma down the magnetotail (5). The rate of plasma loss through this process, on average, should roughly balance the supply of plasma to the magnetodisk from Io deep in the magnetosphere. The emptied and shortened flux tubes, rooted to Jupiter, should then return to the inner magnetosphere in response to magnetic and buoyancy forces. This existing paradigm has been built principally on indirect observations. There have been no direct observations of the reconnection process and no indications as to whether reconnection is steady, or episodic as on Earth.

The magnetic measurements obtained from 60 R_J to apojove and back to 60 R_J on Galileo's eighth orbit show an irregular square-wave pattern on the radial and azimuthal components as the current sheet crosses back and forth over the spacecraft because of the 10-hour rotation of the planet (Fig. 2). Although not evident on the scale plotted here, the radial and azimuthal components are anticorrelated, because the magnetic field lines are swept back out of the meridian plane, in much the same way as the magnetic field is in the solar wind. Unlike the solar wind, the swept-back jovian spiral field accelerates the material in the current sheet in the corotational direction, restoring some of the angular velocity lost to the conservation of angular momentum as material moves outward. The magnetic field strength is also modulated by the rotation, because the magnetic field is weaker inside the current sheet. On top of these quasi-periodic variations, a general unsteadiness is seen that manifests itself in a number of ways. The magnitude of the magnetic field rises and falls on time scales of several days, sometimes gradually and sometimes abruptly. The field direction can also become predominantly unidirectional for several planetary rotations, such as seen from 1 to 5 June. At these distances and corresponding magnetic pressures, the field configuration is sensitive to the solar wind conditions, because the typical dynamic pressure of the solar wind at Jupiter is about the pressure exerted by a 10-nT magnetic field. We therefore believe that the field magnitude variations could correspond to variations in solar wind dynamic pressure, and the apparent movement of the current sheet into continual residence above or be-

Fig. 2. The radial, theta, and azimuthal component of the magnetic field on orbit 8. The radial component is positive outward from Jupiter, the theta component positive southward, and the azimuthal component positive in the direction of Jupiter's rotation.



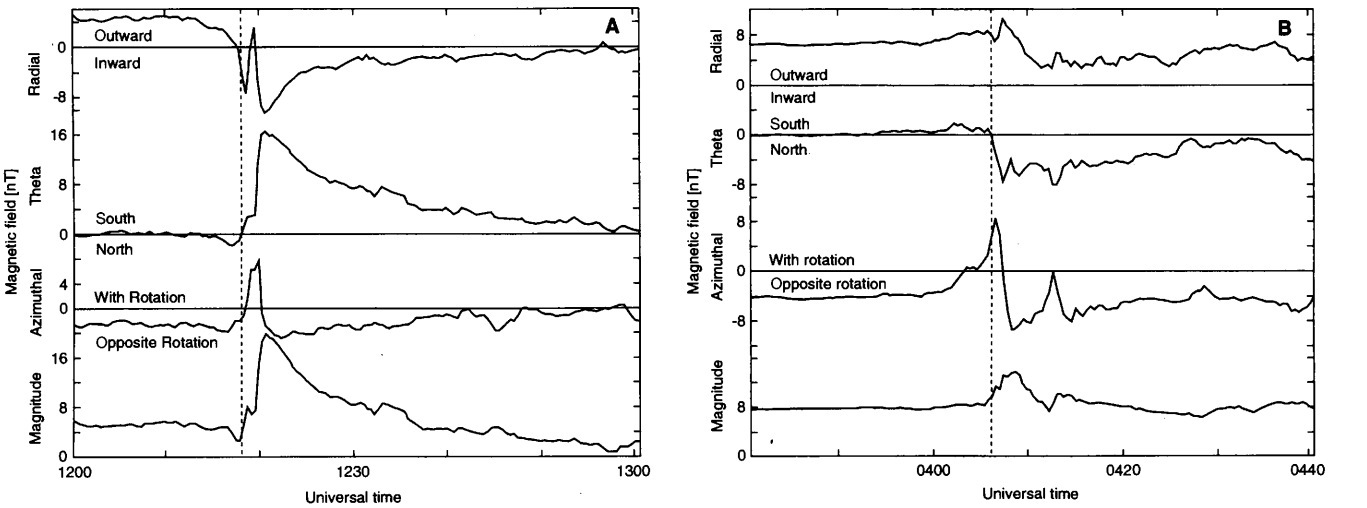


Fig. 3. The radial, vertical, and azimuthal components of the magnetic field for 1 hour surrounding the transient event. The vertical dashed lines indicate the time of the zero crossing of the north-south component. (**A**), 17 June 1997; (**B**), 14 June 1997.

low the spacecraft could be caused by north and south deviations of the solar wind flow direction.

Through this period, the theta component (perpendicular to the rotational equator and positive southward) appears to be relatively steady, averaging about 1 nT (Fig. 2). Occasionally after 26 May, there are several apparent "glitches" in the theta component. These are not telemetry noise. Rather, they are the signatures of strong negative and positive (northward and southward, respectively) turnings of the field, some so strong that they more than double the background field strength. We examine in greater detail two of these events indicated by arrows in Fig. 2.

The largest of these events was a southward turning of the magnetic field that occurred at 12:19 UT on 17 June 1997, as the spacecraft was crossing the current sheet from north to south at a distance of 74 R_J and a local time of 02:45 (Fig. 3A). The initial crossing of the current layer, as indicated by the reversal in the radial component, is brief compared to other crossings, suggesting that the current layer is locally thin or rapidly moving. The initial multiple reversals in the radial component may simply be due to oscillations in the position of the sheet caused by the onset of the event. The azimuthal component reverses across the current sheet, as we expect for the swept-back field geometry, but becomes stronger than expected and does not reverse its sign when the radial component does. Thus, after the initial transient behavior, the field becomes "swept forward" out of the meridian plane. After a short dip, the theta component rises abruptly and decays almost exponentially with time over the next 40 min. The field strength reaches 20 nT, more than triple the immediate ambient field magnitude and more than twice the field strength observed when the spacecraft was completely out of the current sheet.

A smaller event occurred at 04:06 UT on 14 June 1997, when Galileo was at a distance of 85 R_J at a local time of 02:20 (Fig. 3B). At the onset of this event, the spacecraft was not in the current sheet, nor did it cross the sheet during the event because the radial component of the field remains outward at all times. In this instance, the field turned impulsively northward and remained northward for 66 min. The transient behavior in the azmuthal component 6 min after the initial transient appears to be a second but weaker "impulsive change." As with the previous event, the field strength and the azimuthal field began to change before the onset of the northward turning. The azimuthal component reversed again after the northward turning. Here, the azimuthal component is negative and the radial component is positive. Thus, the field returned to a swept-back configuration. We discuss this point below.

These two events are interpreted as transient reconnection in a rapidly rotating magnetized plasma. The opposite directions of turning in the two events illustrated indicate that the events occurred on either side of the null point in the center of the current sheet (Fig. 4). We believe that the onset of reconnection occurs when the current sheet becomes locally thin, analogous to the paradigm for a terrestrial substorm (*7*). The abrupt increase in the strength of the vertical component occurs when the magnetic field that has reconnected at some radial distance away from the location of the spacecraft is brought rapidly to the vicinity of the spacecraft by the accelerated plasma. The black hemispheres denote the relatively massive current disk in a region where thinning has not taken place (Fig. 4). As in the case of reconnection in the terrestrial magnetotail, reconnection may proceed slowly at first in the denser current sheet and become much more rapid when it reaches the low-density lobes. Activity before the sudden southward or northward turning is present in both events.

The rotation of Jupiter produces important differences between the terrestrial magnetotail and the jovian magnetodisk. Angular momentum conservation imposes predictable perturbations in the azimuthal component of the magnetic field, as the

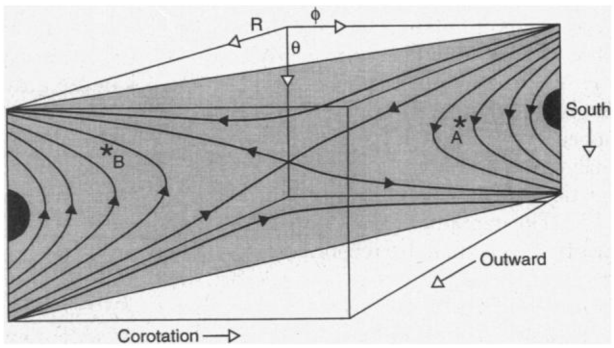


Fig. 4. A slice through the current sheet in the twisted magnetic meridian showing the reconnection point and the magnetic field piled against the magnetodisk plasma both inside and outside the reconnection point. Asterisks mark the inferred locations of the spacecraft for the two events corresponding to Fig. 3, A and B.

magnetized plasma is convected either toward or away from Jupiter by the reconnection process. The angular velocity of the plasma initially increases inward of the reconnection point, producing a corotation lead. Outward from this point, it decreases and the field is swept backward out of the meridian plane. This backward sweep of the field began before the sudden northward turning on 14 June and lasted about 4 min. Then, the field reverted to the usual anticorrelated radial and azimuthal fields characteristic of quiet times. The 17 June event has the anticorrelated radial and azimuthal fields for the entire period of enhanced vertical field.

On short time scales when the reconnection rate is high, the inertia of the mass of the thicker part of the current sheet represents an obstacle to the reconnected plasma. The newly reconnected magnetized plasma piles up against the current sheet and creates a thick region of plasma surrounding it. Evidence for the thickening can be seen in the noise and weakened radial field in the smaller event. The noise and weakened radial field are signs of hot plasma far from the center of the current sheet ($\sim$7 R_J), as estimated from a model (8).

The vertical transients in the magnetic field (Fig. 2) occurred throughout June 1997 when Galileo was at local times greater than 00:40 and radial distances >50 R_J, but few were as strong as our two examples. Similar behavior is seen in the shorter segments of data on other Galileo orbits in the region postmidnight (before 3 AM local time) and >50 R_J from the planet. These orbits also contain energetic particle bursts possibly associated with a reconfiguration of the magnetic field (9). Voyager 2 was the only previous mission to pass through this region and did not observe such magnetic events (3). The absence of similar magnetic signatures in the Voyager 2 data may relate to its greater radial velocity so that Voyager spent much less time in the active region.

It is difficult with a single satellite to determine the size of the affected region, especially in the radial direction. The disturbed vertical field lasted about 30 min, during which time the planet rotated about 20°. The arc of rotating plasma that moves past Galileo in 30 min at these distances is about 25 R_J if the plasma is nearly corotating. We would expect that the radial extent might be similar. Thus, these disturbances appear to be large but not global events and may represent only a fraction of the reconnection taking place in the magnetodisk (10). The rapidity of the onset is not surprising given that the reconnection should accelerate the plasma to the order of the Alfven velocity that may be higher than 5000 km/s in the tail lobes. Thus, a radial displacement of 12.5 R_J might occur in a time as short as 3 min, not inconsistent with the onsets of our two observed events.

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Ferromagnetism in $LaFeO_3$-$LaCrO_3$ Superlattices

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Ferromagnetic spin order has been realized in the $LaCrO_3$-$LaFeO_3$ superlattices. Ferromagnetic coupling between Fe^{3+} and Cr^{3+} through oxygen has long been expected on the basis of Anderson, Goodenough, and Kanamori rules. Despite many studies of Fe-O-Cr–based compounds, random positioning of Fe^{3+} and Cr^{3+} ions has frustrated the observation of ferromagnetic properties. By creating artificial superlattices of Fe^{3+} and Cr^{3+} layer along the [111] direction, ferromagnetic ordering has been achieved.

A magnetic interaction between two magnetic ions through a nonmagnetic ion (such as oxygen) was first proposed by Kramers (*1*) and was systematized by Anderson (*2*). Later, this so-called superexchange interaction was refined by Goodenough (*3*) and Kanamori (*4*) at a level so that this theory can be applied to various magnetic materials. According to their rules, we can estimate and predict whether a magnetic interaction through a superexchange interaction between two spins has a ferromagnetic (FM) or antiferromagnetic (AF) character. Many researchers have used this idea as a starting point for synthesizing ferromagnets. On the basis of these rules, the 180° superexchange interaction in a metal dimer bridged via oxygen that has a d^3-d^5 electron state ($\angle$M-O-M = 180° and M = Fe^{3+}, Cr^{3+}, and so forth) is predicted to have FM order (*4*). The most typical and still unachieved combination is Fe-O-Cr systems (*5*). It is expected that if Fe^{3+} and Cr^{3+} ions are introduced alternately in the B site of perovskite-type transition metal oxides (ABO_3), the synthesis of FM materials can be achieved. Although some attempts to synthesize such materials have been made by sintering methods, the atomic order of Fe-O-Cr has not been achieved because such materials phase separate into Fe oxide and Cr oxide phases (*6*). As a result, a FM ordered phase has not been obtained, and the materials have been shown to have an AF character (*7, 8*).

The single-phase $LaCrO_3$ and $LaFeO_3$ have AF structures with both inter- and intralayer antiparallel spin alignments and Neel temperatures (T_N) of 280 and 750K, respectively (*9–11*). If an artificial superlattice of $LaCrO_3$-$LaFeO_3$ is synthesized by depositing alternating layers of $LaCrO_3$ and $LaFeO_3$ along the [111] direction, it may be possible to form films that have various magnetic properties by controlling the stacking periodicity. Ferromagnetism can occur especially in the case of one layer by one layer stacking on the (111) surface because Fe^{3+} and Cr^{3+} ions are bridged by oxygen ions alternately in the film (Fig. 1).

We have synthesized a FM artificial superlattice by alternately stacking one unit layer of $LaCrO_3$ and $LaFeO_3$ on a $SrTiO_3$ [111] single crystal by laser molecular beam epitaxy (MBE) (Fig. 1). Such materials cannot be obtained in the conventional bulk phase because they are thermodynamically unstable (*6–8*). Furthermore, even if phase separation is avoided so that Fe^{3+} and Cr^{3+} ions mix randomly, AF interactions are dominant in the material because the Fe^{3+}-O-Cr^{3+} ordered phase could not be

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