PATCHY RECONNECTION AND MAGNETIC ROPES IN ASTROPHYSICAL PLASMAS

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ABSTRACT

Reconnection is clearly observed at the terrestrial magnetopause but seldom in the simple geometry originally proposed. Most often reconnection is patchy, forming tubes of twisted flux. The passage of one of these twisted tubes has been called a flux transfer event. Similar twisted tubes, or flux ropes, are formed at Venus by velocity shear. These tubes become so highly twisted that they become kink unstable. The presence of the kink instability suggests a way of creating compound flux ropes as have been postulated to be necessary to explain photospheric magnetic structure.

1. INTRODUCTION

Reconnection in astrophysical plasmas is difficult to treat theoretically and difficult to study observationally. Most places where we believe reconnection is occurring such as on the sun, in pulsar magnetospheres and in radio galaxies the site of reconnection is inaccessible to direct probing. Thus, we must infer what is occurring from indirect evidence. In planetary magnetospheres, however, we do have in-situ data and can directly probe the reconnection site. Nevertheless, we still must infer, rather than observe, many of the properties of the reconnection process. Reconnection, perhaps because it is a time-varying phenomenon, or perhaps because of the intrinsic three-dimensionality of planetary magnetospheres, produces three-dimensional structures. These three-dimensional structures are difficult to investigate with our spacecraft because they are carried over the point of observation with usually unknown velocities. Further, these structures may not be time stationary. If these complexities were not enough to slow down progress, there is yet one more complication, velocity shear. Reconnection, occurring on the forward hemisphere of planetary magnetospheres, does so at the interface between two flowing plasmas whose direction of flow might be quite different. The existence of velocity shear in addition to magnetic shear is often not appreciated in treating reconnection at the magnetopause.

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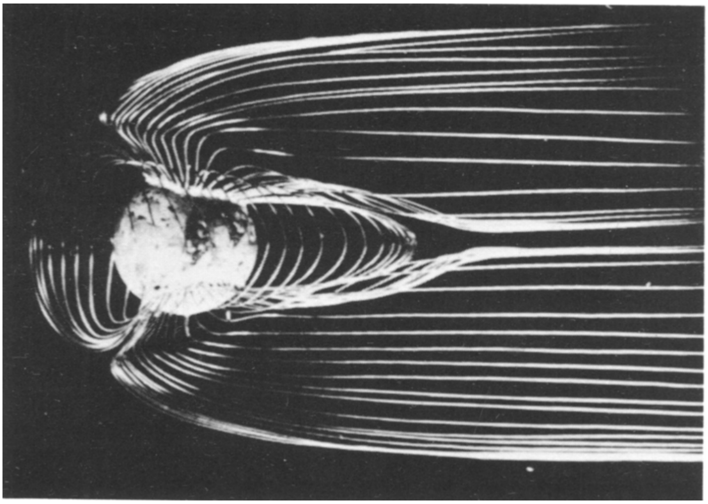


Figure 1. Wire model of magnetosphere.

Velocity shear produces flux ropes, twisted bundles of magnetic field lines. At a planetary magnetopause such flux ropes connect the magnetospheric plasma and field to that of the shocked solar wind. Flux ropes are also found in the Venus ionosphere and on the sun. In order to understand some of the behavior of such flux ropes, we will examine the observed properties of Venus flux ropes and draw some inferences regarding the possible behavior of solar flux ropes.

2. RECONNECTION AT THE TERRESTRIAL MAGNETOPAUSE

The geometry of the reconnection process at the terrestrial magnetopause is intrinsically three-dimensional. Figure 1 shows a three-dimensional wire model of the terrestrial magnetic field (Podgorny, 1976). The polar field lines are swept back by the tangential stresses of the solar wind plasma, including the Maxwell stress due to reconnection. The solar wind plasma is super-magnetosonic and thus a standing, detached shock wave forms in front of the terrestrial magnetosphere. The interplanetary magnetic field is carried by the solar wind through this bow shock and it becomes distorted as the shocked solar wind is deflected around the magnetospheric cavity. Not only is this distortion difficult to treat analytically but also the magnetic stresses affect the flow field. Thus, global treatments of this problem generally involve computer models and simulations.

If we assume that the reconnection process is steady-state and that one need not consider the global geometry, then the configuration sketched in Figure 2 applies. Magnetized plasma flows from the left (shocked solar wind) and the right (magnetosphere), and exits top and bottom, being accelerated by the magnetic sling shot configuration. In this way magnetic tension produces directed flow. A spacecraft such as the

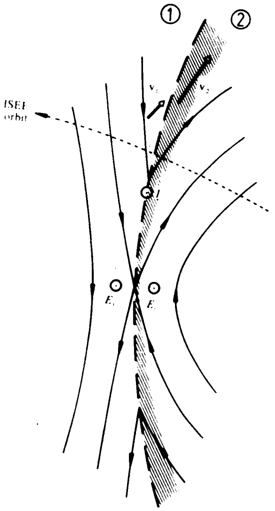


Figure 2. Reconnection at magnetopause.

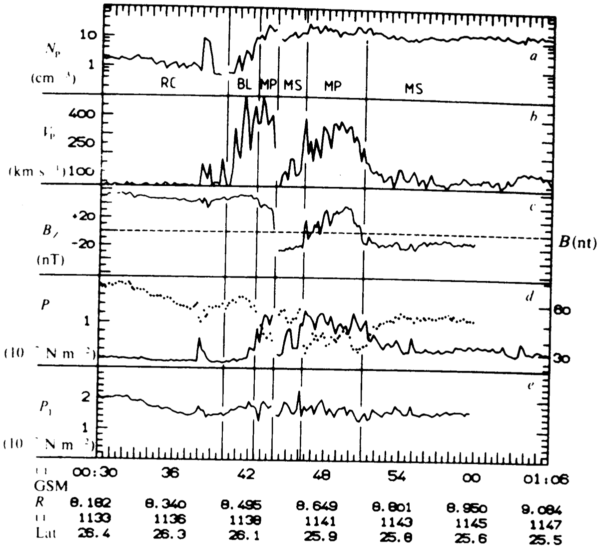


Figure 3. ISEE observations of reconnection.

International Earth-Sun Explorer (ISEE) would see these various flows sequentially as the magnetopause crossed the spacecraft. ISEE, in fact, does see such flows on occasion as shown in Figure 3 (Paschmann et al., 1979). As indicated in the top panel (plasma number density, N_p), the spacecraft passes out of the ring current plasma (RC), into the boundary layer plasma (BL) which is denser and cooler than the magnetospheric ring current plasma. Then the spacecraft moves through the magnetopause (MP) and into the magnetosheath (MS). The magnetopause is oscillating at this time and moves back over the spacecraft again but the spacecraft does not return entirely to the magnetosphere. Rather the magnetopause moves back towards the earth and the spacecraft enters the magnetosheath plasma once and for all. While in the magnetopause, and to a certain extent on either side of it, vertical (northward directed) flows are observed quantitatively, not just qualitatively, as expected for reconnection. The middle panel, B_z, shows the vertical component of the magnetic field. The sudden changes in this quantity marks the current layer which is the magnetopause. The bottom two panels give respectively the two components of the plasma pressure, kinetic and magnetic, and their sums. The magnetic pressure (dots) dominates here, both in the magnetosphere and the magnetosheath, but not in the magnetopause.

This early observation with the ISEE mission was an important one because it showed for the first time that plasma was accelerated at the magnetopause as predicted by simple reconnection theory. However, such behavior was not always observed. Nevertheless, a sufficient number of similar events occurred so that it was clear that such reconnection was an important contributor to magnetospheric energetics (Sonnerup et al., 1981).

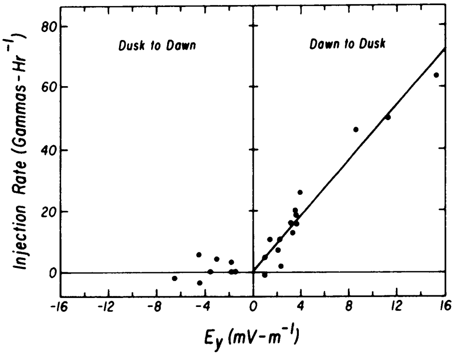


Figure 4. Ring current injection rate as a function of the interplanetary electric field.

These in-situ observations prove that reconnection occurs on the dayside magnetopause, but there are too few of these observations to establish clearly the factors that control the rate of reconnection. It has been postulated that the magnetosphere behaves as a half-wave rectifier, reconnecting with the magnetosheath magnetic field whenever the angle between the magnetospheric and magnetosheath fields exceeds 90°. The support for this postulate comes from indirect evidence, i.e., from the response of geomagnetic activity to varying directions of the interplanetary magnetic field. Figure 4 shows that the energization rate of the ring current, which is the main energy storage reservior during a magnetic storm, is proportional to the east-west interplanetary electric field, i.e., the product of the solar wind velocity and the north-south component of the interplanetary electric field, whenever the magnetic field has a southward component, and is zero otherwise.

The site of reconnection is also under study. It has been proposed that reconnection occurs most rapidly where the magnetosheath magnetic field is exactly antiparallel to the magnetospheric magnetic field (Crooker, 1979). To calculate where these sites are located one must calculate how the magnetosheath magnetic field is distorted by the magnetosheath flow field as well as take into account the distortions in the magnetosheath field. This has been done (Luhmann et al., 1983) and the predicted sites of reconnection are found to be quite sensitive to the direction of the interplanetary magnetic field. Attractive as the Crooker conjecture appears, it does not appear that the magnetopause behaves as predicted. Sonnerup et al. (1981) find that a near equatorial merging site could explain all their data, whereas the Crooker reconnection sites only occur near the equator for a small range of orientations of the interplanetary field. More recently Daly et al. (1983) have demonstrated that patchy reconnection in the ISEE data appears always to start in the equatorial region.

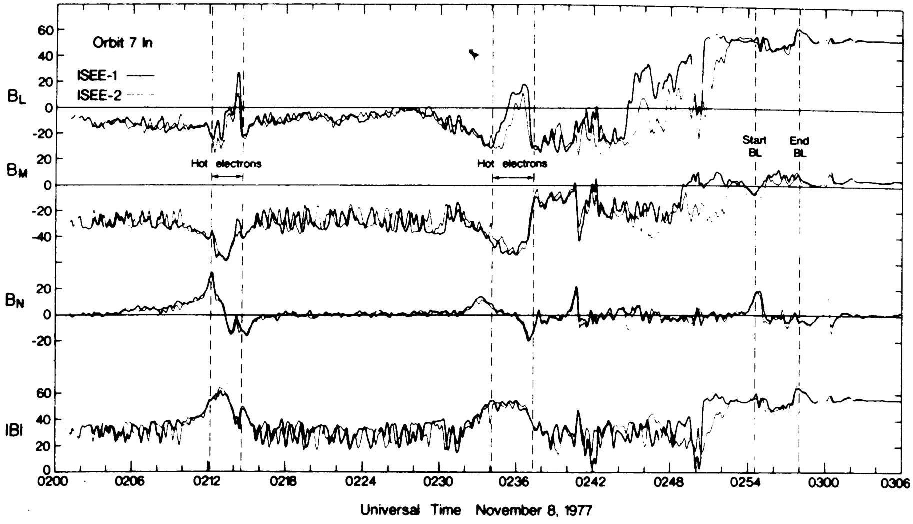


Figure 5. ISEE-1 and -2 magnetometer observations of flux transfer events in the magnetosheath near the magnetopause.

3. PATCHY RECONNECTION

The ISEE-1 and -2 spacecraft were launched into the same orbit with the capability of varying their separation to allow the measurement of boundary velocities and hence allow their thicknesses to be determined. Figure 5 shows magnetic field measurements from the two ISEE spacecraft surrounding a magnetopause traversal that occurred at about 0250 UT (Russell and Elphic, 1978; 1979). The magnetic field is displayed in boundary normal coordinates. The BN component is along the expected boundary normal and the BM component is in the plane of the boundary roughly along the direction of the magnetospheric field. This figure illustrates the irregularity of the magnetosheath field even under moderately quiet conditions as we have here. The magnetic field profile across the magnetopause looks quite different at the two spacecraft. These differences are in part due simply to the variability of the magnetopause velocity. Not only is this velocity large but it is quite variable and irregular.

Two very strange features appear in the data at 0214 and 0236 UT. The field first points outward from the magnetopause and then points inward. At the same time the BM component strengthens in the downward direction and the BL component varies in a manner suggestive of a partial magnetopause traversal. The plasma data at this time indicates the spacecraft did not leave the magnetosheath. However, the energetic electron and ion data resemble magnetospheric data.

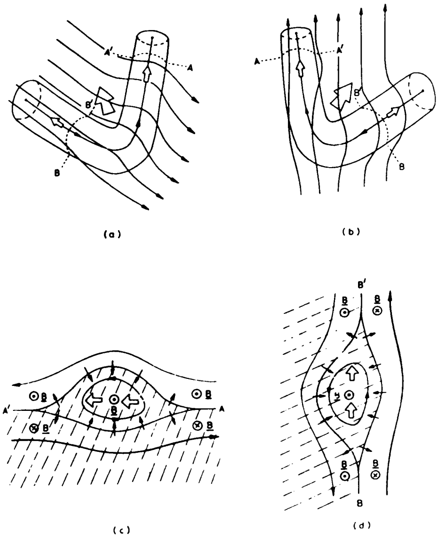


Figure 6. Schematic of a flux transfer event.

Our explanation of this phenomenon is shown in Figure 6 (Cowley, 1982). A flux tube of magnetosheath field has become connected to the magnetospheric field and energetic particles are leaking out. Panel (a) shows the tube as seen from the magnetosheath. Magnetosheath field lines drape up and over it. Panel (b) shows the tube as seen from the magnetosphere. The magnetospheric field lines are also distorted by the presence of the tube. As the tube moves across the magnetopause, both carried along by the flow and because of the straightening up of the flux tube, a characteristic +/- signature is created in the normal component of the magnetic field. In panels (c) and (d) are shown cross sections of the flux tube. This interpretation is supported by various studies of the particle signatures (Scholer et al., 1982; Daly and Kepler, 1982, 1983a,b; Daly et al., 1981, 1983).

Such structures occur in pairs, one connected to the southern hemisphere and one to the north. If they are formed close to the north-south dividing line of the flow field, they will be pulled to the south and north, respectively. However, it is possible that southern connected events get pulled northward and vice-versa. Energetic particle data allow this to be sorted out (Daly et al., 1983). ISEE measurements were initially in the northern hemisphere so that only northward moving FTE's were seen at the start of the mission. However, later southward moving FTE's were detected (Rijnbeek et al., 1982).

The motion of FTE's and the observed particle anisotropy points to the near equatorial region as the site of the initiation of reconnection (Daly et al., 1983). Steady-state reconnection is thought to occur there too (Sonnerup et al., 1981). In fact, it is not clear whether

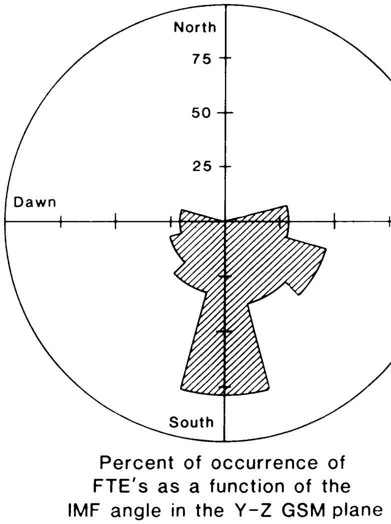


Figure 7. Flux transfer event occurrence rate as a function of the direction of the interplanetary magnetic field in Y-Z plane.

the patchy reconnection characteristic of FTE's is independent of steady-state reconnection. On several occasions both phenomena are observed on the same pass (Rijnbeek et al., 1983). It is possible that flux transfer events are formed at the edges of the "steady-state" reconnection site.

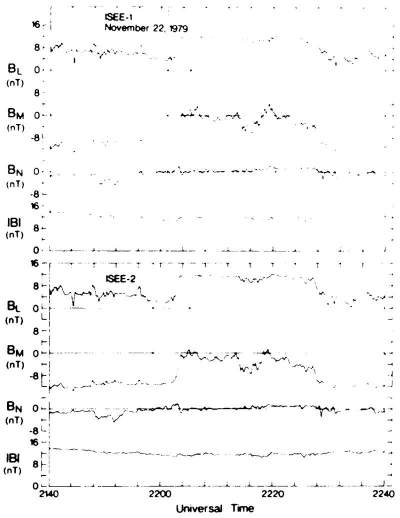


Figure 8. ISEE-1 and -2 magnetometer observations of quiet magnetopause.

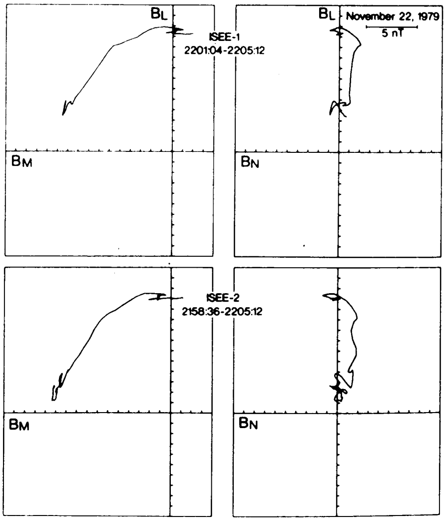


Figure 9. Hodograms of quiet magnetopause crossing.

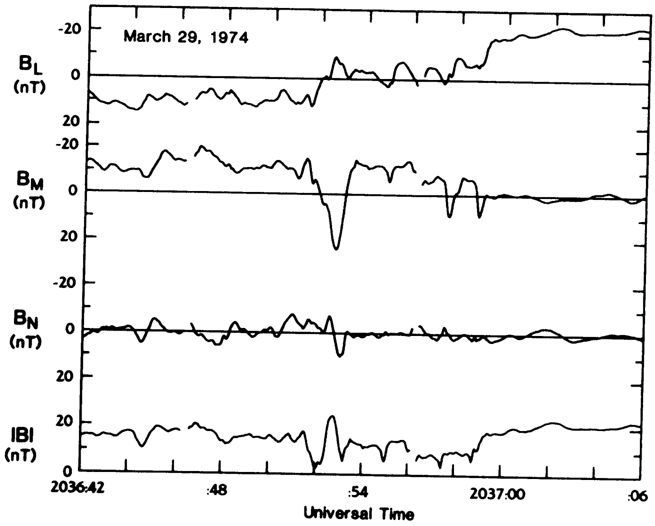


Figure 10. Flux transfer event at Mercury.

The occurrence of flux transfer events is controlled intimately by the direction of the interplanetary magnetic field (IMF). When the IMF is northward in solar magnetospheric coordinates, flux transfer events do not occur. When the IMF is southward, FTE's occur from 50 to 100% of the time depending on the strictness of the definition used. This is shown in Figure 7.

It should be emphasized that the "classical" flux transfer event is the end member of a continuum of structure. Figure 8 shows the magnetic field observed by ISEE-1 and -2 through the magnetopause during a very quiet period when the solar wind was sub-Alfvenic (Gosling et al., 1982). The important point to note is that there is still structure in the normal component. Another representation of the same data is shown in Figure 9. Here hodograms are plotted of the tip of the magnetic field vector in the plane of the boundary on the left and in the orthogonal plane on the right. There is still much structure in the normal component BN. This structure is probably evidence for tearing of the boundary.

We note that patchy reconnection is not restricted to the terrestrial magnetosphere. Figure 10 shows a flux transfer event occurring at the magnetopause of Mercury and Figure 11 shows a flux transfer event at the Jovian magnetopause (Walker and Russell, 1983).

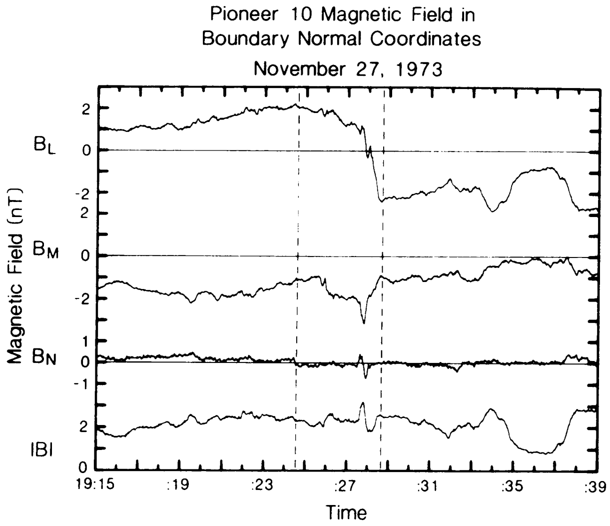


Figure 11. Flux transfer event at Jupiter.

The +/- signature in the normal component as seen in these Figures as well as Figure 5 is only partially due to motion and the draping of field lines. The signature in BN internal to the flux rope suggests this (Paschmann et al., 1982; Cowley, 1982) as does the BM component, especially the BM component seen simultaneously on two opposite sides of an FTE (Saunders and Russell, 1983). This twist probably arises from velocity shear as the flux rope is rolled across the magnetopause while one of its ends is "frozen" into the ionosphere and cannot rotate. The fact that the flux tube is twisted is very important for it helps maintain its shape and hence the distortion of the surrounding field. Thus, patchy reconnection is controlled by two shears, that of the magnetic field and that of the velocity field. This is a very complex situation. Fortunately, there is a simpler situation in which flux ropes are formed in velocity shears and we can study these ropes to learn more about the formation and evolution of magnetic flux ropes without having to worry about the simultaneous effects of reconnection.

4. VENUS FLUX ROPES

The Pioneer Venus Orbiter was placed into orbit about Venus on December 4, 1978 and periapsis gradually lowered so that the spacecraft could study Venus' upper atmosphere and ionosphere. The first deep penetration of the ionosphere was a complete surprise to the magnetometer investigators. These measurements in spacecraft coordinates are shown in Figure 12. The high field regions on the extreme right and left are the magnetosheath. The region of low fields in the middle is the ionosphere and the dashed line marks periapsis. The surprise was the turbulent-appearing impulsive high fields seen within the ionosphere. While

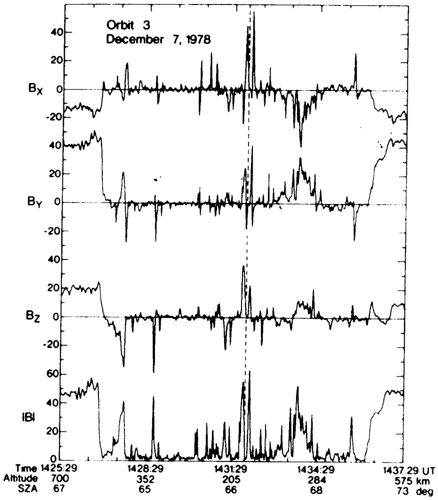


Figure 12. Flux ropes in Venus ionosphere.

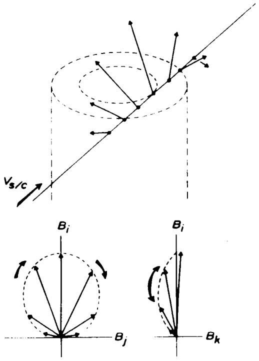
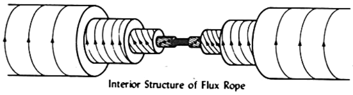
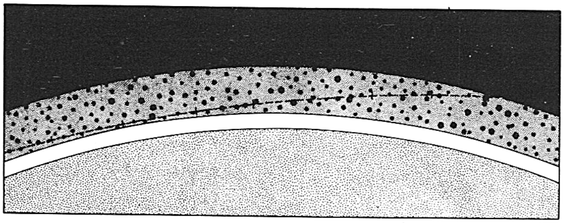


Figure 13. Schematic flux rope traversal.

at first glance these fields seem to be chaotic, there is much order to them at least internally. Figure 13 shows a schematic of the results of minimum variance analysis (bottom panel) and the spatial variation along the trajectory through one of these features (top panel). The hodogram shows that the field variation is intrinsically three-dimensiona rather than two-dimensional. A simple three-dimensional structure which can explain the variation is a flux rope in which concentric shells have varying field strength and pitch relative to the rope axis (Russell and Elphic, 1979). Figure 14 (top) shows the structure we deduce for a Venus flux rope. In the center the field lines are straight. As the distance from the center increases, the field weakens and the field twists to a larger and larger pitch angle with respect to the rope axis. The bottom panel presents a picture of the distribution of flux ropes within the ionosphere.



Interior Structure of Flux Rope



Distribution of Flux Ropes

Figure 14. Flux rope schematic and distribution.

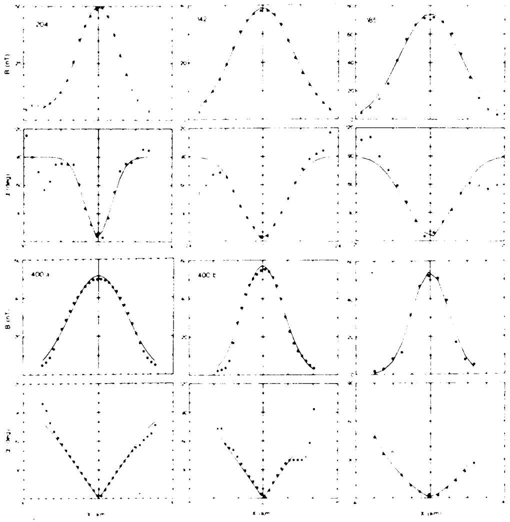


Figure 15. Observed field strength and pitch angle in Venus flux ropes.

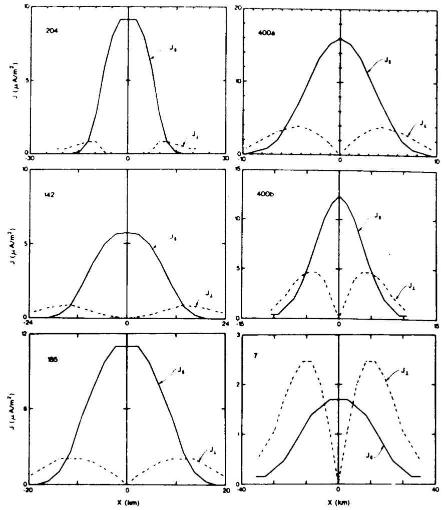


Figure 16. Modeled flux rope currents.

We can model the observed flux ropes in an attempt to deduce their physical properties. Figure 15 shows analytic fits to six flux ropes (Elphic and Russell, 1983). It is possible to model these structures quite well with only a few parameters. Although the field variations in these six ropes look qualitatively very similar, the currents we deduce from our model fit shows quite a variation. Figure 16 presents the parallel and perpendicular currents in each rope. On orbit 204, (top left panel), the rope consists almost entirely of currents flowing parallel to the magnetic field. Whereas on orbit 7 the current is predominantly perpendicular to the field with parallel current only in the center of the rope. In other words, the flux rope on orbit 204 is highly twisted and on orbit 7 is weakly twisted. The rope on orbit 204 is essentially what is called a force-free structure. The magnetic tension in the twist balances the magnetic pressure gradient. The rope on orbit 7 is far from self-balancing and must be contained in part by plasma pressure gradients. Such inferences from the magnetic structure are, in fact, confirmed by comparing with the plasma data on board. Weakly twisted ropes have associated plasma pressure changes; highly twisted ropes do not (Elphic et al., 1980).

It seems quite reasonable to assume that Venus flux ropes arise in much the same way as flux transfer events except that reconnection is not involved here. That mechanism is through velocity shear, perhaps coupled to the Kelvin-Helmholtz instability. The region of velocity shear is principally at the ionopause where there is a steep gradient in magnetic field and large ionospheric flows ∿5 km/sec (Knudsen et al., 1980) which decrease with decreasing altitude. Another possible source is the upper edge of the low altitude magnetic belt that often appears during periods of high solar wind dynamic pressure (Luhmann et al., 1980).

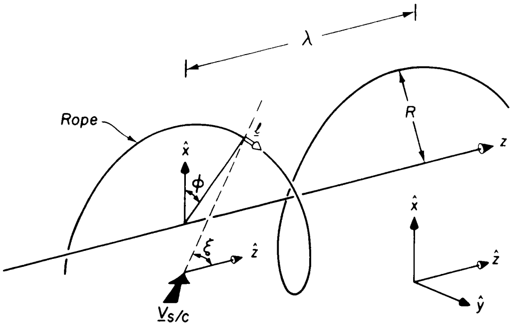


Figure 17. Kink unstable flux rope.

Flux ropes are most greatly twisted at low altitudes on the dayside of Venus. However, their axes seem to become randomized here. This puzzled us at first until we realized that the ropes were becoming so tightly twisted that they were becoming kink unstable (Elphic and Russell, 1983b). Figure 17 shows the resulting corkscrew pattern of the flux rope axis. The fact that Venus flux ropes become kink unstable when they are sufficiently twisted is interesting enough but there are important implications to the fact that the flux rope axis is now three-dimensional. The flux rope can now interact with other flux ropes and get intertwined with them due to the motions of the surrounding plasma. It appears possible to start building more complicated structures such as that shown in Figure 18 in which a compound flux rope is braided out

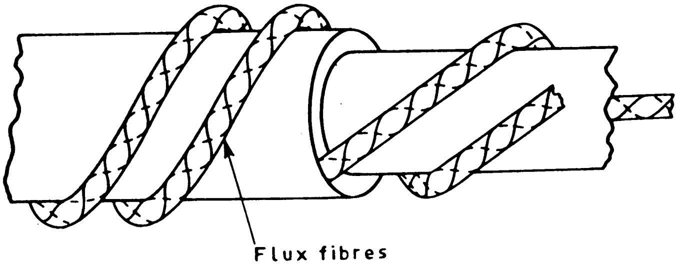


Figure 18. Compound flux ropes.

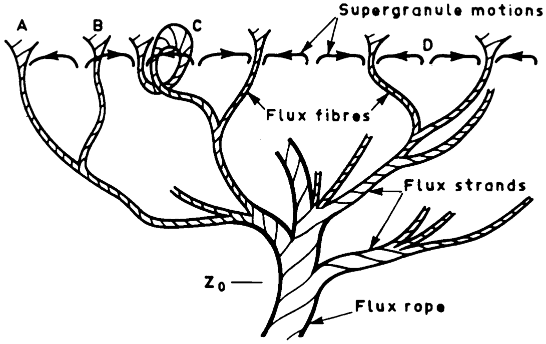


Figure 19. Solar flux rope.

of simpler flux fibers (which correspond to our original flux ropes). We would be hard pressed to see this in the Venus ionosphere where we have to seek out the simplest structures in order to make any sense out of the data. We do not anticipate ever having the luxury of a multiple spacecraft, ISEE-like, mission to Venus. However, there is another region in the solar system in which compound flux ropes have been proposed to exist, that is the sun. Figure 19 shows a compound flux rope, coming up out of the convection zone and splaying out in the photosphere (Piddington, 1981).

5. SOLAR FLUX ROPES

The physics of the photosphere demands the existence of some magnetic structure such as the flux rope depicted here but our ignorance of the convection zone makes it difficult to deduce what goes on there. Thus, one can only conjecture. However, if one were to conjecture based on our Venus experience, we would postulate that deep in the convection zone there is a source of steady magnetic field, probably driven by a solar dynamo. Velocity shear above this magnetized zone wraps up the field into ropes and continued twisting leads to corkscrew flux ropes through the kink instability. Turbulent motions lead to compound intertwined rope structures perhaps through several cycles of kink instability and turbulent intertwining. Finally, perhaps through another kink instability cycle a compound flux rope emerges through the solar surface. At this point the ropes can start to interact through reconnection producing solar flares, etc.

6. SUMMARY AND CONCLUSIONS

Magnetic shear is certainly important for the reconnection process, but velocity shear is also a crucial element in shaping the magnetic structures that we observe in astrophysical plasmas. The simple geometries that we would like to study rarely ever occur. At the terrestrial magnetopause two-dimensional merging occurs either rarely or over a limited region of space. Over most of the magnetopause we find twisted tubes of connected flux. At Venus we also find twisted tubes of flux. Here reconnection seems not to be a critical process in the evolution of these flux ropes. Studying their behavior leads us to the conclusion that they become kink unstable when they become too twisted. The resulting kink instability twists the axis of the flux rope into a corkscrew and enables it to become intertwined with its neighbors. The two key elements in this process are a steep gradient in magnetic field between a magnetized and unmagnetized plasma and velocity shear near the boundary. While we are ignorant of the magnetic properties of the solar convection zone, we conjecture that such a field gradient and velocity shear can be found deep in the convection zone. If so, then they would lead naturally to the formation of compound flux ropes through repeatedly going kink unstable and mixing with other ropes. In conclusion, in studying astrophysical current instabilities, it is often just as important to understand the velocity field as it is to understand the magnetic field.

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DISCUSSION

Priest: A lot of work has been done on the kink instability of flux tubes in the solar context, especially by Van Hoven, Chiuderi, Einaudi, Hood and Priest. Such tubes go unstable very easily, so what is keeping them stable for most of their time? Is it shear or the anchoring of the tubes in denser layers of the ionosphere?

Russell: It is difficult for us to determine why the Venus flux ropes remain stable as long as they do. They are anchored in the magnetosheath and they are immersed in a shear layer. We believe the important points in our observations are that the ropes are formed and transported some distance before they become unstable. In the subsolar region at high altitudes, presumably close to where the ropes are forming, the rope axes appear to be mainly horizontal; whereas at low altitudes the rope axes assume a variety of orientations.

Sturrock: What are the observed dimensions of the FTE flux tubes? More important, we would like to know what determines the dimensions in order to infer what their dimension would be in the sun's atmosphere, if they occur there.

Russell: Flux ropes vary in diameter from about 10 km at 500 km in the subsolar Venus ionosphere to about 6 km below 200 km altitude. They are nearly twice that width near the terminator (Elphic and Russell, J. Geophys. Res. 88, 1993-3003, 1983). These diameters are from 2 to 4 times either the ion gyroradius using the axial field strength in the rope or the ion inertial length. Since the beta of the plasma in the rope is close to unity, we would expect these scale lengths to be similar.

We do not know whether it is coincidental that the ropes have this scale size, or not. My intuition would tell me that the scale size of the velocity shear would play a role.

D. Smith: Although reconnection may not play the dominant role in the sense that flux ropes evolve to the point of becoming kinks unstable, doesn't it play an important role in their evolution? What is the difference between the cases you showed for the terrestrial magnetosphere and the ionosphere of Venus; i.e. why is there no reconnection in the latter?

Russell: Flux ropes and what we have termed flux transfer events both occur in the presence of velocity shear and both evolve into highly twisted structures. The Venus flux ropes occur at the interface between a magnetized and unmagnetized palsma. The terrestrial flux transfer events occur at the interface between two magnetized plasmas. Spatially and temporally limited reconnection forms a flux tube which then rolls along the interface. The absence of an intrinsic planetary magnetic field at Venus keeps the ionosphere field-free and limits reconnection there. Flux ropes could reconnect with themselves when they went kink unstable. This would produce a straighter rope plus a field torus. I do not believe we would recongize such a structure with a single spacecraft if we saw it.

Goldstein: If your spacecraft passes a small current loop, you would see a triple event instead of the double you call an FTE. Have you seen any triples?

Russell: In the well-developed, well-isolated events we have studied closely we have not seen any triples. However, if one examines finer and finer detail in the observations in situations where many events are occurring, one could find the occurrence of triples. I would hesitate to attribute such structure to a current loop without corroborating data from several spaced satellites.

Tsinganos: I wonder if you had some idea as to how these complicated "flux tree" ropes are kept in a steady equilibrium; because from the theoretical point of view, there are indications that these asymmetric and complex structures are unlikely to be found in equilibrium.

Russell: It is not obvious to me that solar magnetic structures are in equilibrium. They are constantly evolving. The way such structures might exist is that they are formed stably in one region and are transported to another in which we observe them out of equilibrium.

Krishan: How do you separate the spatial and temporal fluctuations in the magnetic field?

Russell: At the earth we are probing these structures with dual satellites separated by a controllable separation of from 100 to 1000 km. To the extent that the structure is moderately simple and moving past our two spacecraft rapidly, we can separate temporal from spatial changes. At Venus our one spacecraft is passing through the ionosphere at a super-Alfvenic velocity so that the structure does not have time to change during the measurement interval.

Vlahos: In one of your figures the interacting fields were homogeneous. What localized the ropes?

Russell: The figure to which I believe you refer concerned the formation of Flux Transfer Events at the earth's magnetopause. These events appear to result from temporally and spatially localized reconnection. I presume that whatever modulates the reconnection rate controls the size of an event. Perhaps fluctuations in the direction of the interplanetary magnetic field do this. Perhaps the scale size of natural variations in the boundary structure such as caused by the Kelvin-Helmholtz instability are responsible.