MAGNETIC FIELD RECONNECTION AT THE DAYSIDE MAGNETOPAUSE

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ABSTRACT

Magnetic field reconnection is a fundamental energy conversion process, and the energy liberated during this process gives rise to phenomena which can be observed in space and laboratory plasmas. At the dayside magnetopause reconnection results in a coupling between the solar wind and the magnetosphere. Manifestations of this include large disturbances in the magnetic field known as flux transfer events, and accelerated plasma flows along the magnetopause. Progress has been made in the development of a physical model incorporating such phenomena, aided by experimental data from various spacecraft missions.

Keywords: Reconnection, magnetopause.

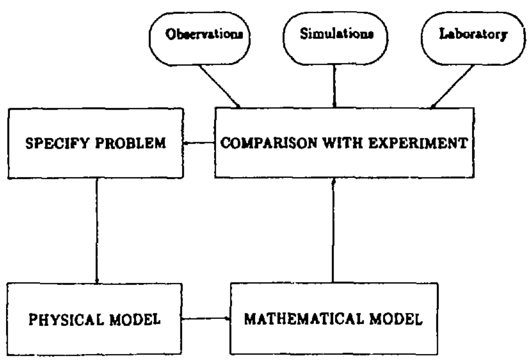

Figure 1: The modelling process.

1. INTRODUCTION

Observations of the various phenomena in space indicate that the plasma is never static, but always highly non-uniform and in constant motion. This implies that the underlying physical processes are dynamic in nature, and there should be a constant interchange between the various forms of plasma energy and that residing in the electromagnetic fields permeating the plasma. In our own solar system we can observe a variety of phenomena, such as flares on the sun, disconnection of cometary tails, and large-scale disturbances in the magnetospheres of planets, which are all associated with an explosive-like release of magnetic field energy (Ref. 1). Although at first sight these observations all look very different in nature, physicists like to synthesize different phenomena and the observations are interpreted in terms of a single underlying process: magnetic field reconnection.

In our attempts to understand reconnection we have already passed the stage of mere observation and are now in the process of developing a physical model. The modelling process is summarised in Figure 1, which shows that the problem is tackled on a broad front combining theory with experiment. In practice the development of a physical model is not an easy task, because on the one hand we would like the model to apply quite generally to the various different contexts in which reconnection occurs, whereas on the other hand it is necessary to be very specific and include a lot of detail before we can satisfactorily reproduce the observations and reveal all aspects of the problem. The Earth's magnetopause (Figure 2), which refers to the current sheet separating the terrestrial magnetic field environment (magnetosphere) from the interplanetary medium filled by the outflow of plasma and magnetic field from the sun (solar wind), is an example of a situation which is complicated to analyse because we need to include so many specific details in order to account for the observed behaviour and model the phenomena. Matters are further complicated because in the observations we cannot easily isolate reconnection from other processes which are likely to occur, and we have to place the findings in the context of the solar wind-magnetosphere system as a whole. However, it is precisely the availability of experimental data which has led to substantial progress in our understanding and which makes the study of this application so worthwhile.

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So far we are still in the initial stages of developing a physical model of reconnection at the magnetopause, and even the fundamentals of the approach to be used are still open to question (Refs. 2, 3). The research may therefore seem fragmented at times, against the general grain of physics in which different strands of research are unified whenever possible.
The aim in this article is to give a brief overview of how the problem of reconnection is approached on a general level, and to include just sufficient detail to show that the basic ideas have some validity for describing phenomena in nature, in particular those observed at the magnetopause; the data presented here give an inkling of the rich variety of observations which need to be accounted for. For recent reviews of the subject the reader is referred to Refs. 4-10.

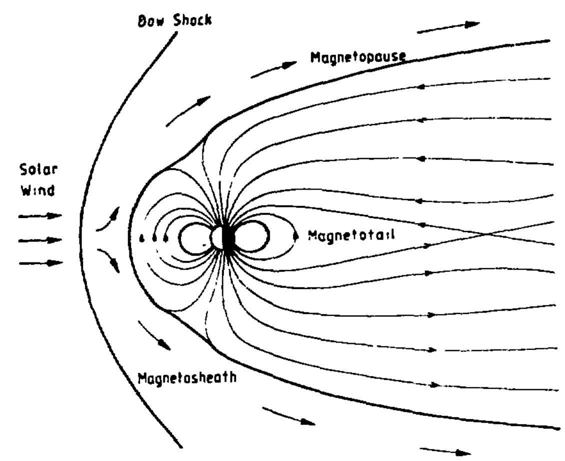

Figure 2: Global view of the solar wind-magnetosphere system.

2. THE PROBLEM

One of the major applications in which the concept of reconnection is studied is the solar wind-magnetosphere interaction (e.g., Ref. 11). At the Earth's magnetopause reconnection acts to couple the solar wind and the magnetosphere, and the resulting interchange of mass, momentum and energy affects the dynamics of the entire magnetosphere-ionosphere system, as originally suggested by Dungey (Ref. 12). Dungey's model of the magnetosphere, in which reconnection is assigned a primary role, helps to organise a variety of different magnetospheric and ionospheric phenomena and to explain their relationship to the upstream solar wind parameters, such as the orientation of the interplanetary magnetic field. Originally, before detailed spacecraft measurements became available, the role of reconnection in the solar wind-magnetosphere interaction was discussed in a global context and in terms of a time-averaged configuration. Thus, there was no detailed knowledge of how reconnection operates and what determines its behaviour at the magnetopause.
Spacecraft missions specifically designed for the purpose have allowed us to identify various in-situ manifestations of reconnection, so that the magnetopause has become a testing ground for theoretical research. One discovery in particular, that of the large-scale disturbances in the magnetic field component perpendicular to the magnetopause, referred to as flux transfer events (Ref. 13), led to the realisation that a time-averaged configuration was not suited to modelling magnetopause phenomena, and that it was necessary to expand our understanding of reconnection. This realisation led to many efforts at extending and improving the reconnection model in order to incorporate the magnetopause phenomena; these efforts span all components of the modelling process indicated in Figure 1, ranging from phenomenological descriptions (Refs. 13-19), theoretical and data analysis (Refs. 10, 20-25), laboratory experiments (Refs. 26, 27), to numerical simulations (Refs. 28-32). It is outside the scope of this article to review all this work, and our aim instead will be to obtain a flavour of the modelling process by trying to establish a (fairly general) model for reconnection with which to explain and interpret at least some of the magnetopause observations. We start with a physical description of the process.

3. PHYSICAL DESCRIPTION

For the physical description we do not consider the magnetopause in all its detail and complexity, but confine attention to a simple theoretical system consisting of a 2-D current sheet separating two uniform and identical plasmas with oppositely directed magnetic fields. This is a non-potential magnetic field configuration and we can think of the current sheet as a store or reservoir of free energy in the system. On a large scale (compared to a characteristic length such as the gyroradius) the plasma obeys the frozen-in approximation

$$\mathbf{E} + \mathbf{v} \times \mathbf{B} \approx 0, \qquad (1)$$

which implies that motion of the plasma and the magnetic field are closely coupled. As a result the plasma and magnetic field from different sources do not intermix and occupy separate regions, which gives rise to a cellular structure in space (Figure 2; Ref. 2). In principle it would therefore seem possible to accumulate free energy indefinitely simply by adding magnetic flux from the outside, and storing it at the current sheet. Eventually, however, the gradients there become so sharp that the plasma loses the frozen-in property, with the result that the flow and the field decouple and reconnection can occur.

Since in nature current sheets such as the magnetopause are highly non-uniform, it seems reasonable to suppose that the breakdown of the frozen-in approximation does not occur instantaneously throughout the whole length of the current sheet. Instead, we consider the breakdown to be initiated locally through some kind of dissipation mechanism. We then have to ask ourselves how this localised disruption of the current sheet is communicated to the system at large. For space and astrophysical applications magnetic field diffusion (Refs. 33, 34) is too slow to be of interest but, as realised by Petschek (Ref. 35), disturbances can be transmitted through the plasma via large-amplitude waves; these are referred to as MHD waves, since magnetohydrodynamics is the framework in which this aspect of reconnection is usually analysed. The MHD waves rapidly escape the dissipative region where reconnection is initiated, transfer the reconnection-associated disturbances to other parts of the current sheet, and establish an outflow region for the plasma streaming towards the current sheet (Figure 3a). Plasma entering the outflow region is accelerated and heated at the expense of the magnetic field energy (although for certain regions of the magnetopause the reverse may be true (Ref. 36)). The outflow region is also referred to as a field-reversal region (Ref. 37), since it connects magnetic field lines across the current sheet, thus establishing a topologically new region of reconnected flux. The size of the outflow region rapidly outgrows that of the dissipative region, so that the former provides the dominant means of converting and transporting energy and momentum during the reconnection process. Thus, through this wave mechanism reconnection can be considered as a large-scale transport process which is far more significant than magnetic field diffusion acting on its own.

In view of the dynamical behaviour of the plasma in nature, Petschek's wave mechanism, if it applies, does not operate continuously and at all times. At some stage reconnection should therefore switch off (Figure 3b), in which case no more reconnected flux is added to the system. The separatrices, which refer to the boundaries of the reconnected flux region formed by the magnetic field lines passing through the diffusion-dominated region, detach from the former site of reconnection at the time of switch-off. Since the diffusion region no longer acts as a generator of MHD waves, the outflow region will also detach from the reconnection site, and it propagates like a pair of solitary waves in opposite directions along the current sheet. The MHD waves previously generated continue their propagation towards the edges of the system, so that the outflow region continues to change shape and increase in size even though no more reconnected flux is added.

This, then, is a basic description of the reconnec-

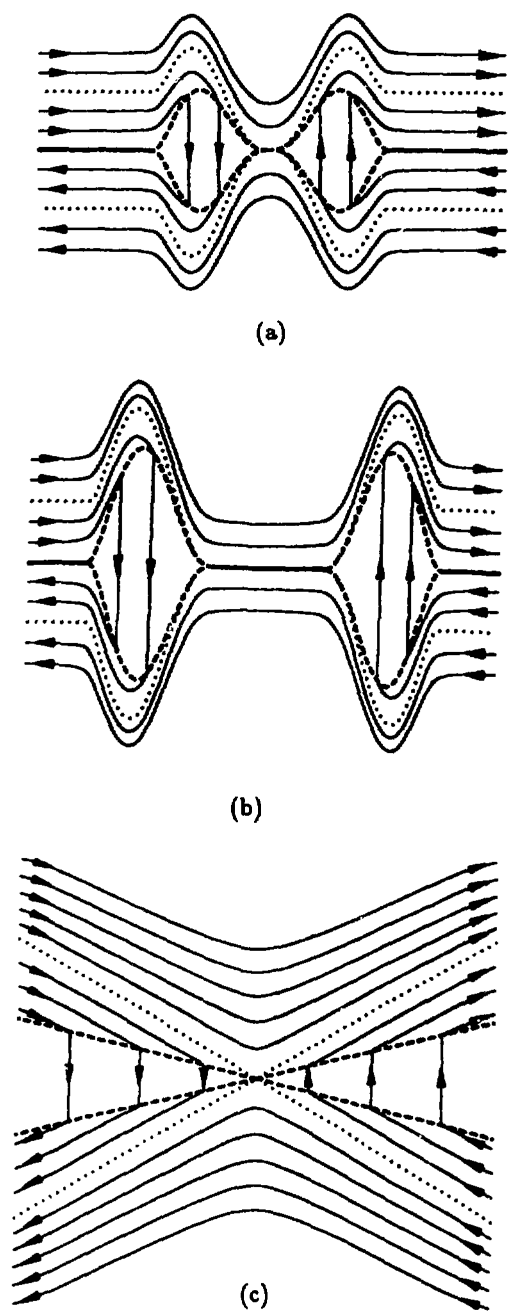

Figure 3: Three possible stages in the evolution of the reconnection process. The current sheet (thick solid line) separates two plasmas with antiparallel magnetic field orientations. Dashed lines show the shocks bounding the outflow region, arrowed lines the magnetic field lines, and dotted lines the separatrices bounding the region of reconnected flux. (a) Switch-on phase. (b) Switch-off phase. (c) Steady state with standing waves.

tion process. We now proceed to the mathematical model corresponding to this description, but before doing so add a few remarks. So far research has been concentrated either on the dissipation-dominated aspect of reconnection or on the large-scale behaviour. In the analysis of the various dissipation mechanisms reconnection appears as an intrinsically time-varying process. Dissipation alone cannot account for the large-scale manifestations, however, and so it is generally considered that the energy conversion is somehow regulated through a process involving Petschek's wave mechanism. This process is often assumed to be a steady-state one, whereby it seems forgotten that this assumption is based on a mathematical approximation, and not on any specific plasma-physical process or arguments of physics. A steady state implies that the reconnection rate is somehow constrained to remain constant over a time scale much longer than the time it takes for the MHD waves to propagate from the source (the diffusion-dominated region) to the edges of the system, and thereby to establish a standing-wave structure across the entire length of the system (Figure 3c). At the magnetopause it can be estimated that for this to happen the reconnection rate should remain constant for longer than ~ 10 mins.; this is of order or longer than the time over which major variations in the solar wind parameters typically occur. These and other considerations lead to the conclusion that it is not realistic to expect a true steady-state to apply at the magnetopause. Instead, we should consider reconnection as a dynamic process and the reconnection rate to vary over a range of space and time scales. Probably, the overall behaviour is determined by the global boundary conditions imposed on the system, and shorter space and time variations result from the particular dissipative process(es) and the local conditions imposed at the diffusion region(s). Since the magnetopause is only a small component of the entire solar wind-magnetosphere system, it is clear that in order to examine the behaviour at the magnetopause we need to take into account all aspects of the reconnection process described so far.

4. MATHEMATICAL MODEL

The physical description of reconnection helps us to progress and carry the modelling process a stage further. To test our physical understanding we need experimentally verifiable predictions and to make a comparison with the observations at the magnetopause, and this in turn requires development of a mathematical model. Unfortunately, plasma theory has not been developed sufficiently to supply the reconnection theorist with the tools required for a completely self-consistent model, i.e. a mathematical formalism which includes all important aspects of the plasma behaviour and its interaction with the electromagnetic fields, and which is analytically tractable. Efforts are made to rectify this situation, but for the moment we have to resort to simplifications, approximations and phenomenological arguments in order to bridge the gaps in our current knowledge and understanding. In this connection particular mention should be made of the relationship between the plasma behaviour on macroscopic scales and the dissipative microprocesses, which is still imperfectly understood. As a result of this a somewhat artificial division has to be introduced into the analysis of reconnection (e.g., Ref. 38).

One part of the analysis concerns the identification and behaviour of the dissipative mechanisms which give rise to reconnection. The sharp gradients leading to the breakdown of the frozen-in approximation are initially confined to the current sheet, and dissipation is usually considered important in some part of the current sheet referred to as the diffusion region. Sweet and Parker (Refs. 33, 34) investigated the evolution of a system with uniform plasma conductivity in which the energy conversion is regulated by ohmic heating throughout the entire length of the current sheet, with a correspondingly long diffusion region. This mechanism is described as magnetic field annihilation rather than reconnection, since essentially the magnetic flux carried towards the current sheet is destroyed without a change in magnetic field topology. The conclusion which can be drawn from the Sweet-Parker model is that sufficiently fast energy conversion rates can only be achieved through the localisation of dissipation, so that the length scale of the diffusion region must be small compared to the overall size of the system. Dissipative mechanisms which achieve such localisation are many and varied (e.g., Refs. 37-39). Possibilities include current-driven instablilities (Refs. 40-42), the nonlinear stage of the tearing mode (Refs. 20, 21, 43), current sheet rupture (Ref. 44) and stochastic motion of charged particles (Refs. 6, 45, 46). A proper discussion of all these mechanisms is outside the scope of this article, especially as it is not clear yet which, if any, of the ones described in the literature are the appropriate ones to choose for a given situation. Thus, although there does not seem to be much doubt that reconnection is a reality in both space and laboratory plasmas (Ref. 1), we cannot do much more than state that there exist a variety of possible physical mechanisms to initiate this process.

Although the required localisation of dissipation can be achieved through some instability or other, we still have to account for the large-scale phenomena which are observed. The resolution of this problem forms the second part of the analysis, in which we consider the behaviour outside the diffusion region, in the so-called convection region. As suggested by Petschek, the size of the diffusion region is small relative to that of the convection region; in fact, the diffusion region is often considered as a singularity and referred to as the reconnection or X line.

As mentioned before, the relationship between the microscale dissipation processes and the large-scale behaviour of a plasma is not well-understood. To cover this gap in our knowledge, and in order not to get overburdened with all of the details concerning the different possible dissipation mechanisms, we adopt a semi-phenomenological approach: we represent the plasma-physical processes in the diffusion region through a parameter $\epsilon(\mathbf{r}, t)$ which is a quantitative measure of the reconnection rate defined as

$$\epsilon \equiv \frac{E^*}{v_{A0} B_0}, \quad (2)$$

where E^* is the electric field along the reconnection line, and v_{A0} and B_0 are characteristic values of the Alfvén speed and magnetic field in the system. We note that this parameter corresponds to the Mach number M_A used by Petschek in his analysis (Refs. 35, 37), but here it is an arbitrary function of space and time, rather than a constant as implied by steady-state models of reconnection. The reconnection rate is therefore given the role of linking the dissipation mechanisms which give rise to reconnection to the large-scale behaviour of the plasma, and it is determined through a self-consistent coupling of the analysis concerned with the diffusion region and the convection region.

The most common approach in the analysis of the convection region is to treat the plasma as a hydromagnetic medium. This naturally leads us to consider Petschek's wave mechanism to explain the fast reconnection rates and the large-scale behaviour implied from the experimental observations. To a large extent this aspect of reconnection can be analysed through the equations of ideal MHD, but it should be pointed out that in addition to the sharp gradients which are initially confined to the current sheet there are thin dissipative structures such as shocks which appear as part of the reconnection process. Mathematically, such thin structures may be treated as discontinuities, and the upstream and downstream parameters determined using the ideal MHD equations in integral form. A more detailed analysis of the diffusion region and other dissipative structures can be performed by including transport parameters in the MHD equations, ideally with their values determined through a kinetic analysis of the underlying physical processes.

Some caution should be exercised when applying results obtained from MHD analysis, in particular when considering a collisionless plasma medium. Thus, numerical simulations seem to show that sometimes the use of the infinite conductivity approximation ($\sigma = \infty$) may give misleading results when applied

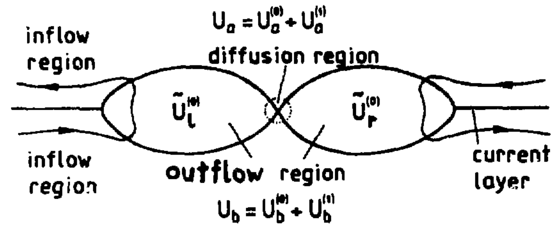

Figure 4: Schematic of the mathematical model of Petschek's wave mechanism.

to systems where the conductivity is large, but finite ($\sigma \rightarrow \infty$); the controversy about the existence of so-called intermediate shocks deserves particular mention in this respect (Refs. 47-51).

The continuum approach does not incorporate all aspects of the plasma behaviour, and in particular we have to take into consideration the discrete nature of the plasma. This problem is dealt with in single-particle descriptions of reconnection (e.g., Refs. 6, 52), which form an important complement to MHD analysis. Although self-consistent particle/field models still seem out of reach, the outcome of the approach based on MHD theory and that based on studying the motion of particles in model electromagnetic fields are similar enough to suggest that eventually they may be combined into a unified mathematical model of the plasma behaviour (Refs. 37, 53).

4.1 Analysis of Petschek's wave mechanism

The space-time dependent analysis of Petschek's wave mechanism provides us with an analytical tool to model and interpret magnetopause phenomena. It has been tried and tested through a comparison with spacecraft observations (Refs. 24, 25, 54, 55) and numerical simulations (Refs. 56-58). For this reason we consider an outline of the analysis in order to understand the basis of the mathematical model originally conceived by Petschek (Ref. 35, 37) and developed more recently by Semenov (Refs. 5, 10, 11, 59).

In essence, it is assumed in the analysis that the plasma in the convection region obeys the equations of ideal MHD in either differential or (in the case of discontinuities/shocks) integral form, at least to a first approximation. The specifics of the behaviour is introduced through applying the initial and boundary conditions appropriate to the problem, in the form of the functional behaviour of the reconnection rate $\epsilon(\mathbf{r}, t)$ and the specification of the initial current sheet configuration. The current sheet is modelled as a tangential discontinuity and the properties of the plasma and magnetic field are represented through the MHD state variables, or more succinctly through the MHD state vector $\mathbf{U}(\rho, p, \mathbf{v}, \mathbf{B})$.

For the analysis we divide the convection region into the outflow region, which is the region bounded by shocks containing the reconnected plasma, and the external or inflow region (Figure 4). In a generally asymmetric configuration we also have to distinguish between the properties of the outflow region on opposite sides of the diffusion region, $\tilde{\mathbf{U}}_r$ and $\tilde{\mathbf{U}}_l$, and the properties of the inflow region on opposite sides of the current sheet, $\mathbf{U}_a$ and $\mathbf{U}_b$.

For analytical simplification we restrict the reconnection rate ϵ to small values:

$$\epsilon \ll 1, \tag{3}$$

and then expand the MHD variables in terms of this small parameter in both the inflow region

$$\mathbf{U}_{a,b} = \mathbf{U}^{(0)}_{a,b} + \epsilon \mathbf{U}^{(1)}_{a,b} + \epsilon^2 \mathbf{U}^{(2)}_{a,b} + \cdots \tag{4}$$

and the outflow region

$$\tilde{\mathbf{U}}_{r,l} = \tilde{\mathbf{U}}^{(0)}_{r,l} + \epsilon \tilde{\mathbf{U}}^{(1)}_{r,l} + \epsilon^2 \tilde{\mathbf{U}}^{(2)}_{r,l} + \cdots \tag{5}$$

With the above restriction on the reconnection rate we can treat the outflow region as a thin boundary layer in the analysis and apply the standard techniques used for such problems (Ref. 60). The perturbations in the external or inflow region are small, so that we can use the initial state as our zero-order solution $\mathbf{U}^{(0)}_{a,b}$. This gives us the necessary matching condition to determine the zero-order solution $\tilde{\mathbf{U}}^{(0)}_{r,l}$ in the outflow region. This in turn allows us to find the first-order corrections of the solution in the inflow region, and so on:

$$\begin{aligned} \mathbf{U}^{(0)}_{a,b} &\rightarrow \tilde{\mathbf{U}}^{(0)}_{r,l}, \\ \tilde{\mathbf{U}}^{(0)}_{r,l} &\rightarrow \mathbf{U}^{(1)}_{a,b}, \\ &\ldots\ldots \end{aligned} \tag{6}$$

This scheme can be continued indefinitely, but usually only the first two or three steps are considered since the analysis gets increasingly complex and tedious, and there is no physical justification for finding higher order terms in a model which is in itself only an approximation of the plasma and field behaviour. Thus it is well-known that there are many observable effects resulting from non-ideal behaviour at the magnetopause (e.g., Refs. 14, 55, 61-66).

When implementing the scheme suggested by the perturbation analysis, it turns out that we can describe the whole procedure as a combination of three separate problems (Ref. 10):

- *The Riemann problem* (Ref. 67) is the nonlinear part of the analysis and leads to the specification of the appropriate combination of large-amplitude MHD waves and the tangential components of the magnetic field and the velocity in the outflow region;
- *Surface wave analysis* leads to the determination of the perpendicular field and flow components and the shape of the outflow region;
- A problem analogous to that of the *flow around a thin obstacle* leads to the determination of the external disturbances.

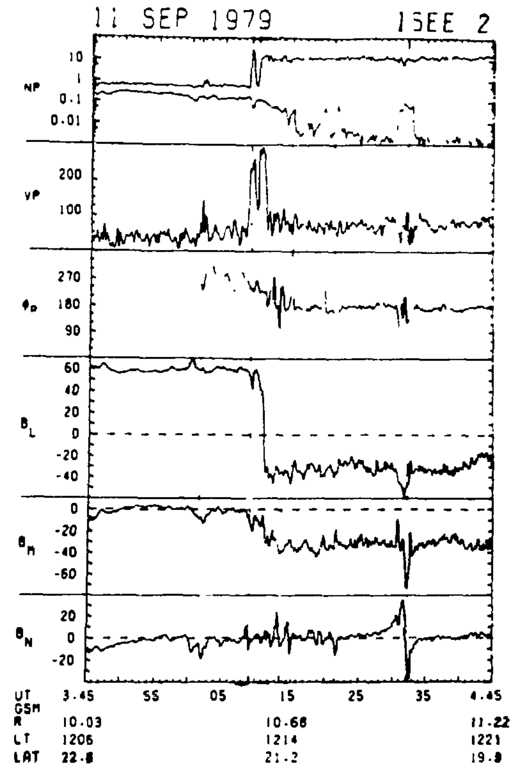

Figure 5: Spacecraft observations at the magnetopause showing manifestations of the reconnection process.

Each of these problems is important in its own right, and there are many applications outside the context of reconnection.

5. COMPARISON WITH OBSERVATIONS

Having equipped ourselves with a model for reconnection we can test our physical understanding through a comparison with experimental data. Here we shall do no more than perform a preliminary test, and for this purpose let us consider Figure 5. This figure shows observations from the spacecraft ISEE 2 during an outbound pass through the magnetopause region on 11 September 1979. The top panel shows the total plasma density N_p in cm^{-3}, and the density of the high-energy (> 10 keV) component of the plasma (dotted line). The next two panels show the bulk speed V_p of the plasma in km/sec, and the angle φ_p of the velocity vector in the ecliptic plane in degrees, with an angle of 180^0 and 90^0 indicating a vector pointing anti-sunward and duskward, respectively. The bottom three panels show the behaviour of the magnetic field (in nT) along the spacecraft trajectory, plotted in boundary normal coordinates (Ref. 13) with B_L and B_M the components tangential to the magnetopause surface (pointing approximately northward and westward, respectively), and B_N the component perpendicular to the magnetopause.

At the start of the interval ISEE 2 was located in the magnetosphere, as can be ascertained from the low number density and the northward-pointing magnetic field (B_L positive). The spacecraft then moved across the magnetopause (4:11 UT) to enter the shocked solar wind region (magnetosheath), which can be identified from the higher number density and the southward-pointing magnetic field.

Although no single instance of a magnetopause crossing can be regarded as typical, the data shown in Figure 5 allow us to identify the prime phenomena identified as manifestations of reconnection at the magnetopause (Refs. 24, 68). These are encounters with accelerated plasma flows along the magnetopause (4:10-12 UT), and large disturbances in the perpendicular magnetic field component B_N (e.g. at 4:32 UT), which are referred to as flux transfer events. The latter are often associated with large deflections in the other magnetic field components, and with a mixture of magnetosheath and magnetospheric particle populations (e.g., Ref. 68). It is possible for the two types of signature to be observed simultaneously in the spacecraft data (4:10 UT).

In order to model the observed magnetopause phenomena we need to know the local behaviour of the reconnection rate as a function of both space and time. We do not have this information, but for the sake of illustration we adopt the time-varying behaviour shown in the inset of Figure 6a, i.e. a regular series of bursts (the unit of time in this plot is arbitrary). To simplify matters we leave aside the question of spatial variations and consider the theoretical system discussed in Section 3, i.e. a configuration consisting of a 2-D current sheet (modelled as a tangential discontinuity) separating two uniform and identical plasma regions with antiparallel magnetic field orientations. Obviously, this is not a realistic representation of the magnetopause, but it serves our limited aim here.

With the analytical model we can sample the plasma and field properties as a function of space and time in the theoretical system. To simulate the spacecraft measurements at the magnetopause we consider three observation points which follow the trajectories labelled P_1, P_2 and P_3 in Figure 6a. At each observation point we calculate the plasma and magnetic field parameters as a function of time. The motion along the trajectory is a small fraction of the ambient Alfvén speed, the speed at which the outflow region propagates along the current sheet. Thus, starting from one side, each observation point gradually moves towards the current sheet and across to the opposite side.

The three plots in Figure 6b show the behaviour of plasma and magnetic field parameters as a function of time along each of the three trajectories. The data are plotted in a format similar to the spacecraft measurements shown in Figure 5, with N the plasma density, V the plasma bulk speed, B_L and B_N the magnetic field components tangential and perpendicular to the current sheet, and B the total field strength. The parameter S in the top panel (dotted trace) takes on three values depending on whether the behaviour is sampled on one or other side of the current sheet or in the reconnected flux region in between. The behaviour of this parameter emulates that of the density measurements of the energetic plasma component at the magnetopause, i.e. a high value in the magnetosphere, a low value in the magnetosheath, and an intermediate value in the reconnected flux region.

The theoretical results show a close correspondence to the behaviour observed at the magnetopause. In Figure 6b we observe encounters with accelerated plasma flows along the current sheet, and large disturbances in the perpendicular magnetic field component. The former correspond to entries into and traversals through the outflow region, whilst the latter can correspond to traversals through any one or a combination of the outflow region, the perturbed region of reconnected flux, or the perturbed region of unreconnected flux (Figure 6a). Using this simple theoretical example it is therefore possible to explain and interpret the accelerated plasma flows and flux transfer events observed at the magnetopause as manifestations of reconnection. It is also interesting to note that close to the reconnection site, along trajectory P_1 in Figure 6, there is an encounter with accelerated plasma flow, but no indication of any disturbances corresponding to flux transfer events. This explains the relative scarcity of flux transfer events close to the magnetic equator along the dayside magnetopause (Refs. 69, 70), the presumed site of reconnection for a southward interplanetary magnetic field orientation. At such a location the MHD waves are still confined to the immediate neighbourhood of the current sheet, and the width of the outflow region is not sufficient to cause disturbances far out. Further

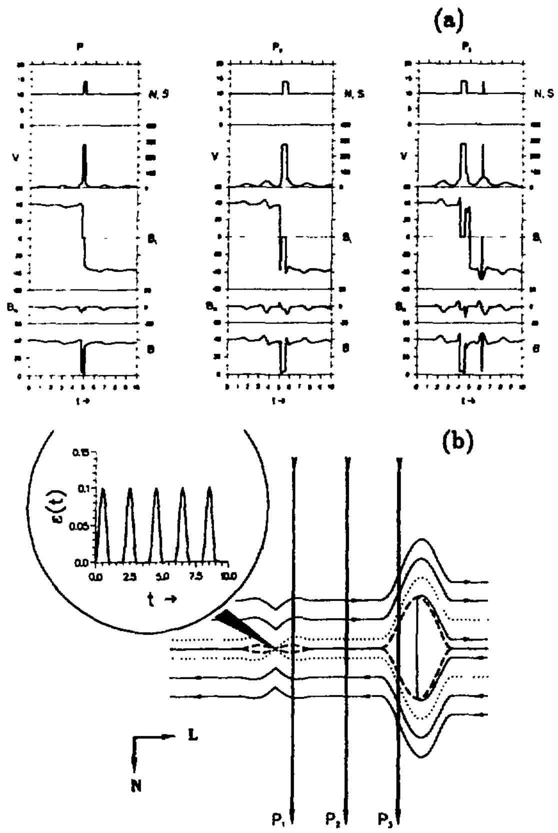

Figure 6: Analytical results showing the behaviour of the plasma and magnetic field in a simple theoretical system. (a) Snapshot of the outflow region and the magnetic field distribution. The insert shows the imposed behaviour of the reconnection rate as a function of time. (b) Variations of the plasma density, speed and magnetic field as a function of time along the three trajectories shown in (a).

investigation is required to account for the observations in more detail, taking into account the asymmetric, non-uniform current sheet configuration at the magnetopause and the nature of the solar wind flow around the magnetosphere (e.g., Ref. 11). We shall not attempt this here, however.

To conclude, we have considered various aspects of reconnection and the problem of modelling this process at the magnetopause. We have been able to account in a qualitative way for some of the observed manifestations of reconnection at the magnetopause. Although some questions were glossed over or not dealt with at all, this article hopefully serves to highlight the continuing efforts being made to develop a physical model of reconnection, one of the fundamental plasma-physical processes which occur in nature.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

1. Hones EW Jr. (Ed.) 1984, *Magnetic Reconnection in Space and Laboratory Plasmas*, Geophys. Mono. 30, AGU, Washington, 386 p.

2. Alfvén H 1981, *Cosmic Plasma*, Reidel, 164 p.

3. Coroniti FV 1985, Space plasma turbulent dissipation: reality or myth?, *Space Sci. Rev.*, 42, 399.

4. Cowley SWH 1984, Solar wind control of magnetospheric convection, in *Achievements of the International Magnetospheric Study (IMS)*, ESA SP-217, 483.

5. Pudovkin MI & Semenov VS 1985, Magnetic field reconnection theory and the solar wind-magnetosphere interaction: a review, *Space Sci. Rev.*, 41, 1.

6. Speiser TW 1988, Plasma sheet theories, in *Modeling Magnetospheric Plasma*, AGU, Washington, 277.

7. Sonnerup BUÖ 1988, Experimental tests of FTE theories, *Adv. Space Res.*, 8, 263.

8. Lee LC 1988, Towards a time-dependent magnetic reconnection model, *EOS Trans. AGU*, 69, 1617.

9. Lockwood M & al 1990, Transient reconnection: search for ionospheric signatures, *EOS Trans. AGU*, 71, 709.

10. Semenov, VS & al 1992, A comparison and review of steady-state and time-varying reconnection, *Planet. Space Sci.*, 40, 63-87.

11. Heyn MF & al (Eds.) 1992, *Solar Wind-Magnetosphere Interactions*, Austrian Academy of Sciences Press, Vienna, 249 p.

12. Dungey JW 1961, Interplanetary magnetic field and the auroral zones, *Phys. Rev. Lett.*, 6, 47.

13. Russell CT & Elphic RC 1978, Initial ISEE magnetometer results: magnetopause observations, *Space Sci. Rev.*, 22, 681.

14. Scudder JD & al 1984, The relation of flux transfer events to magnetic reconnection, in *Magnetic Reconnection in Space and Laboratory Plasmas*, Hones EW Jr. (Ed.), AGU, Washington, 153.

15. Lee LC & Fu ZF 1985, A theory of magnetic flux transfer at the earth's magnetopause, *Geophys. Res. Lett.*, **12**, 105.

16. Lee LC 1986, Magnetic flux transfer at the earth's magnetopause, in *Solar Wind-Magnetosphere Coupling*, Kamide Y & Slavin JA, Terra Scientific, Tokyo, 297.

17. Kan JR 1988, A theory of patchy and intermittent reconnection, *J. Geophys. Res.*, **93**, 5613.

18. Scholer M 1988, Magnetic flux transfer at the magnetopause based on single X line bursty reconnection, *Geophys. Res. Lett.*, **15**, 291.

19. Southwood DJ & al 1988, What are flux transfer events?, *Planet. Space Sci.*, **36**, 503.

20. Quest KB & Coroniti FV 1981, Tearing at the dayside magnetopause, *J. Geophys. Res.*, **86**, 3289.

21. Galeev AA & al 1986, Magnetopause stability threshold for patchy reconnection, *Space Sci. Rev.*, **44**, 1.

22. Biernat HK & al 1987, Unsteady Petschek reconnection, *J. Geophys. Res.*, **92**, 3392.

23. Owen CJ & Cowley SWH 1987, Simple models of time-dependent reconnection in a collision-free plasma with an application to substorms in the geomagnetic tail, *Planet. Space Sci.*, **35**, 451.

24. Sonnerup BUÖ & al 1981, Evidence for magnetic field reconnection at the earth's magnetopause, *J. Geophys. Res.*, **86**, 10049.

25. Paschmann G & al 1986, The magnetopause for large magnetic shear: AMPTE/IRM observations, *J. Geophys. Res.*, **91**, 11099.

26. Baum PJ & Bratenahl A 1980, Magnetic reconnection experiments, *Adv. Electronics electron Phys.*, **54**, 1.

27. Stenzel RL & Gekelman W 1979, Experiments on magnetic-field-line reconnection, *Phys. Rev. Lett.*, **42**, 1055.

28. Fu ZF & Lee LC 1985, Simulation of multiple X line reconnection at the dayside magnetopause, *Geophys. Res. Lett.*, **12**, 291.

29. Sato T & al 1986, Formation of field twisting flux tubes on the magnetopause and solar wind particle entry into the magnetosphere, *Geophys. Res. Lett.*, **13**, 801.

30. Ogino T & al 1989, A magnetohydrodynamic simulation of the formation of magnetic flux tubes at the earth's dayside magnetopause, *Geophys. Res. Lett.*, **16**, 155.

31. Scholer M 1989, Asymmetric time-dependent and stationary reconnection at the dayside magnetopause, *J. Geophys. Res.*, **94**, 15099.

32. Otto A 1990, 3D resistive MHD computations of magnetospheric physics, *Comp. Phys. Commun.*, **59**, 185.

33. Sweet PA 1958, The neutral point theory of solar flares, in *Electromagnetic Phenomena in Cosmical Physics*, Lehnert B (Ed.), Cambridge Univ. Press, 123.

34. Parker EN 1963, The solar flare phenomenon and the theory of reconnection and annihilation of magnetic fields, *Astrophys. J. Suppl. Ser.*, **8**, 177.

35. Petschek HE 1964, Magnetic field annihilation, *NASA Spec. Publ.*, **SP-50**, 425.

36. Scudder JD 1984, Fluid signatures of rotational discontinuities at the earth's magnetopause, *J. Geophys. Res.*, **89**, 7431.

37. Vasyliunas, VM 1975, Theoretical models of magnetic field line merging, *Rev. Geophys. Space Phys.*, **13**, 303.

38. Coroniti FV & Eviatar A 1977, Magnetic field reconnection in a collisionless plasma, *Astrophys. J. Suppl. Ser.*, **33**, 189.

39. Smith DF 1977, Current instability in reconnecting current sheets, *J. Geophys. Res.*, **82**, 704.

40. Papadopoulos K 1979, The role of microturbulence on collisionless reconnection, in *Dynamics of the Magnetosphere*, Akasofu S-I (Ed.), Reidel, 289.

41. Haerendel G 1978, Microscopic plasma processes related to reconnection, *J. Atmos. Terr. Phys.*, **40**, 343.

42. Huba JD 1985, Anomalous transport in current sheets, in *Unstable Current Systems and Plasma Instabilities in Astrophysics*, Kundu MR & Holman GD (Eds.), Reidel, 315.

43. Furth HP & al 1963, Finite-resistivity instabilities of a sheet pinch, *Phys. Fluids*, **6**, 459.

44. Syrovatskii SI 1981, Pinch sheets and reconnection in astrophysics, *Ann. Rev. Astron. Astrophys.*, **19**, 163.

45. Martin RF Jr. 1986, Chaotic particle dynamics near a two-dimensional magnetic neutral point with application to the geomagnetic tail, *J. Geophys. Res.*, **91**, 11985.

46. Büchner J & Zelenyi LM 1986, Deterministic chaos in the dynamics of charged particles near a magnetic field reversal, *Phys. Lett. A*, **118**, 395.

47. Kennel CF & al 1989, MHD intermediate shock discontinuities. Part 1. Rankine-Hugoniot conditions, *J. Plasma Phys.*, **42**, 299.

48. Lee LC & al 1989, On the stability of rotational discontinuities and intermediate shocks, *J. Geophys. Res.*, **94**, 8813.

49. Richter P & Scholer M 1989, On the stability of rotational discontinuities, *Geophys. Res. Lett.*, **16**, 1257.

50. Wu CC 1990, Formation, structure and stability of MHD intermediate shocks, *J. Geophys. Res.*, **95**, 8149.

51. Lin Y & al 1992, The role of intermediate shocks in magnetic reconnection, *Geophys. Res. Lett.*, **19**, 229.

52. Cowley SWH 1980, Plasma populations in a simple open model magnetosphere, *Space Sci. Rev.*, **26**, 217.

53. Cowley SWH 1985, Magnetic reconnection, in *Solar System Magnetic Fields*, Priest ER (Ed.), Reidel, 121.

54. Feldman & al 1984, Evidence for slow mode shocks in the distant geomagnetic tail, *Geophys. Res. Lett.*, **11**, 599.

55. Rijnbeek RP & al 1989, The structure of the reconnection layer observed by ISEE 1 on 8 September 1978, *Ann. Geophysicae*, **7**, 297.

56. Sato T 1979, Strong plasma acceleration by slow shocks resulting from magnetic reconnection, *J. Geophys. Res.*, **84**, 7177.

57. Scholer M 1989, Undriven magnetic reconnection in an isolated current sheet, *J. Geophys. Res.*, **94**, 8805.

58. Ugai M 1984, Self-consistent development of fast magnetic reconnection with anomalous plasma resistivity, *Plasma Phys. Contr. Fusion*, **26**, 1549.

59. Semenov, VS & al 1983, Time-dependent field line reconnection, *Soviet Astr. J.*, **60**, 1138 (in Russian).

60. Lagerstrom PA 1988, *Matched Asymptotic Expansions*, Springer-Verlag, 250 p.

61. Daly PW & Fritz TA 1982, Trapped electron distributions on open magnetic field lines, *J. Geophys. Res.*, **87**, 6081.

62. Lyons LR & al 1987, Ion precipitation from the magnetopause current sheet, *J. Geophys. Res.*, **92**, 6147.

63. Curran DB & Goertz CK 1989, Particle distributions in a two-dimensional reconnection field geometry, *J. Geophys. Res.*, **94**, 272.

64. Paschmann G & al 1989, High speed flows of H^+ and He^{++} ions at the magnetopause, *Geophys. Res. Lett.*, **16**, 567.

65. Fuselier SA & al 1991, Ion reflection and transmission during reconnection at the Earth's subsolar magnetopause, *Geophys. Res. Lett.*, **18**, 139.

66. Smith MF & DJ Rodgers 1991, Ion distributions at the dayside magnetopause, *J. Geophys. Res.*, **96**, 11617.

67. Heyn MF & al 1988, The structure of reconnection layers, *J. Plasma Phys.*, **40**, 235.

68. Paschmann G & al 1982, Plasma and magnetic field characteristics of magnetic flux transfer events, *J. Geophys. Res.*, **87**, 2159.

69. Rijnbeek RP & al 1984, A survey of dayside flux transfer events observed by ISEE 1 and 2 magnetometers, *J. Geophys. Res.*, **89**, 786.

70. Southwood DJ & al 1986, A survey of flux transfer events recorded by the UKS spacecraft magnetometer, *Planet. Space Sci.*, **34**, 1349.