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RECONNECTION IN PLANETARY MAGNETOSPHERES

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ABSTRACT

Current sheets in planetary magnetospheres that lie between regions of "oppositely-directed" magnetic field are either magnetopause-like, separating plasmas with different properties, or tail-like, separating plasmas of rather similar properties. The magnetopause current sheets generally have a nearly limitless supply of magnetized plasma that can reconnect, possibly setting up steady-state reconnection. In contrast, the plasma on either side of a tail current sheet is stratified so that, as reconnection occurs, the plasma properties, in particular the Alfven velocity, change. If the density drops and the magnetic field increases markedly perpendicular to the sheet, explosive reconnection can occur. Even though steady state reconnection can take place at magnetopause current sheets, the process often appears to be periodic as if a certain low average rate was demanded by the conditions but only a rapid rate was available. Reconnection of sheared fields has been postulated to create magnetic ropes in the solar corona, at the Earth's magnetopause, and in the magnetotail. However, this is not the only way to produce magnetic ropes as the Venus ionosphere shows. The geometry of the reconnecting regions and the plasma conditions both can affect the rate of reconnection. Sorting out the various controlling factors can be assisted through the examination of reconnection in planetary settings. In particular we observe similar small-scale tearing in the magnetopause current layers of the Earth, Saturn, Uranus and Neptune and the magnetodisk current sheet at Jupiter. These sites may be seeds for rapid reconnection if the reconnection site reaches a high Alfven velocity region. In the Jupiter magnetosphere this appears to be achieved with resultant substorm activity. Similar seeds may be present in the Earth's magnetotail with the first one to reach explosive growth dominating the dynamics of the tail.

INTRODUCTION

While many researchers have contributed to the understanding of the reconnection process, it was J. W. Dungey who established the first credible role for reconnection in space plasmas (Dungey, 1961). Dungey postulated that reconnection could drive a convection of plasma in the Earth's magnetosphere when the interplanetary magnetic field was southward. In this model, shown in the top panel of Figure 1, the interplanetary and magnetospheric magnetic fields become coupled at the subsolar point and the momentum of the solar wind drives circulation in the magnetospheric plasma. Reconnection also occurs at a neutral point in the tail balancing, at least on average, the dayside rate. This is a roughly steady process with plasma returning to the dayside to complete the cycle.

Dungey (1963) also postulated the reconnection model shown in the bottom panel for northward IMF. In some senses this process is the reverse of that for southward IMF. Magnetic flux is reconnected at neutral points on the tail magnetopause. This adds a flux tube draped across the magnetopause and leads to a convection pattern from the dayside to the nightside where the field reconnects with the solar wind field and the process repeats. Again this is a steady state process but unlike the top model, it may be very dependent on the closeness of the field to perfect north-south alignment. If the same field line does not connect at both north and south sites a flux tube is not added to the dayside magnetosphere (Russell, 1972).

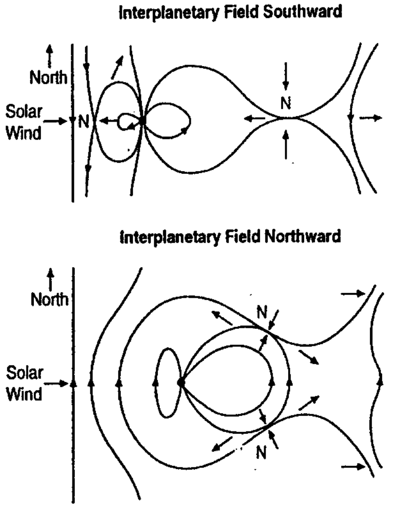


Fig. 1. Dungey's models of the reconnecting magnetosphere. (Top) The noon-midnight meridian when the IMF is southward (Dungey, 1961). (Bottom) The noon-midnight meridian when the IMF is northward (Dungey, 1963).

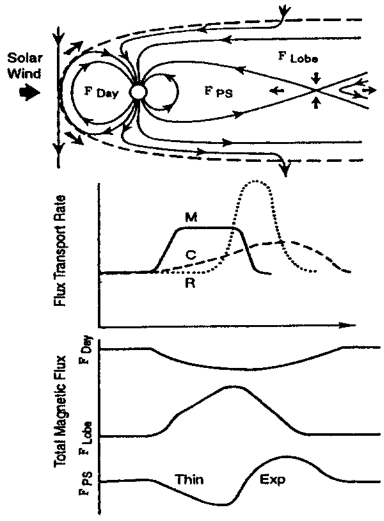


Fig. 2. The near-Earth neutral point model of substorms. (Top) Flows and fields in the noon-midnight meridian. (Middle) The flux transport rates: M, dayside to tail; R, tail to plasma sheet; C, plasma sheet to dayside. (Bottom) The total magnetic flux in each of the dayside magnetosphere, the tail lobes and the plasma sheet versus time.

Dungey's southward reconnection model has been incorporated in the near-Earth reconnection model of substorms (Russell and McPherron, 1973). Figure 2 illustrates this model. In this model the IMF turns southward at the beginning of the events leading to a substorm. Reconnection begins at the subsolar point at a rate, M. This process removes magnetic flux from the dayside magnetosphere and transports it to the lobes of the tail. The deficit of magnetic flux on the dayside causes convection from the night magnetosphere to replace it at a rate C, and, since reconnection has not begun yet in the tail, the plasma sheet thins. Eventually the reconnection point in the tail is activated and when the reconnection reaches the low-density lobe, the reconnection rate, R, increases rapidly, exceeding the dayside rate, and pushing more magnetic flux toward the dayside. This onset of reconnection in the tail ends the growth phase in which energy is stored in the tail lobes and begins the expansion phase in which energy is removed from the tail reservoir.

The feature added to the steady-state Dungey model to create a model for substorms is the driving of reconnection on the magnetopause by a changing IMF coupled with delayed responses that allow later unloading of energy into the inner magnetosphere and ionosphere. Although there has been much debate about the substorm process, no model has successfully challenged the quantitative predictability of this model. Nevertheless there is much about the reconnection process and the triggering of substorms that we do not understand.

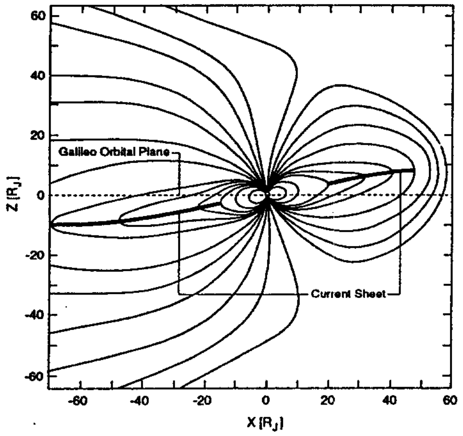


Fig. 3. The noon-midnight meridian of the jovian magnetosphere (Russell et al., 1998b).

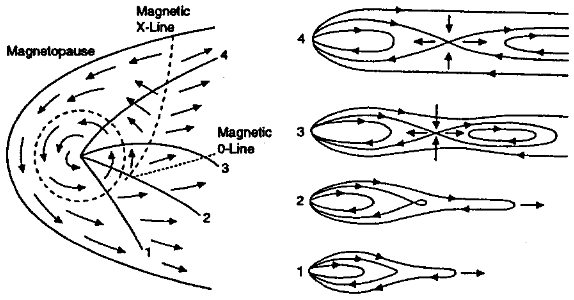


Fig. 4. The circulation pattern and magnetic meridian views of steady-state jovian reconnection (Vasyliunas, 1983).

The other planets can help us in this regard. They come in different sizes from the tiny Mercury magnetosphere to the giant jovian magnetosphere that dwarfs the sun. Moreover, they find themselves in different plasma settings, different plasma betas, different pressure regimes etc. Figure 3 shows us the noon-midnight meridian of the jovian magnetosphere. The size of the jovian magnetosphere is so vast that it takes 6 hours for the solar wind to cross the distance sketched in this diagram. Since substorms on Jupiter occur more rapidly than once every 6 hours, we suspect that solar-wind driven processes are not responsible. Implicit in this diagram is the rapid rotation of the jovian magnetosphere. The centrifugal force of the magnetospheric plasma, supplied mainly by the moon Io, at a jovicentric distance of 5.9 jovian radii (R_J), is sufficient beyond 24 R_J to stretch out the magnetic field lines into a disk on both the dayside and the nightside. This current sheet resembles an extreme tail current sheet bounded by a very, very low-density plasma, perhaps less than 10^{-4} particles per cm^3. The Alfven velocity in these lobes can be very high, perhaps as high as several tens of thousands of km/s.

The equivalent of the Dungey magnetosphere for this giant rapid rotator was proposed by Vasyliunas (1983) and is shown in Figure 4. The panel on the left shows the equatorial plane of the jovian magnetosphere. In this plane there are two neutral lines: an X-type neutral line and an O-type neutral line. This pair of neutral lines allows the stretched out magnetic field lines to be cut off, releasing magnetic islands of iogenic ions to be flung off down the tail toward Saturn. The panels on the right show magnetic meridians at various longitudes, illustrating the development of reconnection and a magnetized island of plasma. As in the Dungey model, this model works in the steady state and, as in the Dungey model, in situ observations force us to consider a time-varying model to explain the data. However, in the case of the Earth's magnetosphere, these time variations are driven by a varying IMF. At Jupiter, the solar wind appears not to play a role in triggering substorms. Rather, the addition of ions to the jovian magnetosphere at Io provides a time-varying stress. There may be some lessons for the terrestrial reconnection process in these jovian substorms.

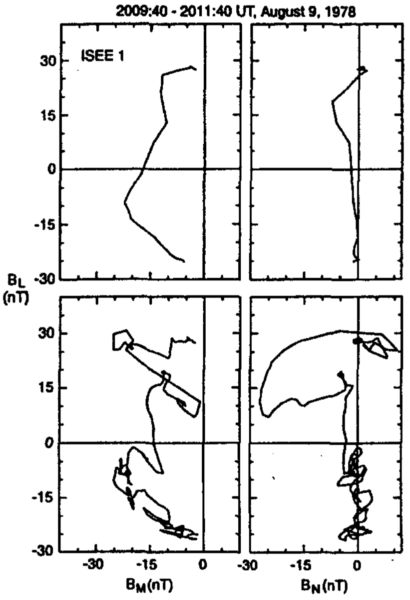


Fig. 5. Hodograms of the variation of the magnetic field across the magnetopause (left) in the plane of the boundary and (right) containing the normal direction. Top panels are at low temporal resolution and bottom panels at high resolution (Russell, 1995).

In this review we first examine the fine magnetic structure of current sheets, both magnetopause and tail-type. Then we examine steady state and explosive reconnection, the former process at the Earth and the latter process at Jupiter. Then we examine transient patchy reconnection, or the flux transfer event. Finally, we look at the formation of flux ropes in various settings.

FINE SCALE STRUCTURE IN CURRENT SHEETS

It is often not appreciated that the Earth's magnetopause contains structure on scale sizes much smaller than the overall thickness of the current sheet. Usually a hodogram of the magnetic field variation through a magnetopause will show a quasi-rotational feature in the plane of the boundary and a quasi-steady normal component across the boundary such as shown in the top panel of Figure 5 (Russell, 1995). However, when that same crossing is examined at much greater temporal resolution as in the bottom pair of panels, brief intervals of large normal components are revealed and much structure in the plane of the boundary as well. Dual spacecraft measurements have been generally too far apart to reveal much about this structure and upcoming multiple-satellite missions also have large planned separations relative to the fine-scale structure.

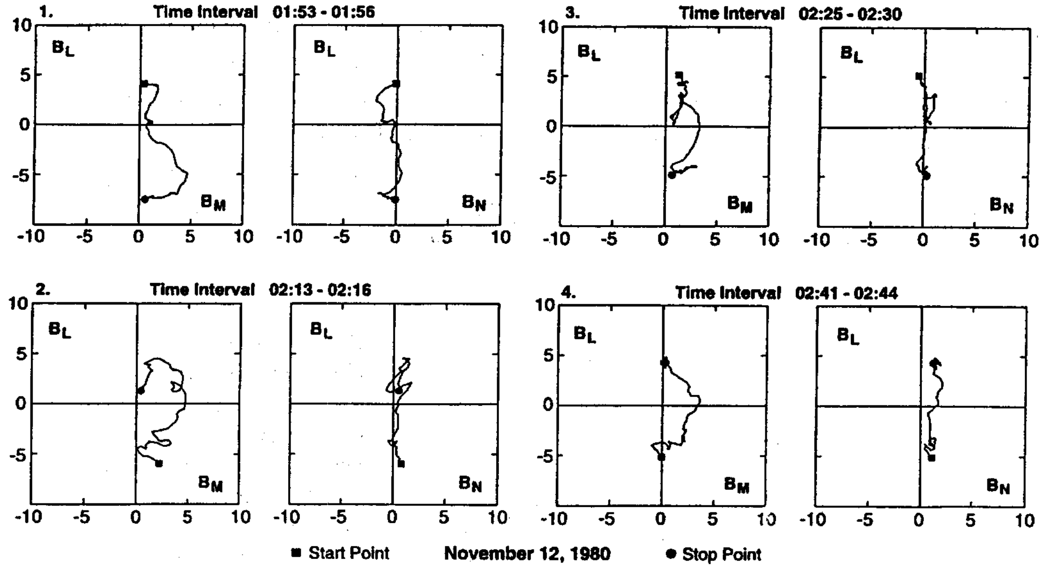
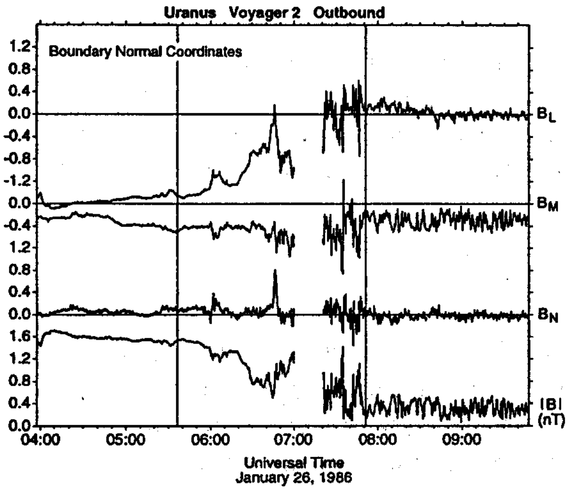


Fig. 6. A collection of magnetopause hodograms from Saturn (Huddleston et al., 1998).

While it may be difficult to prove the importance of the observed structure or tearing of the current sheet, it is not difficult to show that this structure is ubiquitous in solar system current sheets. Figure 6 shows a collage of hodograms of the Saturn magnetopause [Huddleston et al., 1998]. All crossings have structure in the normal and in-plane components, some quite significant. In three of the cases the field across the current sheet has both positive and negative components suggesting the presence of small islands of magnetic field loops within the current layer.



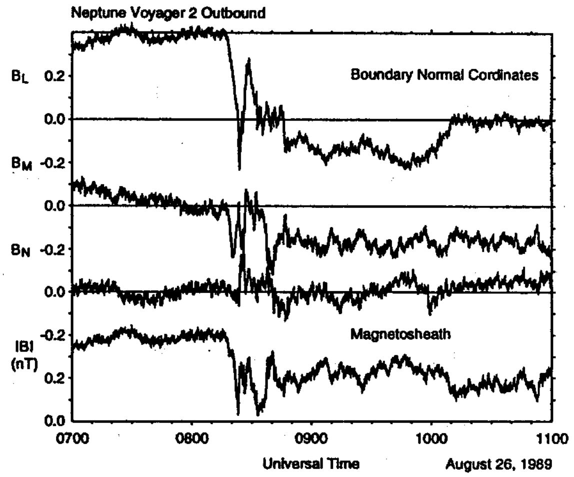


Fig. 7. Magnetic field in principal axis coordinates across the magnetopause of Uranus (Huddleston et al., 1998).

Fig. 8. Magnetic field in principal axis coordinates across the Neptune magnetopause (Huddleston et al., 1998).

Figure 7 shows a time series in boundary normal coordinates for the Uranus magnetopause. Right in the center of the crossing in the weakest part of the field the field turns almost at right angles to the boundary. Note that there is almost no hint of this normal component over most of the current sheet crossing. Figure 8 shows a crossing of the Neptune magnetopause. Again there is a strong normal component in the middle of the current sheet crossing.

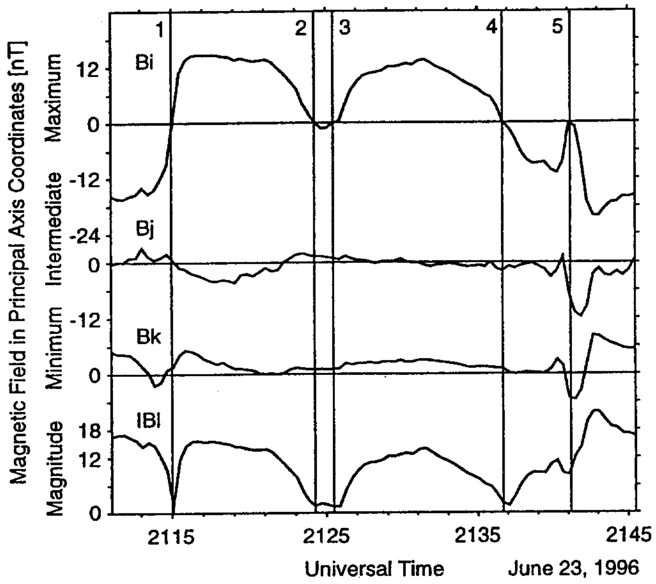


Fig. 9. The magnetic field across a disturbed current sheet in the jovian magnetodisk expressed in average current sheet coordinates. To obtain these coordinates, the data were first low pass filtered to remove the effects of high frequency structure. Then the data were rotated into the minimum variance coordinate system with k along this direction and i along the maximum variance direction. Five current sheet crossings are indicated by vertical lines. Only the last of these has a signature that is believed to be due to tearing of the magnetic field into magnetic islands.

Similar structure is seen in tail-type symmetric current sheets as well. Figure 9 shows the normal component at 46 R_J in the jovian magnetodisk current sheet (Russell et al., 1998a). There are 5 crossings of the current sheet here labeled 1 to 5. Three of them have positive, southward components across the current sheet in the direction of the dipolar field. The first one occurs away from the crossing and because B_k is well correlated with B_i, it appears that the negative component is just due to a tilt of the current sheet from its average orientation at this time. However, at crossing 5, where the spacecraft skims the current sheet there is a strong negative component right at the current sheet similar to the magnetopause structures discussed above. Such structure appears to be a universal feature of current sheets with large shear.

STEADY-STATE RECONNECTION

Reconnection is generally an unsteady process but on occasion it can achieve a quasi-steady state. One such occasion was at the Earth's magnetopause on September 9, 1978 when ISEE-1 and 2 executed multiple crossings of the magnetopause while it was reconnecting. These data are shown in Figure 10 (Sonnerup et al., 1981). However, even here, the classic steady-reconnection case, the velocity is pulsing and the density is irregular on the scale of tens of seconds. We cannot tell whether this is irregularity in the face of steady boundary conditions or the oscillations are driven by varying solar wind conditions. We also have evidence of a type of reconnection whose periodicity does not seem to be driven by anything in the solar wind, but before we examine this phenomena we examine the case for explosive reconnection, reconnection that lies dormant for a long time and then suddenly erupts.

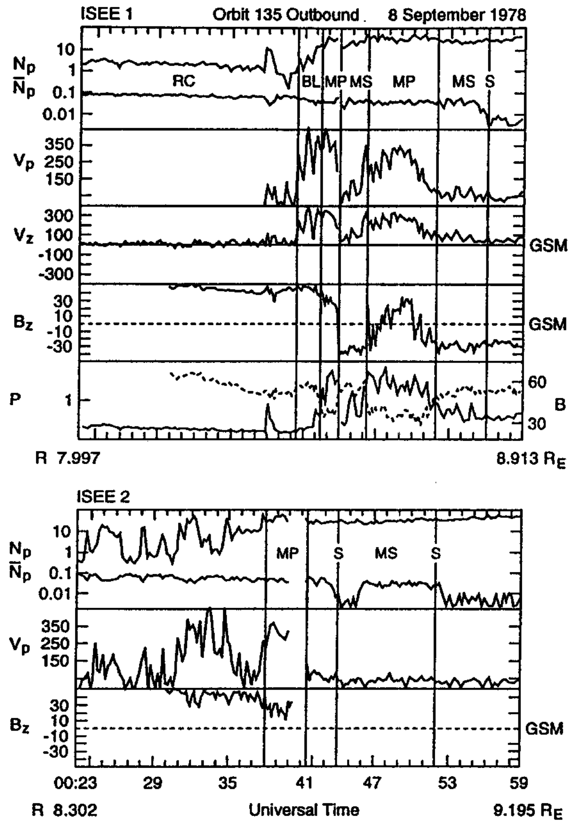


Fig. 10. ISEE 1 and 2 measurements during steady-state reconnection at the Earth's magnetopause. (Top) ISEE-1 proton and hot proton density, proton velocity, northward velocity, northward component of the magnetic field and the plasma kinetic and magnetic pressures. (Bottom) ISEE-2 proton and hot proton number density, proton velocity and northward component of the magnetic field (Sonnerup et al., 1981). Plasma regions are labeled: RC – ring current, BL – boundary layer, MP – magnetopause, MS – magnetosheath and S-separatrix.

EXPLOSIVE RECONNECTION

The case for explosive reconnection can easily be made using substorm-associated observations in the Earth's magnetotail. Nevertheless the substorm community has evolved into camps with strong biases who argue their positions strenuously so that nothing appears to be clear. One of these camps rules out explosive reconnection out of hand (Akasofu, 1985). Since the Earth's magnetotail is very sensitive to the interplanetary magnetic field, perhaps the tail at substorm onset is merely responding to a change in the solar wind. Fortunately observations of reconnection are also available from deep inside the jovian magnetosphere, well away from the influence of the solar wind. These observations show that tail-type current sheets do reconnect explosively. Figure 11 shows the magnetic field measured by the Galileo spacecraft at a distance of 60 to 100 R_J on its eighth orbit (Russell et al. 1998b). The theta component is the field crossing the current sheet. The periodic reversals of the B_R and B_ϕ components occur as the magnetodisk current sheet sweeps past Galileo due to the tilt of the dipole and the rotation of Jupiter. The features to be noted here are the positive and negative pulses in the magnetic field. These pulses are not telemetry errors but northward and southward turnings much like those seen in the Earth's magnetotail. Figure 12 shows one of these events at much higher resolution. The southward turning of the magnetic field is extremely strong and sudden. The new vertical field is three times stronger than the pre-existing radial field. Reconnection has occurred so rapidly the newly connected field lines have piled-up against the unreconnected part of the magnetodisk. Figure 13 shows the geometry of this event and a similar one on the other side of the neutral point. These events occur almost randomly with an average separation of about six hours.

If these events are not triggered by the solar wind what could cause them? One possibility is that there are irregularities in the current sheet. These could be imposed by unsteadiness in the outward convection of plasma or it could be imposed by the fine scale structure in the current sheet that we examined earlier. The fine scale structure may have grown out of the confines of the central dense current sheet into the low-density lobe above and below. At that point where the Alfven velocity increases rapidly the current sheet should suddenly and rapidly be disrupted. In a few minutes up to 10 GT could become connected and 10,000 tons of ions released down the magnetotail.

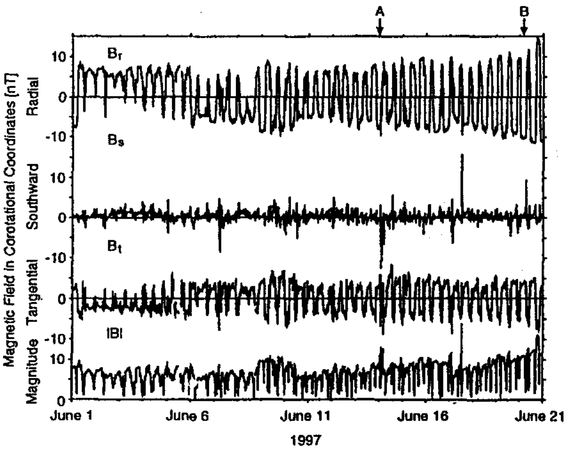


Fig. 11. The radial, southward and corotational components of the magnetic field from 100 to 60 R_J in the jovian equatorial plane on Galileo's eighth orbit. (Russell et al., 1998b).

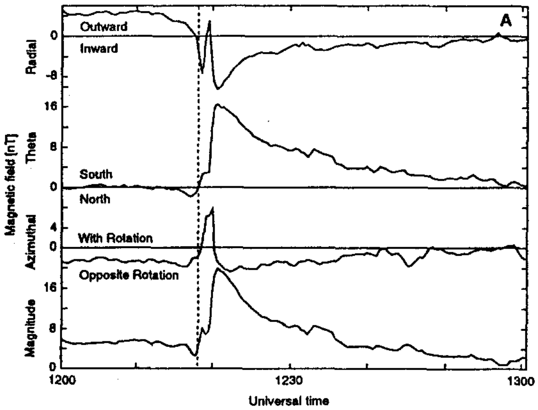


Fig. 12. An expansion of the magnetic field record across the largest positive impulse in the theta component in Fig. 11 (Russell et al., 1998b).

TRANSIENT PATCHY RECONNECTION

When the first ISEE 1 and 2 measurements were obtained it became clear that the magnetosphere was periodically reconnecting for brief periods (Russell and Elphic, 1978). The magnetic field in these events, called flux transfer events or FTEs, contained both magnetosheath and magnetospheric plasma. The events repeated about every 8 minutes. Figure 14 shows a sketch of what an FTE may look like. We do not know if these occur simultaneously with "steady" reconnection or whether they represent a separate state of reconnection at the magnetopause. It is possible that the fine scale structure leads to eventual reconnection on a larger scale as in the jovian magnetosphere but the period appears to be quite regular. Figure 15 demonstrates this and the fact that the periodicity is not simply driven by the solar wind. In this example ISEE-1 is sitting near the magnetopause and ISEE-3 is monitoring the solar wind and IMF. There are no triggering events in the solar wind (Le et al., 1993).

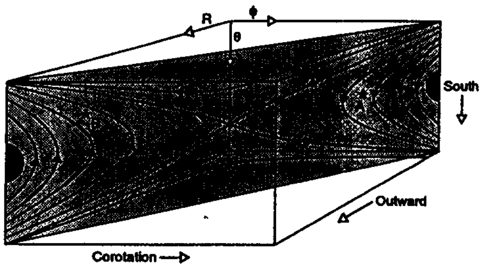


Fig. 13. Interpretation of the field variations at northward and southward turning events in Fig. 11 in terms of reconnection in the swept-back magnetic meridian (Russell et al., 1998).

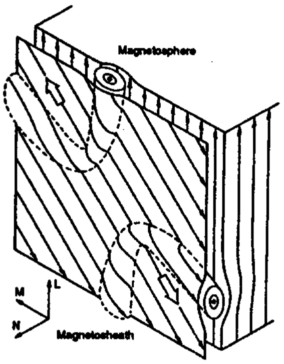


Fig. 14. Schematic of a flux transfer event.

One might ascribe the 8-minute periodicity to some feedback between the ionosphere and the magnetosphere but FTEs are seen at Mercury too where the ionosphere is very weak. Figure 16 shows the Mercury magnetosphere noon-midnight meridian. The planet fills most of the magnetosphere. There is no dynamically significant ionosphere and the overall dimension of the magnetosphere is small, only about 7000 km across at the terminators. Nevertheless Mercury has FTEs as shown in Figure 17. The FTEs last a much shorter period of time but they are clearly present (Russell and Walker, 1985). At the other extreme we look at the largest magnetosphere in the solar system in Figure 18. Here on the jovian magnetopause is clear evidence for an FTE in the normal component. The time scale is comparable to that seen at Earth (Walker and Russell, 1985).

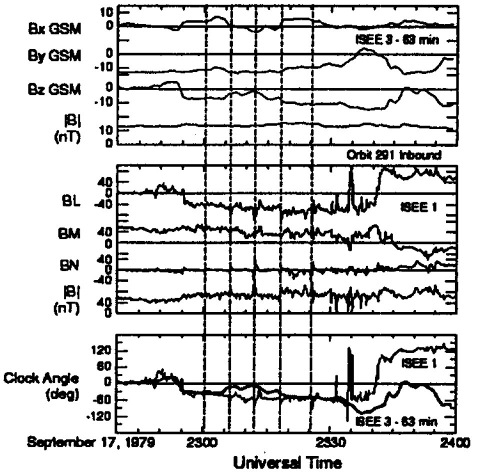


Fig. 15. Demonstration that FTE occurrence is not directly driven by the solar wind. (Top panel) Interplanetary magnetic field observed by ISEE-3. (Middle panel) Magnetic field in boundary normal coordinates near the magnetopause measured by ISEE-1. (Bottom panel) The clock angle of the field around the solar direction for both ISEE-3 and ISEE-1 (Le et al., 1993).

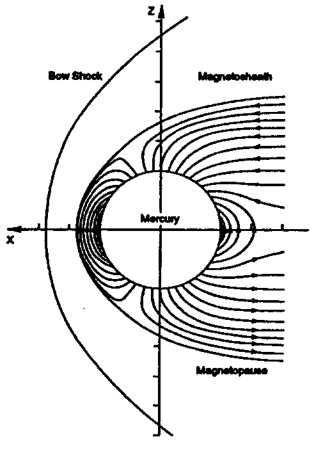


Fig. 16. Sketch of the magnetic field of Mercury in the noon-midnight meridian (Russell et al., 1988).

This examination of planetary FTEs may not have solved the mystery of the source of FTE triggering, but it is clear that whatever controls FTEs works in the absence of an ionosphere, and works on a current layer so vast that it cannot be coupled very intimately to the ionosphere. The FTE seems to be a product of the magnetopause itself.

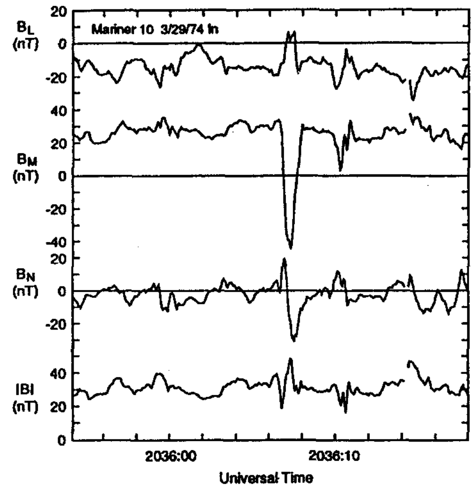


Fig. 17. Magnetic field in boundary normal coordinates at the magnetopause of Mercury showing a flux transfer event (Russell and Walker, 1985).

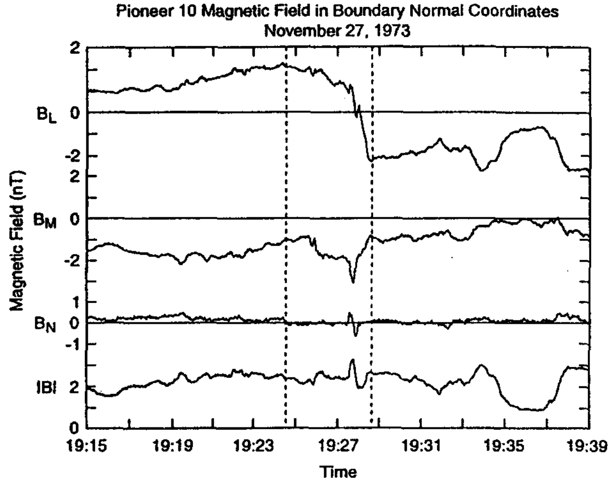


Fig. 18. Magnetic field in boundary normal coordinates at the magnetopause of Jupiter (Walker and Russell, 1985).

FLUX ROPE FORMATION

Reconnection of sheared magnetic fields has been postulated to create magnetic flux ropes in the solar corona, at the Earth's magnetopause and in the magnetotail. However, flux ropes can also be made by velocity shear [Russell, 1990]. This happens in Venus' ionosphere where there is no magnetic field with which to reconnect. In contrast in the solar corona the opportunity for reconnection is great.

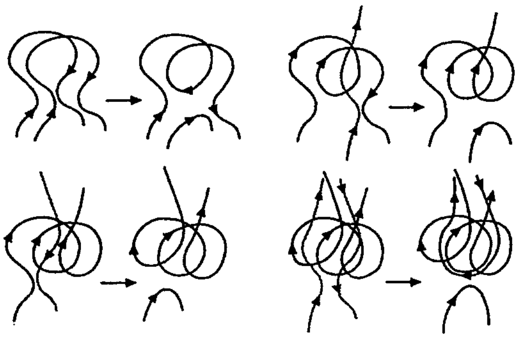


Fig. 19. Proposed mechanism for the formation of a magnetic cloud or flux rope in the solar corona (Gosling et al., 1995).

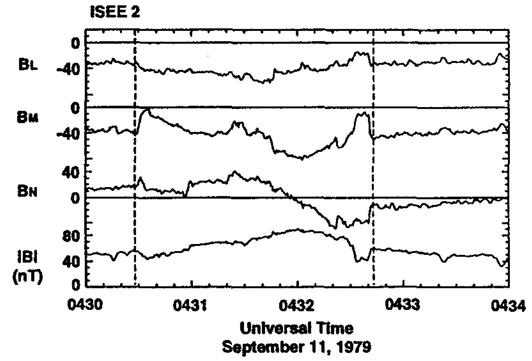


Fig. 20. Magnetic field measurements across a flux transfer event at the terrestrial magnetopause showing the twisted magnetic field in the core an FTE (Le et al., 1998).

Figure 19 shows how reconnection is thought to create the magnetic rope or cloud associated with an interplanetary coronal mass ejection (Gosling et al., 1995). These structures can be 50,000,000 km across. Twisted flux ropes can also be produced on a much smaller scale.

Figure 20 shows the magnetic structure of the core of an FTE when the ISEE spacecraft cut through the center of an FTE (Le et al., 1998). The structure of this core field is almost identical to that seen in an ICME. The process at work in an FTE only about 5000 km across may be very similar to that working on scales nearly 10000 times larger. Nevertheless we must reserve judgement on the similarity of the mechanism. There are no observations that show how ICMEs are created. The formation mechanism for these structures even more of a conjecture than that of FTEs.

CONCLUSION

In this paper we have examined five different aspects of reconnection seen in solar system plasmas that may provide lessons for reconnection in solar and astrophysical plasmas. First, all current sheets lying between strongly sheared fields have significant structure in the components in the plane of the boundary and in the normal component. This structure may provide the seed that grows into a larger scale reconnection "event" at some later time. Such structure is seen in the magnetopause currents of all the planets and in the magnetodisk of Jupiter. Second, there are basically two types of reconnecting currents: those with fairly uniform but quite different plasmas on either side of the boundary and those with similar rarefied plasma on either side but oppositely directed. In the first case "steady state" reconnection could be driven; in the second, reconnection will be slow when the X-line is deep in the current sheet but may proceed explosively when it reaches the rarefied plasma. On Jupiter such reconnection is very, very strong, much more so than even in the Earth's magnetotail.

Third, we find that the steady-state reconnection process is not very steady, although it is certainly continuous. We should comment here that the geometry of the solar-wind interaction with a planetary magnetosphere should enhance the ability of the plasmas to reconnect because there is a place for the products of reconnection to go in steady state. In the explosive reconnection that occurs in jovian and terrestrial substorms the process is shut off when the planetward side of the reconnection region becomes full. In the Earth's case slow convection to the dayside restores the pre-existing equilibrium. In the case of Jupiter it appears that the reconnected volume breaks into small tubes that convect inward.

Fourth, we found that, even in the geometry that allows steady-state or continuous reconnection, the process can be decidedly transient, stopping for much longer than it operates, producing what has been called flux transfer events. The signature of these events has been seen at Mercury, Earth and Jupiter.

Finally, we have found twisted flux bundles in a variety of solar system settings. On Venus, velocity shear is the only possible mechanism for forming these structures. In the solar corona and at planetary magnetopauses reconnection of sheared fields is the most probable cause. The reconnection process can work over a wide variety of scales, from that of the Mercury magnetopause to that of the jovian magnetopause, and from the Earth's tail to that of the jovian magnetodisk, and produce very similar results. This bodes well for the scalability of these "lessons" to other plasma environments.

ACKNOWLEDGMENTS

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