

PETSCHEK–TYPE RECONNECTION AT THE MAGNETOPAUSE: A COMPARISON OF THEORY WITH DATA FROM ISEE 2 ON SEPTEMBER 11, 1979

H.K. Biernat^{*}, B.P. Besser^{*}, G.A. Bachmaier^{*},
M.F. Heyn[†], R.P. Rijnbeek[‡],
V.S. Semenov[§], I.V. Kubyshkin[§], and C.J. Farrugia[¶]

Abstract

We study the process of magnetic field line reconnection at the Earth's dayside magnetopause from the theoretical point of view and compare model predictions with observations made by the ISEE 2 spacecraft on its outbound magnetopause crossing on September 11, 1979. During the process of magnetic field line reconnection all types of magnetohydrodynamic waves can be excited. An analytical treatment of this process is performed in a generalized Petschek-type model. In this approach all wave structures are considered to be steepened and/or sufficiently thin so that they can be described as discontinuities. A direct comparison is made between the predicted structures and spacecraft data, and we show the influence of heavy ions on the mass density, and correspondingly the structure of the reconnection layer.

1 Introduction

The problem of coupling between the solar wind and the magnetosphere is of wide interest in space physics. Although dissenting voices exist, it is widely accepted that for the global interaction between the solar wind and the magnetosphere reconnection is the dominant coupling mechanism at the dayside magnetopause [e.g., Cowley, 1984].

The process of magnetic field line reconnection [see reviews by e.g., Vasyliunas, 1975; Pudovkin and Semenov, 1985; Priest, 1985] involves the ‘cutting’ of magnetic field lines and

^{*}Space Research Institute, Austrian Academy of Sciences, Lustbühelstraße 46, A-8042 Graz, Austria

[†]Space Research Institute, Austrian Academy of Sciences, Steyrergasse 17, A-8010 Graz, Austria

[‡]Mathematical Institute, University of St. Andrews, North Haugh, Fife KY16 9SS, Scotland

[§]Institute of Physics, State University St. Petersburg, St. Petersburg 198904, Russia

[¶]Goddard Space Flight Center, Code 692, Greenbelt, Maryland 20771, USA

their subsequent ‘connection’ to field lines of different topological origin. Alternatively, this process can be described by a redistribution of the currents [see, e.g., Biernat et al., 1987].

Reconnection gives rise to an ‘open’ magnetosphere [Dungey, 1961], i.e., there are magnetic field lines which thread through the magnetopause and are connected into interplanetary space at one end and to the Earth at the other. Reconnection is responsible for many phenomena, and such phenomena are frequently detected by spacecraft, like the example discussed in this paper. Therefore it seems appropriate to discuss this process in more detail. We do this by considering a theoretical model for reconnection first suggested by Petschek [1964]. In this model the dominant role in terms of energy conversion is played by magnetohydrodynamic waves. The original Petschek model is generalized in a series of papers [Semenov et al., 1983; Heyn et al., 1985]. As appropriate for the conditions prevailing at the magnetopause, this model has been generalized for skewed magnetic fields of different strength, a shear in the plasma velocity, and asymmetries in the plasma density [Heyn et al., 1988].

The present paper is organized as follows: In the next section a generalization of the Petschek model for arbitrary tangential plasma flows and skewed magnetic fields of arbitrary strength is discussed. In Section 3 we compare the model with a magnetopause crossing observed by ISEE 2 on September 11, 1979 [Sonnerup et al., 1981; Gosling et al., 1990]. A short discussion concludes this study.

2 Analysis of Petschek–type reconnection

For the description of space plasmas the equations of ideal magnetohydrodynamics (MHD) are frequently applied:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \quad (2.1)$$

$$\rho \left(\frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla \right) \mathbf{v} = -\nabla(p + \frac{B^2}{2\mu_0}) + \frac{(\mathbf{B} \cdot \nabla)\mathbf{B}}{\mu_0}, \quad (2.2)$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}), \quad (2.3)$$

$$\left(\frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla \right) \left(\frac{p}{\rho^\gamma} \right) = 0, \quad (2.4)$$

$$\nabla \cdot \mathbf{B} = 0. \quad (2.5)$$

These equations represent the mass conservation, the equation of motion, the Faraday law for infinite conductivity, the adiabatic law and the solenoidality condition for the magnetic field. Here ρ , $\mathbf{v}$ and p are the plasma density, velocity and thermal pressure. $\mathbf{B}$ is the magnetic field and γ is the adiabatic constant (ratio of specific heats).

These equations apply to the so-called convection region of reconnection, but not to the diffusion region. In the diffusion region there is a breakdown of the frozen-in condition, which allows the interconnection of magnetic field lines which initially belong to topologically different regions. In the field of magnetospheric physics Dungey [1961] proposed

that such regions occur on the dayside magnetopause and in the magnetotail. On the dayside, pairs of interplanetary and geomagnetic field lines are ‘cut’ and ‘connected’ inside a diffusion region to form open flux tubes, i.e., flux tubes with one end at the Earth and the other extending into interplanetary space.

From the point of view of the electromagnetic field reconnection is the process associated with a non-zero electric field component along all or part of a so-called reconnection line [Vasyliunas, 1975; 1984]. This so-called reconnection electric field E_* is associated with effects of finite conductivity. The resulting disturbances lead to the generation of MHD waves.

In the MHD description of a plasma, various wave modes can be excited. These are the fast and slow waves, Alfvén waves, and two structures non-propagating in the plasma reference frame, the tangential pressure balance and the entropy wave. In the non-linear theory of (finite-amplitude) simple MHD waves there arises the formation of shocks and discontinuities, resulting from the combination of steepening and dispersion/dissipation of the wave modes. Under certain conditions the compression waves of the fast and slow modes steepen into fast and slow shocks. The Alfvén, tangential and entropy wave structures do not steepen in the same way, but if they are considered sufficiently thin, they may be classified as discontinuities: the rotational, tangential and contact discontinuities, respectively. Collectively, the MHD waves give rise to the field reversal region, which is the outflow region of reconnected plasma through which the properties of the adjacent inflow regions are matched.

A system containing such discontinuities can conveniently be analysed using the integral form of the MHD equations. With the help of these integral relations the Rankine–Hugoniot conditions for a discontinuity are obtained [e.g., Weitzner, 1983].

In the model of reconnection we restrict ourselves to a reconnection electric field E_* , which is small compared to inflow quantities, magnetic field B_0 times Alfvén speed w_0

$$\epsilon \equiv \frac{E_*}{w_0 B_0} \ll 1. \quad (2.6)$$

This restriction allows an expansion of the MHD variables in terms of the small parameter ϵ . In this case the reconnection layer is a thin boundary layer and the normal components of the magnetic field and velocity satisfy the following inequalities:

$$B_n^2 \ll B_t^2, \quad \rho v_n^2 \ll p + \frac{B^2}{2\mu_0}. \quad (2.7)$$

These inequalities have been shown to be physically realistic for many magnetopause crossings [Sonnerup et al., 1981] and are also fairly well fulfilled in the example which we study in this paper.

Across a thin boundary layer the total pressure P is constant to lowest order:

$$P = p_0 + \frac{B_0^2}{2\mu_0} = \tilde{p}_0 + \frac{\tilde{B}_0^2}{2\mu_0} = \text{const.} \quad (2.8)$$

where the plasma pressure is $p = NkT$ (k is the Boltzmann constant). Quantities with and without tildes refer to values in the magnetosphere and magnetosheath, respectively. Under these circumstances fast mode waves do not appear in the lowest order analysis, since in the absence of strong pressure gradients, fast modes will be weak and can be treated as a perturbation. So we can consider the reconnection layer to be bounded on each side by Alfvén waves A , which rotate the magnetosheath and magnetospheric fields to a common direction. Inside the magnetic field strengths are matched through slow shocks S^- , or for very asymmetric conditions slow expansion waves R^- . Finally, a contact discontinuity, C , is needed in order to match any remaining asymmetries in the number density and temperature of the two plasmas.

The equations for the change in parameter values across all MHD discontinuities are given by Heyn et al. [1988] and Heyn [1992].

3 Reconnection at the Earth's magnetopause on September 11, 1979

The outbound crossing of the terrestrial magnetopause by the ISEE 2 spacecraft on September 11, 1979 is a well-documented crossing and has been frequently discussed and interpreted in terms of reconnection [Sonnerup et al., 1981; Paschmann et al., 1982; Cowley et al., 1983; Rijnbeek, 1984; Gosling et al., 1990]. We examine plasma and field in the light of the theory outlined above. In Figure 1 we show the behaviour of the plasma parameters and magnetic field in the vicinity of the magnetopause crossing at 4:11 UT. The density N , temperature T , and the plasma velocity $\mathbf{v}$ have been obtained by the fast plasma experiment [Bame et al., 1978] with a resolution of 48 s. The magnetic field data in Figure 1 have been observed by the flux gate magnetometer [Russell, 1978] with a time spacing of 12 s. The data are presented in boundary normal coordinates (LMN) using a magnetopause normal of $(0.918, -0.320, 0.235)$, in GSE coordinates, reported by Sonnerup et al. [1981]. We plot the tangential component of the plasma velocity, v_t , its angle α_v anticlockwise with respect to the L -axis, the magnetic field tangential to the magnetopause, B_t , its angle α_B and the normal magnetic field component B_n . In addition in the last two panels of Figure 1a we show the plasma beta β and the total pressure (solid line), which is the sum of the thermal (dashed line) and magnetic (dotted line) pressures. For the calculation of the plasma beta and the total pressure we smoothed the magnetic field data according the resolution of the fast plasma experiment. The density and temperature show considerable variations, accelerated plasma flows are observed (indicating reconnection), a rotation of the plasma flow, the magnetic field varies and shows a strong rotation. These features can be reproduced by the model described above. Additional features are flux transfer events at 4:09 UT, 4:13 UT and 4:15 UT as seen in the B_n -behaviour.

The observations of flux transfer events are commonly interpreted in terms of time-dependent reconnection. For the theoretical description Semenov et al. [1992] developed a generalization of the Petschek model which includes skewed magnetic fields, a finite length of the reconnection line and a time-dependent reconnection rate. But as input for

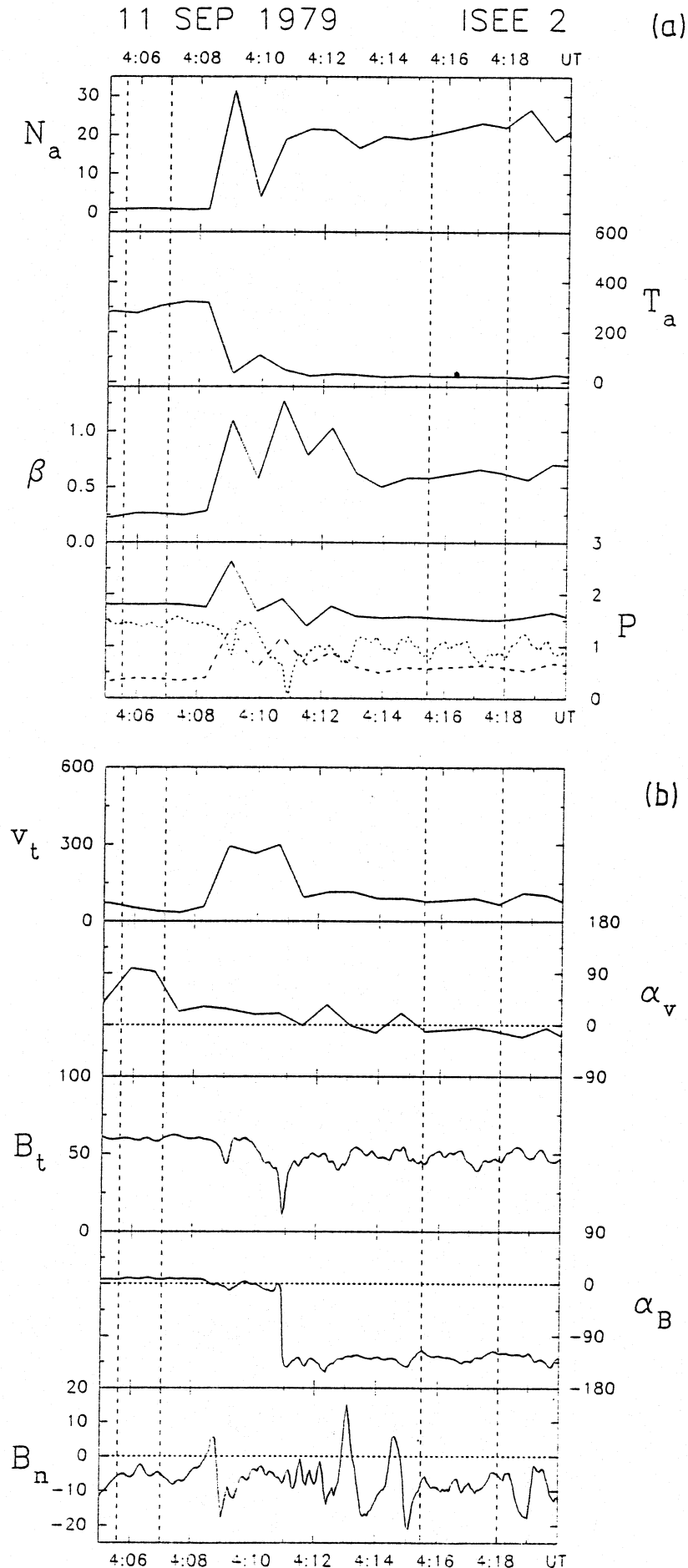


Figure 1: Plasma and magnetic field data from ISEE 2 during an outbound crossing of the Earth's magnetopause on September 11, 1979. a) From top to bottom the quantities plotted are the measured (apparent) density (cm^{-3}), the temperature ($\text{K} \times 10^5$), the plasma beta, and the total pressure ($\text{N/m}^2 \times 10^{-9}$ as the sum of the thermal pressure (dashed line) and magnetic pressure (dotted line)). b) From top to bottom the bulk flow speed tangential to the magnetopause (km/s), its inclination (deg.) with respect to the L -axis (boundary normal coordinates), the tangential magnetic field (nT), and its angle (deg.) with respect to the L -axis, and the normal magnetic field (nT).

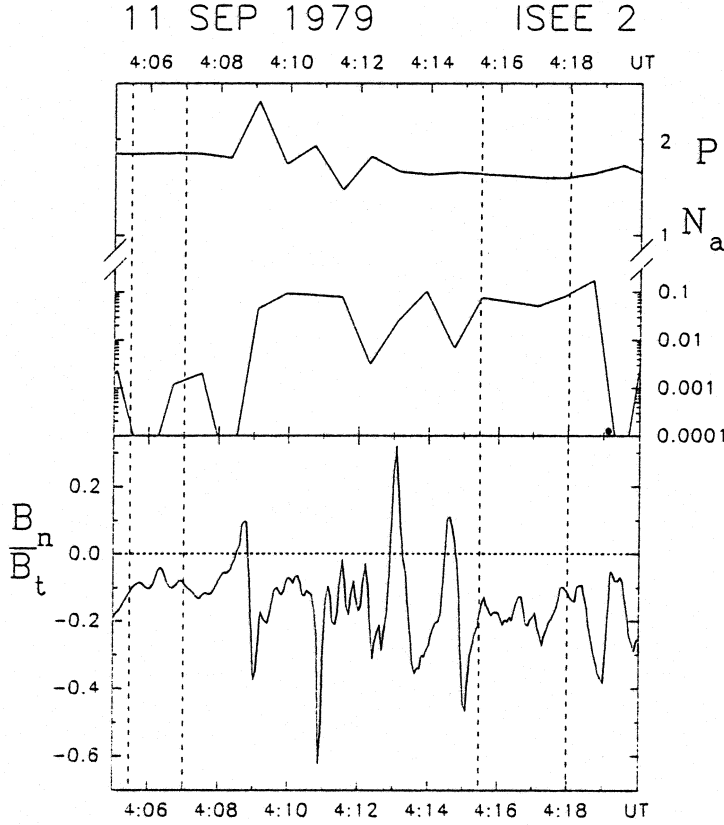


Figure 2: Test for the normal components of field and flow. The top panel shows the total pressure, and the quantity $\rho_a v_n^2$ (both in $\text{N/m}^2 \times 10^{-9}$). The bottom panel shows the ratio of the normal to tangential magnetic field components.

our model plasma and magnetic field parameters will be taken from the regions indicated by the dashed vertical lines to the left and right, where no strong variations are observed.

Before applying the model to the data example we have to test whether the total pressure is constant (Equation 2.8) and the perpendicular components satisfy the inequalities (2.7). The bottom panel of Figure 1a and Figure 2 show that they are fairly well satisfied. Peterson et al. [1982] reported measurement from ISEE of ions within the magnetosphere and in the magnetosheath during this pass. Analogous to Rijnbeek et al. [1989] we include the effects of heavy ions in the model described above. In a fluid where two particle species, protons of mass m_p and density N_p and ions with mass m_i and density N_i , are present, single fluid quantities can be estimated as follows. For the number density

$$N = N_p + N_i \quad (3.1)$$

whereas the mass density is given by

$$\rho = \rho_p + \rho_i = N_p m_p + N_i m_i, \quad (3.2)$$

where we may sum over different ion species.

Because the fast plasma experiment does not resolve different ion species Paschmann et al. [1986] pointed out that the measured quantities require a re-interpretation. The experiment measures so-called apparent values which are given by

$$N_a = N_p + \left(\frac{m_p}{m_i}\right)^{\frac{1}{2}} N_i. \quad (3.3)$$

Table 1: Inflow parameter values

$\tilde{N}_a$ (cm ⁻³)	N_a (cm ⁻³)	$\tilde{T}_a$ (K×10 ⁵)	$\tilde{v}_t$ (km/s)	$\tilde{\alpha}_v$ deg	v_t (km/s)	α_v deg	$\tilde{B}_t$ (nT)	$\tilde{\alpha}_B$ deg	B_t (nT)	α_B deg
0.94	21.6	290	45.8	95	77.2	-9.6	59.2	9.1	47.1	-127.3

For the determination of the input values for our theoretical model we have to satisfy the pressure balance Equation (2.8). Because of lack of detailed information about the temperatures of the different ion species we satisfy this equation by taking apparent values

$$[N_a k T_a + \frac{B^2}{2\mu_0}] = 0. \quad (3.4)$$

We favour this choice because the thermal pressure is slightly underestimated in case of equal temperature for all particle species whereas it is slightly overestimated if the thermal pressure of the ions is negligible.

Unfortunately the three-dimensional measurements show that in our example this equation is not completely satisfied by the observed values (bottom panel of Figure 1a). The total pressure is higher in the magnetosphere than in the magnetosheath. However, two-dimensional measurements show a higher temperature in the magnetosheath. By insisting that we satisfy Equation (3.4) we can prescribe the values in the magnetosphere and the density and the magnetic field in the magnetosheath and determine the magnetosheath temperature. This derived temperature is in good agreement with the two-dimensional measured temperature.

For the determination of the input values we use arithmetic averages of the data shown in Figures 1a and 1b within the intervals indicated by the dashed lines in the magnetosphere and the magnetosheath. These reference values are given in Table 1. Quantities without tildes refer to magnetosheath values next to the reconnection layer, and the magnetosphere inflow parameters are shown with tildes. The tangential magnetic field and the bulk speed of the plasma (in Boundary Normal Coordinates) are given in nT and in km/s, respectively. N_a (in cm⁻³) and T_a (in K × 10⁵) refer to the density and temperature, respectively, of the inflowing plasma. The magnetosheath temperature is not shown because it is calculated from the requirement of pressure balance, given by Equation (3.4), using the other parameters in Table 1.

Tangential velocities in the inflow regions, as they occur in our example, may lead to two theoretical difficulties as discussed by Biernat et al. [1989; 1990]. Firstly, they possibly may render the magnetopause Kelvin-Helmholtz unstable. Secondly, tangential velocities impose the additional constraint that the component of the plasma velocity perpendicular to the reconnection line must not exceed the corresponding Alfvén speed. Our example in Table 1 fulfills these conditions and for a more detailed discussion we refer to Biernat et al. [1989; 1990].

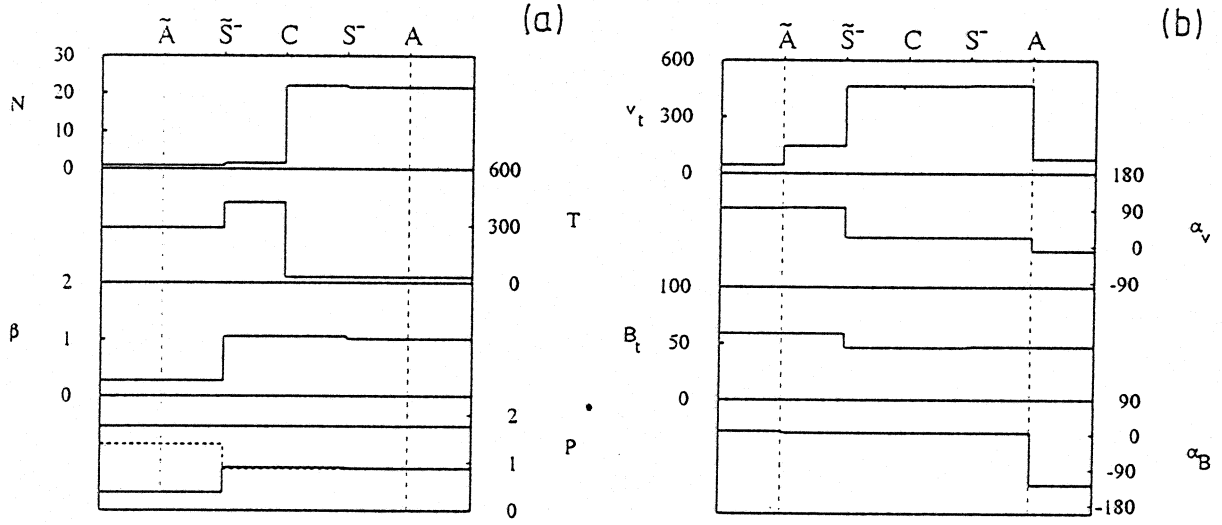


Figure 3: Plot showing the calculated plasma and magnetic field parameters in the inflow regions and through the reconnection layer. Parameter values for the inflow regions are listed in Table 1. The dashed vertical lines enclose the reconnection layer. The magnetosphere and the magnetosheath appear on the left and right side, respectively. a) From top to bottom the parameters are: the fluid density (cm^{-3}) and the temperature ($\text{K} \times 10^5$), the plasma beta, and the pressure (magnetic pressure (dashed), thermal pressure (solid) and their sum in $\text{N/m}^2 \times 10^{-9}$). b) From top to bottom the parameters are the tangential velocity (km/s), its angle (deg.) with respect to the L -axis, the tangential magnetic field (nT), and its angle (deg.) with respect to the L -axis.

Now we prescribe the inflow parameters as in Table 1 and use the theoretical model of Heyn et al. [1988] to calculate the various magnetic field and plasma parameters across the magnetopause region. In the following we study two different theoretical cases. In the most simple case we neglect the presence of heavy ions and therefore identify $N = N_a = N_p$. The results are shown in Figures 3a and 3b. The dashed vertical lines enclose the reconnection layer interval. The magnetosphere and the magnetosheath regions appear, respectively, to the left and right of this interval. The spacing between the discontinuities is chosen constant for the following reasons. By comparing our theoretical results with spacecraft data one has to identify the horizontal axis with the time axis of the spacecraft while it is crossing the magnetopause region (Figure 1 and 2). In this point one has to be careful because the magnetopause is practically always in motion, e.g., as the result of changes of the magnetosheath's parameters. Since we do not know how the reconnection rate varies, we cannot predict the relative spacing.

In Figures 4a and 4b we incorporate the presence of He^+ ions. Peterson et al. [1982] found a considerable amount of He^+ near the magnetopause. We include the effects of this particle species in our MHD model as follows. For determining the particle number and mass density in the inflow regions we take $\tilde{N}_{\text{He}^+} = 0.05 \text{ cm}^{-3}$ in the magnetosphere and $N_{\text{He}^+} = 0.06 \text{ cm}^{-3}$ in the magnetosheath. Taking the apparent values for $N_a = 0.82$, which has been measured by ISEE 2 at the time ISEE 1 measured the helium density and assuming the ratio N_{He^+}/N_p being constant, we derive from Equation (3.1) a value

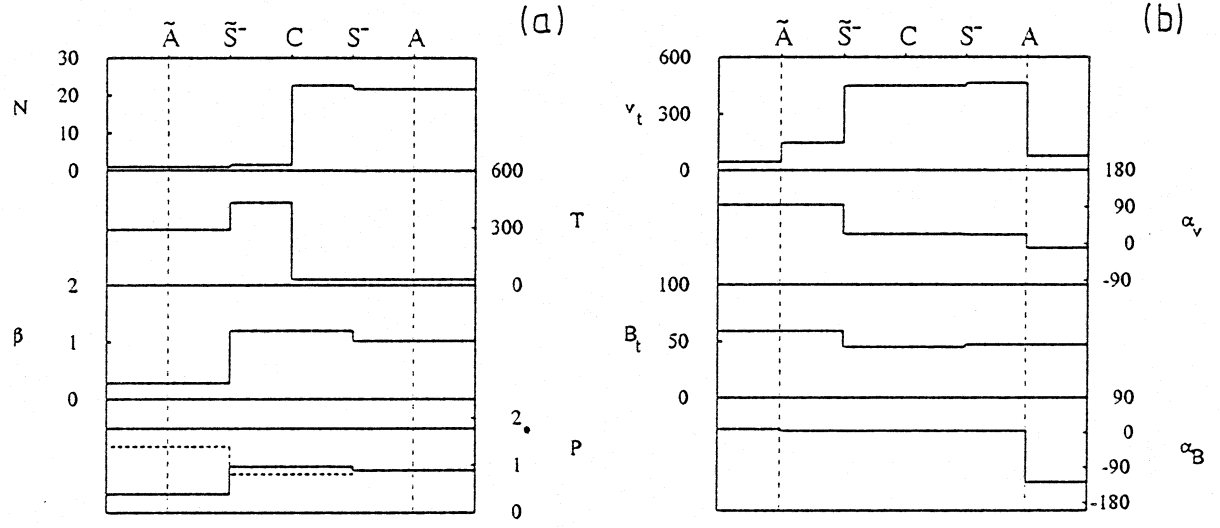


Figure 4: As for Figure 3 but including consideration of singly-charged helium ions.

of $\tilde{N} = 0.97 \text{ cm}^{-3}$. For the magnetosheath we get the value of $N = 21.64 \text{ cm}^{-3}$. In this way we obtain new mass density values from Equation (3.2).

4 Discussion

Both Figures 3 and 4 show the dominant role of the magnetosheath Alfvén discontinuity (A). However, there is also evidence for well-developed slow shocks ($\tilde{S}^-$) and a contact discontinuity (C).

In the data example the Alfvén discontinuity can clearly be identified by the rotation of the magnetic field. The contact discontinuity may also be identified in the data from the density and temperature changes. In addition, the increase of the tangential velocity and the decrease of the magnetic field on the left boundary can be interpreted as evidence for a slow shock.

The highly asymmetric configuration shown in this paper gives rise to only a very small decrease of the magnetic field inside the reconnection layer [compare Biernat et al., 1989; 1990]. Therefore we would like to make clear that Petschek-type reconnection should not simply be identified with a pronounced magnetic field decrease in the magnetopause region. This field decrease is only typical for a symmetric current sheet configuration in which slow switch-off shocks appear [Petschek, 1964]. We would also like to point out that Figure 4 indicates that the admixture of ions leads to a slightly stronger decrease of the magnetic field inside the layer than would otherwise be predicted.

We would like to point out that the considered spacecraft example shows clear evidence for time-varying features. Therefore it seems to be appropriate to apply reconnection models with a time-varying reconnection rate [Semenov et al., 1992].

An interesting feature of the data example is the magnetic field dip close to the centre of the layer. If we include He^+ ions our calculations lead to a higher field decrease compared to the pure proton model (Figure 3), but the decrease is still too small to explain the short dip in magnetic field strength. We have no explanation for this dip but we can speculate it may be due to one of the following reasons which may be interrelated:

- 1) The magnetic field dip may represent a structure convected from inside the diffusion region, where the magnetic field is expected to drop to small values, or even convection of the diffusion region itself following the switch-off of reconnection along all or a portion of the reconnection line. The short duration of the encounter with the accelerated plasma flows would seem to indicate that the magnetopause crossing occurred not far from the reconnection site.
- 2) The observation may correspond to a magnetic cavity as reported by Lühr and Klöcker [1987], and/or bear a relation to the magnetic field decreases observed by LaBelle et al. [1987] for the so-called ‘crater-like’ FTEs. Note that similar observations have been reported previously [e.g., Russell and Elphic, 1978].
- 3) The plasma data do not resolve this structure well enough, but it may correspond to a density enhancement/inhomogeneity, such as may result from a detached plasmasphere region convecting to the magnetopause [e.g., Freeman et al., 1977]. Note that an enhanced ion density in the magnetosphere decreases the asymmetry across the magnetopause and hence leads to stronger slow shock features, i.e., a bigger decrease in the magnetic field strength.

Acknowledgements: We thank Profs. S. J. Bauer, W. Riedler and M. I. Pudovkin for their support of this work and Dr. R. J. Fitzenreiter and W. Macher for numerous discussions. This work is supported by the Austrian ‘Fonds zur Förderung der wissenschaftlichen Forschung’, Project P 8046 GEO. RPR is funded by a SERC Advanced Fellowship. CJF would like to thank the Universities Space Research Association for its financial support. We would like to thank the ISEE 1 and 2 investigator teams for the experimental data, in particular Profs. C. T. Russell and R. C. Elphic.

References

- Bame, S.J., J.R. Asbridge, H.E. Felthaus, J.P. Glore, G. Paschmann, P. Hemmerich, K. Lehmann, and H. Rosenbauer, ISEE-1 and ISEE-2 fast plasma experiment and the ISEE-1 solar wind experiment, *IEEE Trans. Geosci. Electron.*, **GE-16**, 216–220, 1978.
- Biernat, H.K., M.F. Heyn, and V.S. Semenov, Unsteady Petschek reconnection, *J. Geophys. Res.*, **92**, 3392–3396, 1987.
- Biernat, H.K., M.F. Heyn, R.P. Rijnbeek, V.S. Semenov, and C.J. Farrugia, The structure of reconnection layers: Application to the Earth’s magnetopause, *J. Geophys. Res.*, **94**, 287–298, 1989.

- Biernat, H.K., M.F. Heyn, R.P. Rijnbeek, V.S. Semenov, and C.J. Farrugia, Reconnection at the Earth's dayside magnetopause in the presence of sheared flows and skewed fields, *Ann. Geophys.*, **8**, 69–78, 1990.
- Cowley, S.W.H., Solar wind control of magnetospheric convection, in *Proc. Conf. Achievements of the IMS*, ESA **SP-217**, 483–494, 1984.
- Cowley, S.W.H., D.J. Southwood, and M.A. Saunders, Interpretation of magnetic field perturbations in the Earth's magnetopause boundary layers, *Planet. Space Sci.*, **31**, 1237–1258, 1983.
- Dungey, J.W., Interplanetary magnetic field and the auroral zones, *Phys. Rev. Lett.*, **6**, 47–48, 1961.
- Freeman, J.W., H.K. Hills, T.W. Hill, and P.H. Reiff, Heavy ion circulation in the earth's magnetosphere, *Geophys. Res. Lett.*, **4**, 195–197, 1977.
- Gosling, J.T., M.F. Thomsen, S.J. Bame, R.C. Elphic, and C.T. Russell, Plasma flow reversals at the dayside magnetopause and the origin of asymmetric polar cap convection, *J. Geophys. Res.*, **95**, 8073–8084, 1990.
- Heyn, M.F., H.K. Biernat, V.S. Semenov, and I.V. Kubyshkin, Dayside magnetopause reconnection, *J. Geophys. Res.*, **90**, 1781–1785, 1985.
- Heyn, M.F., H.K. Biernat, R.P. Rijnbeek and V.S. Semenov, The structure of reconnection layers, *J. Plasma Phys.*, **40**, 235–252, 1988.
- Heyn, M.F., MHD models of magnetic field diffusion and reconnection, in *Solar Wind–Magnetosphere Interactions*, edited by M.F. Heyn, H.K. Biernat, V.S. Semenov, and R.P. Rijnbeek, Austrian Academy of Sciences, Vienna, pp. 85–112, 1992.
- LaBelle, J., R.A. Treumann, G. Haerendel, O.H. Bauer, G. Paschmann, W. Baumjohann, H. Lühr, R.R. Anderson, H.C. Koons, and R.H. Holzworth, AMPTE IRM observations of waves associated with flux transfer events in the magnetosphere, *J. Geophys. Res.*, **92**, 5827–5843, 1987.
- Lühr, H. and N. Klöcker, AMPTE–IRM observations of magnetic cavities near the magnetopause, *Geophys. Res. Lett.*, **14**, 186–189, 1987.
- Paschmann, G., G. Haerendel, I. Papamastorakis, N. Sckopke, S.J. Bame, J.T. Gosling, and C.T. Russell, Plasma and magnetic field characteristics of magnetic flux transfer events, *J. Geophys. Res.*, **87**, 2159–2168, 1982.
- Paschmann, G., I. Papamastorakis, W. Baumjohann, N. Sckopke, C. W. Carlson, B. U. Ö. Sonnerup, and H. Lühr, The magnetopause for large magnetic shear: AMPTE/IRM observations, *J. Geophys. Res.*, **91**, 11099–11115, 1986.
- Peterson, W.K., E.G. Shelley, G. Haerendel, and G. Paschmann, Energetic ion composition in the subsolar magnetopause and boundary layer, *J. Geophys. Res.*, **87**, 2139–2145, 1982.
- Petschek, H.E., Magnetic field annihilation, *NASA Spec. Publ.*, **SP-50**, 425–439, 1964.

- Priest, E.R., The magnetohydrodynamics of current sheets, *Rep. Progr. Phys.*, **48**, 955–1089, 1985.
- Pudovkin, M.I. and V.S. Semenov, Magnetic field reconnection theory and the solar wind–magnetosphere interaction: A review, *Space Sci. Rev.*, **41**, 1–89, 1985.
- Rijnbeek, R.P., Flux transfer events: Impulsive reconnection signatures at the Earth’s magnetopause, *Ph.D. thesis*, London, 1984.
- Rijnbeek, R.P., H.K. Biernat, M.F. Heyn, V.S. Semenov, C.J. Farrugia, S.J. Southwood, G. Paschmann, N. Sckopke, and C.T. Russell, The structure of the reconnection layer observed by ISEE 1 on 8 September 1978, *Ann. Geophys.*, **7**, 297–310, 1989.
- Russell, C.T., The ISEE–1 and –2 fluxgate magnetometers, *IEEE Trans. Geosci. Electron.*, **GE–16**, 239–242, 1978.
- Russell, C.T. and R.C. Elphic, Initial ISEE magnetometer results: Magnetopause observations, *Space Sci. Rev.*, **22**, 681–715, 1978.
- Semenov, V.S., I.V. Kubyshkin, M.F. Heyn, and H.K. Biernat, Field–line reconnection in the two–dimensional asymmetric case, *J. Plasma Phys.*, **30**, 321–344, 1983.
- Semenov, V.S., I.V. Kubyshkin, V.V. Lebedeva, M.V. Sidneva, H.K. Biernat, M.F. Heyn, B.P. Besser, and R.P. Rijnbeek, Time–dependent localised reconnection of skewed magnetic fields, *J. Geophys. Res.*, in press, 1992.
- Sonnerup, B.U.Ö., G. Paschmann, I. Papamastorakis, N. Schopke, Haerendel, S.J. Bame, J.R. Asbridge, J.T. Gosling and C.T. Russell, Evidence for magnetic field reconnection at the Earth’s magnetopause, *J. Geophys. Res.*, **86**, 10009–10067, 1981.
- Vasyliunas, V.M., Theoretical models of magnetic field line merging, 1, *Rev. Geophys. Space Phys.*, **13**, 303–336, 1975.
- Vasyliunas, V.M., Steady state aspects of magnetic field line merging, in *Magnetic Reconnection in Space and Laboratory Plasmas*, edited by E.W. Hones, Jr., 25–31, American Geophysical Union, Washington, D.C., 1984.
- Weitzner, H., Linear wave propagation in ideal magnetohydrodynamics, in *Handbook of Plasma Physics*, Vol. 1, edited by A.A. Galeev and R.N. Sudan, 201–242, 1983.