COMPUTER SIMULATION OF RECONNECTION IN PLANETARY MAGNETOSPHERES

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Abstract. The earth's magnetosphere provides an ideal opportunity to model reconnection in well known geometries that are close enough to the idealized analytic models to make a comparison of the computer models with analytic theory meaningful. In addition more detailed, even three-dimensional, models can be used for a comparison with extended data from in situ observations. The computer studies have basically confirmed the reconnection picture that was based on two-dimensional steady state models and linear analytic theory. The three-dimensional models in particular have also added a lot more information on the reconnection process and the structure of flow, magnetic fields, and currents including many features that are consistent with observations and empirical models of geomagnetic substorms.

1. INTRODUCTION

Modeling reconnection in the Earth's magnetosphere has several advantages that cannot be met anywhere else. On the one hand, the underlying equilibrium structures are well known from observation and can be described, in some cases even to a high degree of sophistication, by self-consistent analytic models. They are close enough to simplified structures, such as, for instance, a plane current sheet, that form the base of most analytic work on reconnection, to make a comparison with such analytic work meaningful. The equilibrium or quasi-equilibrium structures, however, also contain small deviations from the simple geometries, which might be important in influencing the reconnection process. An example is the small magnetic field component perpendicular to the current sheet or plasma sheet in the geomagnetic tail. There is no doubt that there can be a stabilizing effect of such a normal component, and as we will see later it also influences the dynamic evolution by the asymmetry that is associated with its presence.

On the other hand, there is the great advantage that the results from reconnection models can be compared with in situ satellite

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measurements, which are provided even in much more detail than any present theory can cope with.

Although reconnection processes have been suggested to occur also in other than the earth's magnetosphere (e.g., Nishida, 1983), all computer studies of magnetospheric reconnection have been devoted to processes in the earth's magnetosphere, mainly because of the above mentioned detailed knowledge about those processes from observations but also because the earth might serve as a representative example for any magnetospheric reconnection. Also, most of the present reconnection models are highly idealized and therefore general enough to have applications not only in magnetospheres but possibly also in stellar atmospheres and other, even extragalactic, objects.

Reconnection in the earth's magnetosphere is a consequence of the interaction with the solar wind plasma as demonstrated by Fig. 1. At the frontside reconnection leads to a transfer of magnetic flux from the solar wind and the region of closed magnetospheric field lines into the region of open field lines that have only one foot connected to the earth. The occurrence of front side reconnection is strongly favored by a southward component of the interplanetary magnetic field. Without additional reconnection in the tail the magnetic flux on open field lines must increase in time and become stored in the lobes of the geomagnetic tail. On the average (but not necessarily at each instant of time) this flux transfer must be compensated by a transfer of flux from the nightside lobes back into the solar wind and into the closed field line region. The widely accepted view is that this occurs by a nonsteady process in the near tail at about 15 R_E, in so called magnetospheric substorms, but possibly also by a more steady reconnection process in the far tail beyond the moon's distance. Before lobe field lines can reconnect (Fig. 1c) in the near tail, the closed plasma sheet field lines in between them must reconnect first. This leads to somewhat shorter more dipolar-like field lines earthward from the reconnection region and to detached closed loops forming a so-called plasmoid tailward from it (e.g., Hones, 1979). This plasmoid moves tailward and leaves a very narrow plasma sheet behind (Fig. 1b). This process seems to occur quasi-periodically with a reformation of the original plasma sheet in between.

2. THE MODELS

The optimum model would include the entire magnetosphere using the earth's dipole and the ionosphere on one side and the unperturbed solar wind on the other side as boundary conditions. There are indeed such models which will be discussed in Section 3, in two and even three space dimensions. The drawback of most of these models is that resistivity, which is necessary to allow for reconnection, is provided by numerical effects rather than by a physical interaction. Still they have given relevant results on the global shape of the magnetosphere and reconnection sites.

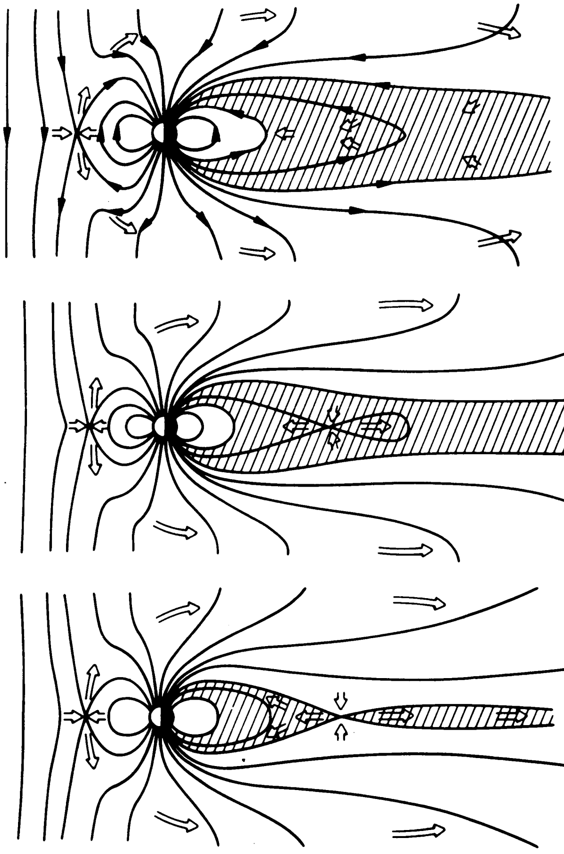

Figure 1. Schematics of reconnection regions of the earth's magnetosphere. The figure shows magnetic field lines in the noon-midnight meridian plane and flow vectors (open arrows). a. Frontside reconnection with transfer of magnetic flux from the solar wind and the front side magnetosphere into the lobes of the night side magnetotail. b. New reconnection in the tail with the formation of a magnetic island ("plasmoid") that subsequently moves tailward. c. Later stage of magnetotail reconnection with transfer of magnetic flux from the lobes into the closed nightside region and the solar wind.

On the other side there are models dealing with more localized regions, such as the magnetotail, or with current sheets in general. These models can give a more detailed knowledge of structural changes, flows, currents, and so on generated by the reconnection process. These models do not include the interaction with the solar wind, or account for it only by some assumed magnetospheric response at the simulation boundary inside the magnetopause. None of the models so far includes the interaction with the ionosphere and a possible feedback from ionospheric currents and electric fields.

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In this paper we will concentrate on the results of the most advanced, primarily three dimensional, nonlinear time dependent computer models of reconnection. We will not deal with the models of laboratory experiments with their mostly toroidal or cylindrical geometry which produce some peculiarities.

The mean free path for binary collisions in the magnetosphere is extremely long, much longer than any other length in the magnetosphere. The plasma can therefore be treated as collision free. The best method of simulation, at least in principle, would include the full ion and electron dynamics. Such models (e.g., Katanuma and Kamimura, 1980) are, however, until now restricted to simulation system sizes of several Debye lengths only, i.e., of the order of several hundreds of meters. This is much smaller than the typical equilibrium scales, which are a few R_E for the plasma sheet half-width and roughly 1000 km for the magnetopause thickness. Hybrid codes that include the full ion dynamics but treat electrons as a fluid (e.g., Terasawa, 1981) can at present deal with scale sizes of a few ion Larmor radii (from several hundreds to a few thousands of km) which is comparable to the thickness of the magnetopause but still somewhat smaller than the plasma sheet thickness, at least before thinning associated with the dynamic phase of substorms has occurred. These codes, however, loose the electrostatic effects from individual electron motion.

The very large scale structures and dynamics finally can be dealt with only by fluid or MHD approaches. The microscopic collisonless process that leads to the deviation from ideal MHD with frozen-in fields is usually represented by some more or less ad hoc scalar resistivity. This model can be justified by the following view of the initiation of reconnection:

A driving force leads to a gradual compression of the current sheet until a stability limit for a microscopic instability is exceeded. The microinstability leads to wave turbulence and through wave particle interaction to an anomalous resistivity which initiates the large scale reconnection process. The mostly discussed candidate for this microturbulence is the lower-hybrid drift instability because of its relatively low threshold (Huba et al., 1978).

An alternative is the possibility that the collisionless instability itself is of large spatial scale. Again a driving force is needed to compress the current sheet and in particular reduce a normal magnetic field component until ions become non-adiabatic in the center and are no longer tied to the field lines (Schindler, 1974; Galeev and Zelenyi, 1977; Goldstein and Schindler, 1982).

In either case, deviations from ideal MHD are important only in very localized regions inside the current sheets. It is therefore plausible that the large scale spatial pattern of magnetic field and flow velocity is governed by ideal MHD regardless of what localized process enables the growth of the reconnection mode. This is also a possible justification of discussing reconnection within ideal MHD models, where resistivity is purely numerical. The situation might be comparable to the theory of shocks where useful jump conditions can be derived without knowledge of the details and the dissipation mechanism within the shock.

In this paper we will focus on the large scale structures and dynamics of the reconnection process and therefore discuss mainly the results from the MHD models.

3. GLOBAL MODELS

The first attempt to model a two-dimensional magnetosphere in a global way including a (line) dipole field for the earth and the streaming solar wind was made by Leboeuf et al. (1978). As a consequence of a discontinuity in their solar wind boundary condition representing a southward rotation of the magnetic field they reported enhanced reconnection at the front side and in the tail and the formation and subsequent tailward motion of a region of closed magnetic loops corresponding to the plasmoid in phenomenological substorm models (e.g., Hones, 1979). The resistivity in the so-called MHD particle code by Leboeuf et al., however, was purely numerical corresponding to a very low magnetic Reynolds number $R_m \approx 3 - 10$ and a very short diffusion time $\tau_D = R_m \tau_A$ where τ_A is the typical MHD time scale of e.g. Alfvén waves. As a consequence the resulting magnetosphere, which was of the type suggested by Dungey (1961), had a very short tail. It differed only slightly from the simple superposition of a line dipole and a homogeneous interplanetary field which is expected to result for infinitely fast magnetic diffusion. The model also suffered somewhat

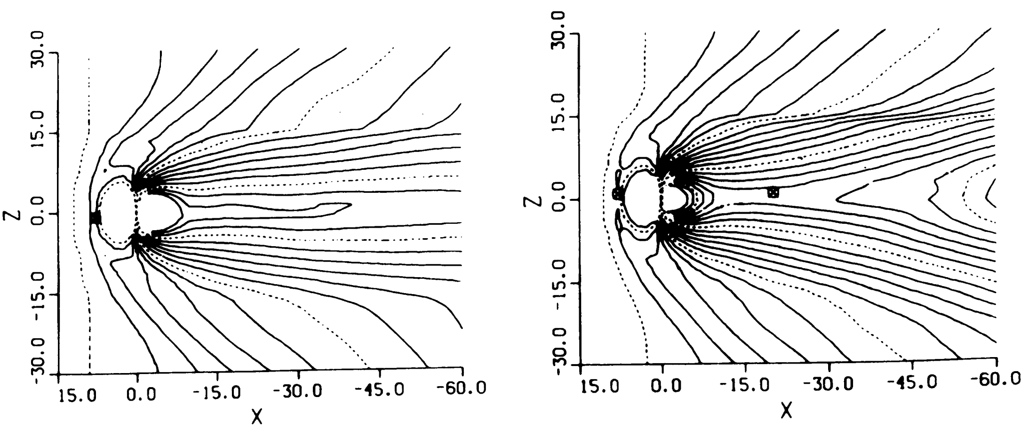

Figure 2. Magnetic field lines in the noon-midnight meridian plane in the global simulation by Lyon et al. (1981). a. After a southward magnetic field has been incident for one hour. b. 20 minutes later at peak of tail reconnection.

from the fact that periodicity in the z direction (north-south) was assumed which meant that instead of the solar wind interaction with a single magnetospheres actually the interaction with a lattice of magnetospheres was treated.

Subsequent 2D global simulations (Lyon et al., 1980, 1981; Brackbill, 1982) tried to reduce the numerical resistivity. Figure 2 shows results from a simulation by Lyon et al. (1981). Following a southward turning of the magnetic field in the incident solar wind, steady reconnection at the frontside was found leading to tailward convection of magnetic flux stretching the tail and increasing its field strength. About an hour later reconnection in the tail started as a spontaneous process. The resistivity in this model allowing for reconnection was still purely numerical.

More recently, Brackbill (1982) presented a 2-D global simulation using the current density dependent resistivity model of Sato and Hayashi (1979). Because of the inherent numerical resistivity the maximum representable Reynolds number R_m was about 50. Figure 3 shows a sequence of evolution in the presence of southward interplanetary magnetic field showing front side reconnection and subsequently tail deformation and tail reconnection.

Leboeuf et al. (1981) were the first to make their global model three-dimensional. With a southward solar wind magnetic field they found again a Dungey type magnetosphere with X-type neutral lines at the front and in the tail. But because their numerical resistivity was still as high as in the 2-D model it is not surprising that their

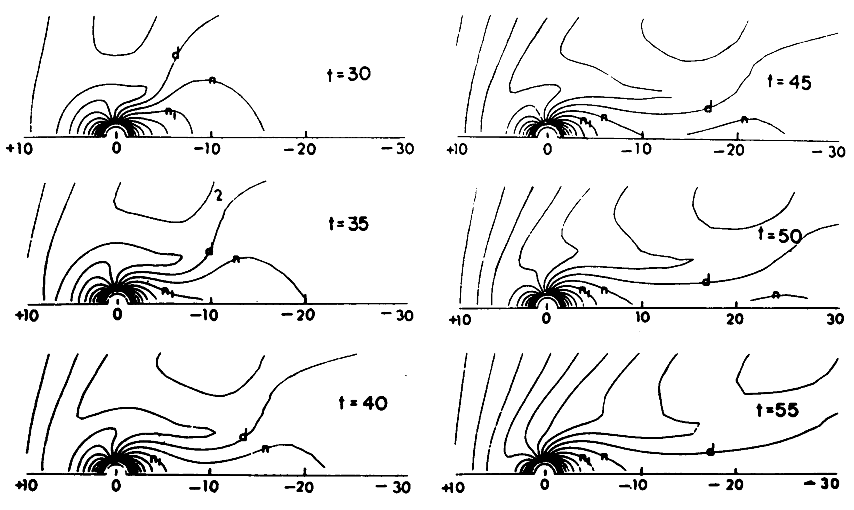

Figure 3. Magnetic field lines in the noon-midnight meridian plane in a global simulation by Brackbill (1982) for time instants indicated in the figures. Time units are R_E/V_s where V_s is the solar wind speed.

resulting configuration was close to the superposition of dipole field and uniform interplanetary field.

Shortly after other global 3-D models followed with reduced numerical diffusion. Brecht et al. (1981) reported results similar to their 2-D simulations with reconnection still based on numerical resistivity. The basic reconnection picture was found again. However, the magnetic field configuration in the tail plasma sheet was found to be more complicated with multiple neutral lines moving tailward while others formed newly closer to the earth. This result is similar to a result by Birn and Hones (1981) using a model of the tail only, which will be discussed in more detail in the following section.

4. MODELS OF LOCAL RECONNECTION

Global models of the magnetosphere including the discontinuities of the bow shock and the magnetopause almost unavoidably contain a large amount of numerical diffusion which makes the study of the dynamic reconnection process and its dependence on physical interaction mechanisms difficult (fortunately, many large scale characteristics seem not to depend much on the details of the interaction mechanism). More local models which deal with only one of the possible reconnection sites usually have less problems with numerical diffusion. They gain more insight into the details of the structures around the reconnection region, however, loose the interaction with the solar wind except for the possibility of prescribing boundary conditions which might reflect this interaction. They usually start from equilibrium configurations which are mostly simple one-dimensional sheets and can be described analytically. The resistivity models, however, vary.

In a 2-D simulation, Ugai and Tsuda (1977) initiated reconnection in a plane current sheet by locally enhancing the resistivity. The maximum resistivity corresponded to $R_m = 10$ with a background value of $R_m = 1000$. They found a pattern of fast flow and a quasi-steady state (Tsuda and Ugai, 1977) similar to analytic steady state models (Petschek, 1964) using open boundary conditions that allowed for free outflow and inflow.

Sato and Hayashi (1979) tried to model the generation of anomalous resistivity by a current dependent resistivity of the form

$$\eta = \begin{cases} \alpha(j-j_c)^2 & \text{for } j > j_c \\ 0 & \text{otherwise} \end{cases}$$

They started also from a one-dimensional plane current sheet using a 2-D code. Because the current density had to exceed the threshold j_c before resisitivity was generated and reconnection could be initiated, a

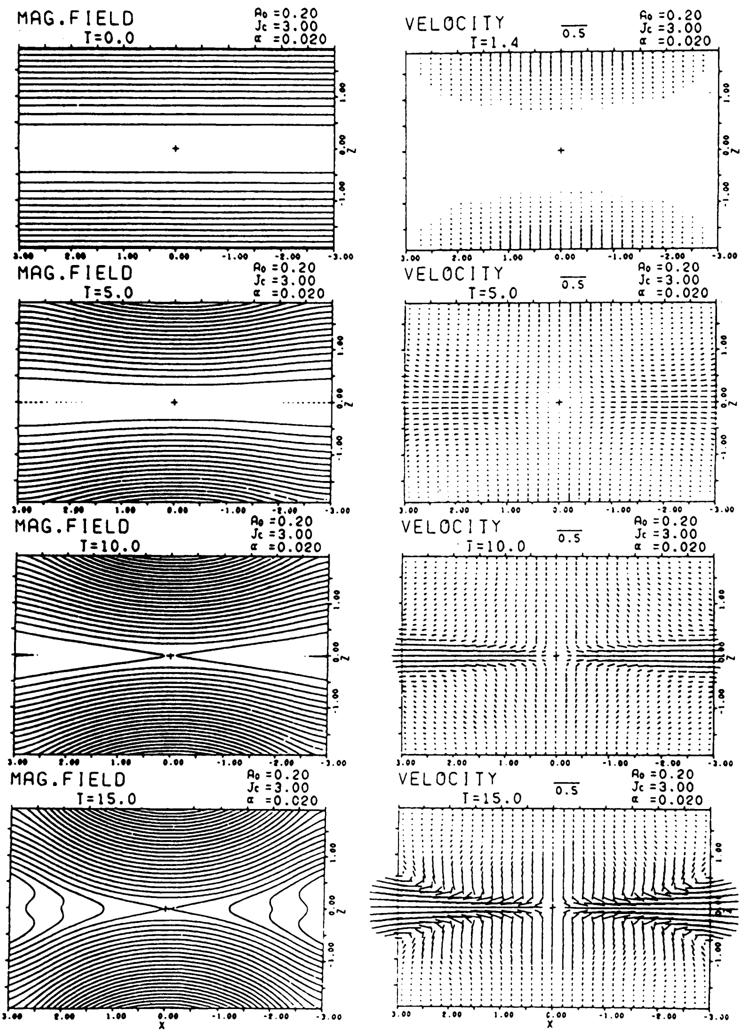

Figure 4. Computer plots of reconnecting magnetic field lines (left) and plasma flow vectors (right) in a two-dimensional model by Sato and Hayashi (1979). All variables are normalized by combinations of the initial maximum magnetic field, density, and plasma sheet half width.

driving force was necessary to gradually compress the current sheet and increase the current density. Sato and Hayashi assumed a nonuniform inflow with a maximum speed of initially typically 20% of the Alfvén speed at the boundaries parallel to the current sheet. The perpendicular boundaries were treated as "free" or "open." Sato and Hayashi found again the typical flow pattern around an X-type neutral point (see Fig. 4) including narrow current layers that were identified as the slow shocks existing in Petschek's (1964) model. They also found that the electric field at the X-point saturated at a level that

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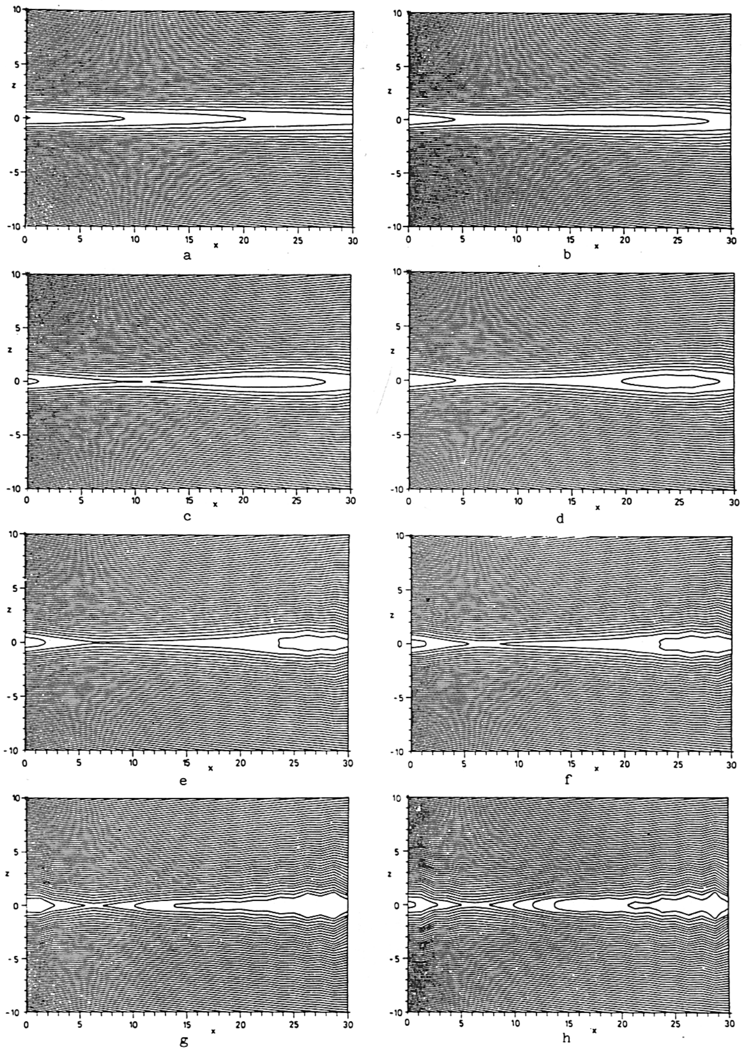

Figure 5. Magnetic field lines in a two-dimensional simulation of tail reconnection by Birn (1980) for selected times: (a) t = 0, (b) t = 110, (c) t = 135, (d) t = 150, (e) t = 165, (f) t = 170, (g) t = 180, and (h) t = 185; all times normalized by L/V_A where L is the characteristic plasma sheet half width and V_A the Alfvén speed.

depended on the inflow velocity, i.e., on the external electric field. This is why they called their reconnection process externally driven.

Different results concerning the role of an external driving mechanism were reported by Birn (1980) and Ugai (1982) using two-dimensional resistive models and by Terasawa (1981) using a two-dimensional hybrid particle simulation code which treated electrons as a fluid. Terasawa started from a Harris plane sheet equilibrum (Harris, 1962) using periodic boundary conditions in the direction along the sheet. He found a phase of nonlinear more rapid growth of the tearing mode before saturation, which was similar to the explosive mode proposed by Galeev et al. (1978). Ugai's model was a continuation of the earlier 2-D calculations by Ugai and Tsuda using a more sophisticated model of localized resistivity which included a threshold for rise and decrease of anomalous resistivity. As the initial drift velocity exceeded the onset threshold slow reconnection started immediately. After some time interval characterized by a decay of the initial resistivity a fast "explosive" increase of reconnection occurred even when the open boundary parallel to the current sheet was replaced by a rigid wall.

Birn (1980) started from a more realistic initial tail configuration including a finite normal magnetic field component and flaring of the lobe field lines (Fig. 5a). After applying constant resisitivity with $R_m = 500$ he found the growth of a tearing instability leading to thinning of the plasma sheet and to the formation of neutral points and a plasmoid moving tailward (Figures 5a-h). A pattern of strong flow was set up around the X-point similar to the Petschek model (Fig. 6). He also found sheets of enhanced current density similar to those found by Sato and Hayashi (1979) related to the slow shocks postulated by Petschek. Similar results were recently obtained by Forbes and Priest (1983) starting from a plane sheet configuration but introducing asymmetry in the x coordinate along the sheet through asymmetric boundary conditions with line-tying at the near earth side and open boundaries elsewhere.

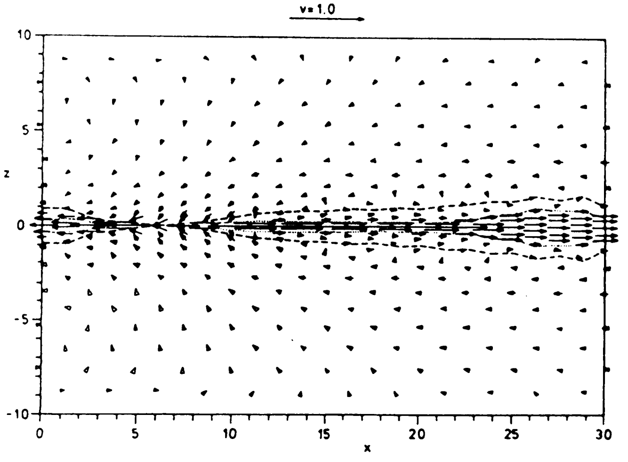

Figure 6. Velocity pattern at t = 180 for the same simulation as in Figure 5. The dashed line represents the magnetic field separatrix through the X-point; the dotted line represents maxima of electric current density for x = const. (from Birn, 1980).

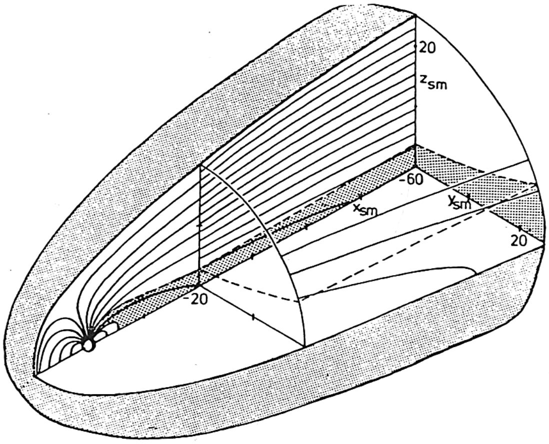

Figure 7. Self-consistent three-dimensional magnetotail equlibrium configuration by Birn (1979) used as initial configuration for the three-dimensional reconnection simulation by Birn and Hones (1981). The figure shows maganetic field lines in the midnight meridian x,z plane and close to the magnetopause boundary. The plasma sheet is indicated by dark shading and the dashed line. The near earth part (not used in the simulation) is not calculated and added only for better illustration (from Birn, 1979).

Subsequently Birn's model was made three-dimensional (Birn and Hones, 1981) starting from a self-consistent three-dimensional tail equilibrium (Birn, 1979; Fig. 7). Again the growth of the tearing mode was initiated by the onset of (constant) resistivity (R_m = 200). Plasma sheet thinning and the formation of a neutral line and the tailward moving plasmoid were observed again with the picture in the midnight meridian plane very similar to the 2-D model (Figs. 5 and 6).

The third dimension, however, enabled new results not present in the 2-D models. This is demonstrated by Figure 8 which shows flow velocity vectors and the neutral lines (dotted lines) in the equatorial x,y plane. Reconnection and strong flows do not occur across the entire tail as they would in a 2-D model but are restricted to a center region where also the thinning takes place. This is a consequence of the 3-D equilibrium with plasma sheet thickening and correspondingly an increase of the normal magnetic field component B_z toward the dawn and dusk flanks of the magnetotail.

The pattern is also more complicated than in 2-D. The region of strong tailward flow does not exactly coincide with the region where B_z has changed sign, which is enclosed by the neutral line. The neutral line itself is more complicated and can become multiple similarly as reported by Brecht et al. (1981).

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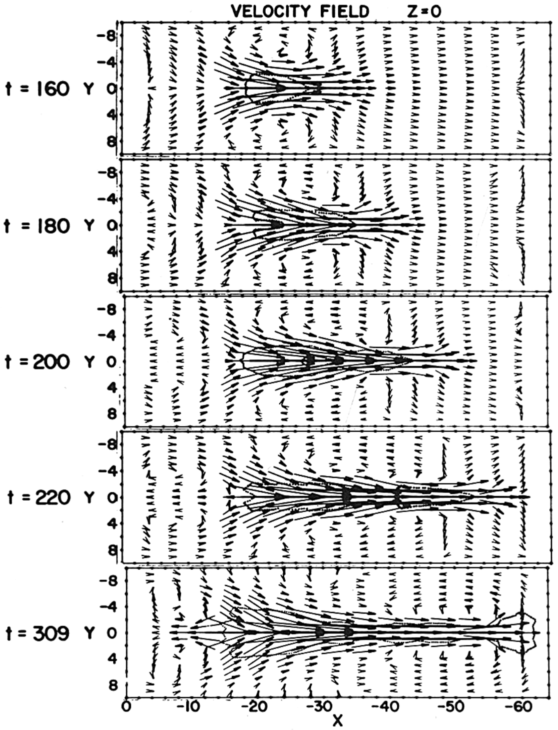

Figure 8. Flow vectors and magnetic neutral lines (dotted lines) in the equatorial x,y plane in a three-dimensional magnetotail reconnection simulation by Birn and Hones (1981). Times as shown on the left are normalized in the same way as for Figure 5. The length of the flow vectors is proportional to the speed with the maximum vectors corresponding to about 0.7 in units of the typical Alfvén velocity.

Of special interest is the current pattern in and around the reconnection region and around the plasmoid. Before we discuss this it is useful to visualize the 3-D structure of field lines in and around the plasmoid as shown in Figure 9. The field lines are represented above the equatorial plane as seen from the tail toward the earth. The centerward draping of the field lines causes a shear of the magnetic field and thereby field aligned currents, in particular close to the separatrix surface, i.e., the field lines originating from the X-line.

The currents are shown in Figure 10 by vectors of current density in the equatorial x,y plane and by projections in a cross-section of the tail. Figure 10a shows a deviation of the current vectors from the original cross-tail direction. The deviation earthward from the main X-line is earthward on the dawnside and tailward on the dusk side. Oppositely directed deviations are found tailward from the X-line. It

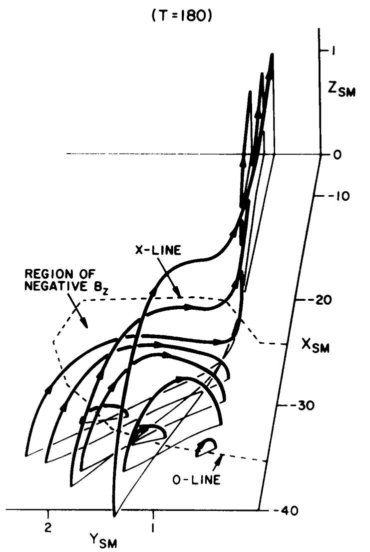

Figure 9. Three-dimensional representation of magnetic field lines computed by the 3-D model of Birn and Hones (1981) for a time about 12 minutes after reconnection begins. Projections of the magnetic field lines into the x,y plane are shown by light lines (from Hones et al., 1982).

looks as if the current tends to flow around the center diffusion region. A similar deviation is found in the cross-sections of constant x at some distance from the X-line. The current tends to flow around the plasmoid. The current density inside the plasmoid is reduced and can even become oppositely directed (Fig. 10b).

Similar results on current deviation are recently reported by Sato et al. (1983) in a model of 3-D driven reconnection. The model was similar to their previous 2-D models already mentioned. The initial configuration was again a plane current sheet. The dependence on the other directions was introduced, and the reconnection was driven by a nonuniform inflow velocity at the boundaries parallel to the sheet with a maximum at some center point. Figure 11 shows the current density vectors in the equatorial x,y plane and some parallel plane above. One can see, even more pronounced than in the model of Birn and Hones, the oppositely directed currents at some distance from the X-line which is in the center of the frame. The currents get partly concentrated right at the X-line and tend to flow around it at higher latitudes.

Although there is some similarity of the two 3-D models discussed above in the changes of current flow, the field aligned currents that are found in both models earthward from the X-line have opposite directions flowing toward the earth on the dawn side and away on the

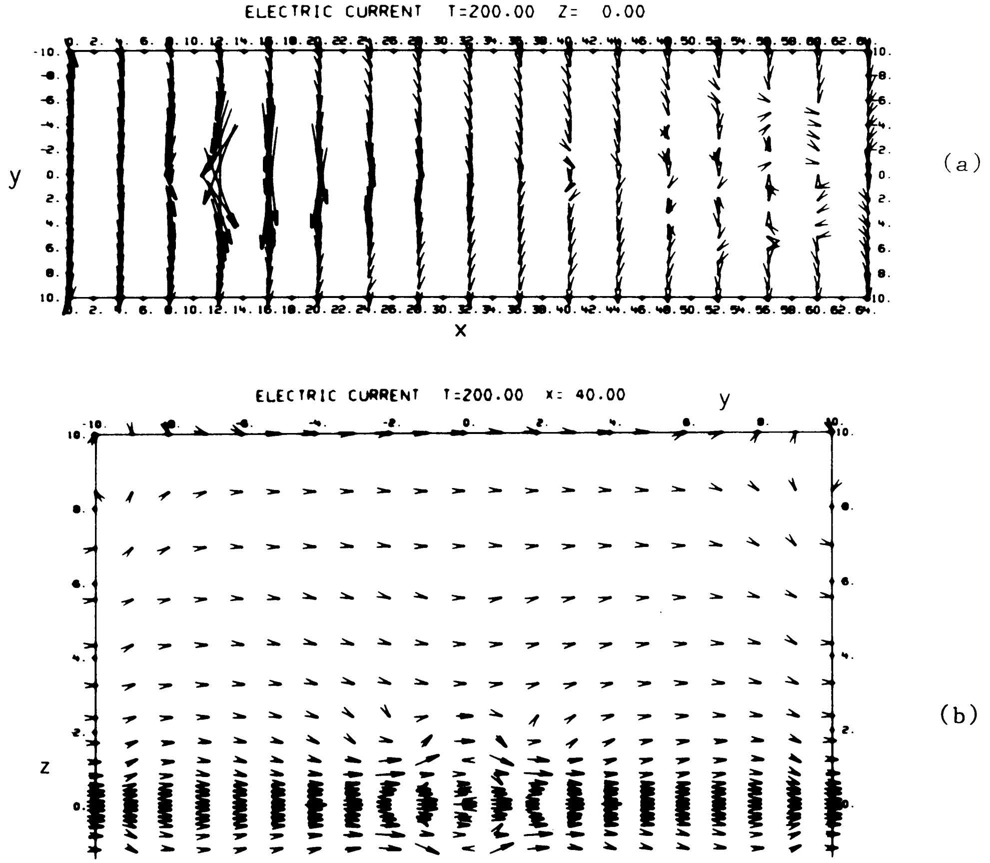

Figure 10. Current density vectors (a) in the equatorial x,y plane and (b) projections in the plane x = 40 for a three-dimensional magnetotail reconnection simulation of Birn and Hones.

dusk side in the model of Sato et al. and the opposite way in the model of Birn and Hones. This need not be contradictory as the two approaches were quite different. Both field aligned current systems are realized in the magnetosphere, and it is indeed conceivable that the outer system which has the signatures of that found by Sato et al. is indeed externally driven while the inner system corresponding to that found by Birn and Hones is caused by the internal dynamics.

5. SUMMARY

We have presented a variety of models of the dynamic evolution of the magnetosphere and sheet like configurations as they are present at the magnetopause and in the magnetotail and probably in many other astronomical objects as well. It seems that the typical reconnection pattern predicted by the 2-D steady state theory (e.g., Petschek, 1964)

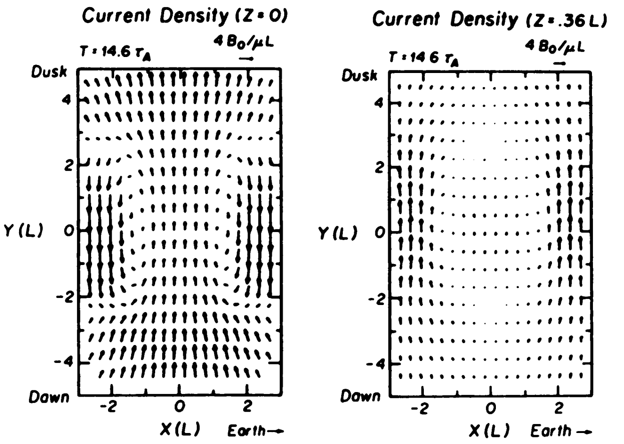

Figure 11. Current density vectors in the equatorial x,y plane (z = 0) and a parallel plane (z = 0.36 L) at t = 14.6 τ_A in a three-dimensional simulation of driven reconnection by Sato et al. (1983).

can be found for a variety of different initial configurations, boundary conditions, and resistivity models, even though most of the models did not reach a steady state. Although the basic view of reconnection formed by Petschek's steady state model and the linear tearing theory (Furth et al., 1963) is thus very well confirmed, the models added also more information about the nonlinear phase of evolution and about the 3-D structure in more realistic geometries especially for the geomagnetic tail. Many of the features that were found are consistent with basic features of phenomenological substorm models, e.g., plasma sheet thinning, neutral line formation, plasma acceleration to speeds of the order of the Alfvén speed, current diversion, and the generation of field-aligned currents. The models have also shown that reconnection may be a localized phenomenon in the sense that it occurs only in a limited region of a current sheet configuration where the normal magnetic field component is weakest. Although this result stems from a magnetotail model, it might also be some clue for the understanding of the patchy type of magnetopause reconnection that is believed to occur in the so-called flux transfer events (Russell and Elphic, 1978).

Improvements are needed to include the particle effects in more realistic geometries including for instance a normal magnetic field component B_z in the magnetotail current sheet. In this context it is useful to point out that it is necessary for such simulations also to include the lobe regions around the plasma sheet where B_z changes sign because a configuration with the same sign of B_z everywhere would be stable (Birn et al., 1975).

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DISCUSSION

Vasyliunas: Your initial state is an equilibrium for zero resistivity. When a non-zero resistivity is introduced, the state is no longer one of equilibrium and will evolve in time; shouldn't that be called simply a time evolution of a non-equilibrium state and not an instability?

Birn: The application of a finite resistivity indeed causes the initial equilibrium configuration to diffuse slowly. This diffusion, however, occurs on a time scale much longer than the rise time of the instability that develops out of the perturbations introduced by the diffusion. The instability therefore is clearly distinguishable from the slow, quasi-steady diffusion.

Steinolfson: The intial state in your 3-D simulation was not in dynamic diffusive equilibrium. As a result, the reconnection was effectively driven (initiated) by the diffusion.

Birn: As I pointed out in my answer to Dr. Vasyliunas, the instability developed from a (slow) diffusion of the initial equilibrium state. However, since this evolution did not require a driving mechanism at the boundary, I would not call this "driven".

Bratenahl: 1) I'm interested in the 3-D field line figure showing the field line shear or rotation as you go up in z. You attributed this shear to field aligned currents. I did not see such currents in your slide showing currents. My comment is that you can get such rotational shear in a potential field, as in my model here. 2) My colleague Peter Baum modified the Schmidt-Harvey field line integrating code to map only through field lines lying on the separator and separatix structures. This can be useful.

Birn: Thank you for your comment.

Mullan: What is the ultimate fate of a plasmoid which forms in the magnetotail following reconnection?

Birn: I don't know. The simulations cannot tell what happens after the plasmoid has reached the tailward boundary of the system. Observationally, the present ISEE-3 mission through the distant tail might give more information about the ultimate fate of the plasmoid.

Wu: I would like to follow Dr. Steinolfson's question a little further, since your initial solution is not an equilibrium solution. I assumed that you also used artificial numerical dissipation in your code. As we all know that all numerical solutions are approximate solutions, then how do you identify whether your reconnection results are due to physical conditions or numerical effects?

Birn: By running the computer code with an without resistivity, I could prove that the reported results are indeed due to the physical resistivity and not to numerical dissipation. The run without resistivity showed no significant changes of the intital configuration.

Wu: What is the resolution of your grid size in the reconnection region?

Birn: I used a variable grid size in the most critical direction perpendicular to the neutral sheet with an innermost grid spacing of about 0.05 in units of the initial plasma sheet half width.

Drake: What boundary conditions do you use on the cross tail current in your 3-D simulation of the tail?

Birn: The velocity was assumed to be zero at that boundary; all quantities which did not vanish, including the cross tail current density, were assumed to have vanishing derivatives perpendicular to the boundary.

Sonnerup: Is the B_y component in the plasmoid predicted by your model consistent with the observed sign and magnitude of B_y in the plasmoid?

Birn: The sign of the B_y component in the plasmoid predicted by my model agrees indeed with observations in the geomagnetic tail; the magnitude of B_y in my model, however, is somewhat smaller than in some of the observations.

Lui: The field-aligned current system in Sato's simulation is consistent with disruption of the cross tail current while in your model it is not. How do you explain this?

Birn: The field aligned current system in my model is realized by the inner ring of "region 2" field-aligned currents found at the earth, which increases with increasing activity. The outer system ("region 1") is probably closer related to a driving mechanism at the boundary and, therefore, to Sato's model. This view is supported by the fact that "region 1" parallel currents are observed to be strong, even during quiet times.

Vasyliunas: Field-aligned (Birkeland) currents are carried by Alfven waves and therefore also involve velocity perturbations; a boundary condition V=0 may thus suppress J in the model, which may account for the discrepancies between various models.

Birn: I agree with your comment on the generation of "region 1" field-aligned currents.