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MAGNETIC RECONNECTION IN THE TERRESTRIAL MAGNETOSPHERE

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ABSTRACT

An overview is given of quantitative comparisons between measured phenomena in the terrestrial magnetosphere thought to be associated with magnetic reconnection, and related theoretical predictions based on Petschek's simple model.¹ Although such a comparison cannot be comprehensive because of the extended nature of the process and the relatively few in situ multipoint measurements made to date, the agreement is impressive where comparisons have been possible. This result leaves little doubt that magnetic reconnection does indeed occur in the terrestrial magnetosphere. The maximum reconnection rate, expressed in terms of the inflow Mach number, M_A , is measured to be $M_A = 0.2 \pm 0.1$.

INTRODUCTION

Magnetic reconnection in a magnetoplasma is a process in which plasma flows across a boundary that separates topologically distinct magnetic cells. This process appears in a variety of settings and proceeds at rates which depend sensitively on the boundary conditions as well as on the ambient plasma state.

There are many equivalent ways of characterizing magnetic reconnection. The definition adopted in Space Plasma Physics requires a nonzero $E_{\parallel}$, the electric field parallel to the magnetic separator. Here the magnetic separator, often called the neutral line, is the line of intersection of two separatrix surfaces. These surfaces define the boundary between distinct magnetic cells.^{2,3,4,5} Alternatively, stressed plasmas containing a nonpotential magnetic field can relax to a more potential configuration while generating hot plasma jets.⁶ When such a condition exists, convected magnetic energy density in the form of a Poynting flux is converted to convected plasma energy density in the form of enthalpy flux and bulk convection flux.

The sudden heating of solar plasma provides the gross observational feature of solar flares. It seemed natural, therefore, to seek an explanation of solar flares in terms of magnetic reconnection. The earliest quantitative theories^{8,9,10,11} considered a single-step process in which magnetic energy was converted to plasma energy through the resistive diffusion of plasmas carrying antiparallel magnetic fields. These fields are in turn forced towards a central current sheet by external boundary conditions. However, reconnection rates predicted by these theories, expressed equivalently either in terms of $E_{\parallel}$ or the upstream inflow Alfvénic Mach number, M_A , were too slow to account for the rates of energy release observed in solar flares. Here, energy was thought to be converted throughout a thin but long layer

requiring a conversion time proportional to the square root of the length.

A solution to this dilemma was provided by Petschek.¹ In his model, the energy conversion process was split into two parts. In the first part, field lines were torn and reconnected in a relatively small diffusion region containing the separator or neutral line. This tearing is accompanied by relatively little energy conversion because of the small volume of the diffusion region. The second part consisted of magnetic field annihilation across the fronts of obliquely propagating intermediate- or slow-mode waves. These waves are expected to develop steep fronts to form rotational discontinuities or slow-mode shocks, respectively. Practically all of the magnetic energy that was converted to plasma energy through reconnection occurred across these fronts because of their much larger areas. The resultant large increase in reconnection rate afforded by this model reflects the large difference between wave speeds and diffusion speeds characteristic of most cosmical plasmas. Reconnection rates allowed by this model were now sufficiently large to account for solar flares.

Because of the difficulty of measuring microscopic details of the electric, magnetic and plasma flow fields within reconnection sites embedded in solar active regions, progress in reconnection theories of solar flares has been relatively slow. Such progress has therefore shifted to theories of the terrestrial magnetosphere where such difficulties are not as severe. Here, as within solar active regions, magnetic reconnection has been suggested as a primary energy-conversion process. Indeed, an early attempt to account for measured convection patterns in the ionosphere found a ready explanation in terms of magnetic reconnection leading to an open magnetosphere.¹² Although the concept of an open magnetosphere has yet a few remaining doubters, an overwhelming mass of observations exists that is well organized by theoretical predictions based on an open magnetosphere. Furthermore, these observations are difficult to understand in toto if the terrestrial magnetosphere is closed.^{4,13,14,15,16,17,18,19}

Two sites for magnetic reconnections are likely; 1) the blunt-nosed surface separating the terrestrial plasma from the solar wind, the subsolar magnetopause, and 2) the current sheet separating north and south lobes of the geomagnetic tail embedded within the plasma sheet. A schematic picture of the terrestrial magnetosphere showing these sites is reproduced from Sonnerup³ in Figure 1. An overview of our current quantitative understanding of magnetic reconnection at the subsolar magnetopause and at the plasma sheet is given in the next two sections, respectively. This overview will not be comprehensive but instead be tailored to the purpose of this workshop; to identify processes which may operate in both solar-terrestrial and astrophysical plasmas. We may then be able to scale relevant solar-terrestrial phenomena to various astrophysical systems, thereby deepening our understanding of both systems. Attention will therefore be confined to a few

Fig. 1. A schematic representation of the interaction between the solar wind with the terrestrial magnetosphere in the noon-midnight meridian when the magnetic field in the magnetosheath is directed due south. Two sites for magnetic reconnection are identified by X points in the figure, 1) the subsolar region of the magnetopause and 2) the central plane of the magnetotail. This figure is reproduced from Sonnerup.³

quantitative results which, in the authors opinion, may prove useful in this regard.

RECONNECTION AT THE MAGNETOPAUSE

The first application of Petschek's model to the magnetopause was given by Levy et al.²⁰ Their schematic representation is shown in Figure 2. In order to match the shocked solar wind flow (which carries a generally turbulent magnetic field having variable orientation) to the terrestrial magnetosphere (a low β plasma having generally northward pointing magnetic field firmly anchored in the earth) the boundary must consist of a pair of wave fronts. Each of these fronts consists of a standing Alfvén wave overlying an inner slow-mode expansion wave. Here β is the ratio of plasma pressure to magnetic pressure. Most of the deflection and acceleration of the incident solar wind flow is effected by the $\underline{J} \times \underline{B}$ force within the front of the Alfvén wave. The Alfvén waves

Fig. 2. A schematic representation of reconnection at the subsolar magnetopause identifying the various MHD structures expected. The forward edge of the interaction between the solar wind and terrestrial magnetosphere is a standing fast-mode shock. This is followed by a magnetopause consisting of a leading Alfvén wave, which in actuality is a rotational discontinuity, and a trailing slow-mode expansion wave. This expansion wave has been identified observationally as a solar wind-magnetosphere boundary layer. This figure is reproduced from Levy et al.²⁰

are expected to be sharply crested, having the appearance of rotational discontinuities. They connect at a relatively small, central volume, the diffusion region, where incident magnetosheath and magnetospheric field lines tear and reconnect to one another. A continuous transition between plasma and field conditions within the diffusion region and the far wave fields, can only be achieved if the plasma inflow rate V_n , is less than about 0.1 to 0.2 of the Alfvén speed, V_A . Both speeds are referenced to conditions just upstream of the magnetopause in the magnetosheath.²⁰ However, because the magnetosheath and all other cosmical plasmas are compressible, this result does not require a maximum merging rate with respect to conditions imposed at the outer boundaries of two adjacent magnetic cells. Indeed, external pressures sufficiently large can cause a compression of the plasma near the interface thereby raising the local upstream Alfvén speed at the magnetopause

to the point where the inflow Mach number at the interface, $M_A = (V_n/V_A) \lesssim 0.2$ ²¹

Much of the original analysis of magnetopause structure near the subsolar region of the terrestrial magnetosphere has since been experimentally verified.^{4,17,18} In particular, detailed analyses of magnetopause structure showed that (1) the upstream boundary of the sunward-facing magnetosphere was a rotational discontinuity at least some of the time,^{22,23} and that (2) it is often followed by a boundary layer (a) having general characteristics intermediate between those of the magnetosheath and the magnetosphere^{24,25,26} but, in a few special cases, (b) composed of plasma jets having transverse momentum sufficient to balance the transverse magnetic stress at the discontinuity.^{27,28,29}

Although clear examples have been found of an open magnetopause having characteristics consistent with the Levy et al. model,²⁰ many examples have also been found of a closed boundary having the form of a tangential discontinuity.³⁰ This result is also consistent with Petschek's model and is in accord with many indirect solar wind-magnetosphere parameter correlation. These correlations indicate that the magnetopause acts as a half-wave rectifier of the interplanetary magnetic field.^{16,31} When the interplanetary magnetic field has a southward component, reconnection at the magnetopause occurs, but when it has a northward component, reconnection ceases. However, an additional feature of the observations not foreseen in early theoretical analyses was the patchy nature of the magnetic interconnection process.^{32,33,34} Reconnection at the magnetopause is often evident as discrete events having a characteristic physical scale size of about one earth radius, R_E . It is estimated that roughly half the magnetic flux transferred from the solar wind to the magnetotail occurs through such discrete flux transfer events.¹⁸

Two approaches have been used to assess the efficiency with which energy is fed into the magnetosphere through magnetic reconnection at the magnetopause. The first is a lower limit which compares the total energy dissipated in the near-earth magnetotail with the total solar wind energy incident on the entire sunward face of the magnetopause.^{35,36,37,38} The lower-limit aspect of this comparison stems from two disparate effects. A combination of the curvature of the magnetopause, the dipole-like character of the terrestrial magnetic field, and the relatively small scale, large-amplitude nature of the magnetosheath turbulence, all together prevent a uniformly maximal efficiency for magnetic reconnection over the entire sunward face of the magnetopause. The second effect is that a fraction of the total energy input to the magnetotail through the magnetopause was not counted in these estimates. In particular, a substantial fraction of the stored magnetotail energy density is released back to the solar wind in the form of plasmoids^{39,40,41} and jetting wake plasma.⁴² Nevertheless, the resultant estimate can provide an order of magnitude value which may prove useful in applications to specific

astrophysical systems. On the average, the maximum solar wind-magnetosphere energy-coupling efficiency through the reconnection process, can range from less than about 1% to about 5%.^{36,37,38} This efficiency is not readily compared with the maximum magnetic reconnection rate deduced by Levy et al.^{20,21}

A closer estimate of this maximal rate was given by Holzer and Slavin^{43,44} who compared the rate of net magnetic flux transfer from the forward hemisphere of the magnetosphere to the geomagnetic tail, with the rate of magnetic flux transported by the solar wind to the sunward face of the magnetopause. The result of their analysis yielded a ratio of inflow to transported rates of about 0.2. This ratio is very close to the maximum inflow Mach number predicted by Levy et al.²⁰ Although the foregoing observed and predicted rates are not directly comparable because the observations are referenced to the far upstream solar wind rate and the theoretical predictions are referenced to the inflow Mach number evaluated just upstream of the magnetopause, the very close agreement is encouraging.

RECONNECTION IN THE GEOMAGNETIC TAIL

Petschek's symmetric model of magnetic reconnection¹ is expected to find its closest realization in the geomagnetic tail.³ Here the interaction between the solar wind and the earth's magnetic dipole fashions two nearly symmetric, low- β lobes of plasma, having oppositely-directed magnetic fields. These fields are pressed together by the solar wind along the center plane of the tail. A schematic view of this topology, in the form of a meridional cut through the tail, is shown in Figure 3.

Tearing of north and south lobe fields occurs at a neutral line in the center of the figure. The field lines just tearing are the separatrices which form the boundaries of neighboring, topologically distinct magnetic cells. According to the Petschek model, the locus of lines parallel to the neutral line along which the fields downstream of the separatrices bend sharply, are four slow-mode shocks which intersect at the neutral line. Relatively slow moving plasma flows southward from the north and northward from the south into the shocks. Within the shock fronts they are redirected, heated, and accelerated to form plasma jets travelling toward (to the left of the neutral line in Figure 3) and away (to the right of the neutral line in Figure 3) from the Earth, respectively. The magnitude of the magnetic field also decreases abruptly within the shocks. If in addition, a neutral line is formed within the near-Earth plasma sheet, (region 2 of Figure 1) then the tailward component of initially reconnected plasma sheet field lines forms nested closed loops, represented in Figure 3 as a tailward-jetting plasmoid.

Many observations of plasma phenomena in the near-Earth magnetic tail are well organized by the foregoing reconnection model of the plasma sheet and surrounding lobes.^{13,14,15,45,46,47}

Fig. 3. A schematic representation of reconnection in the geomagnetic tail identifying the boundaries between the various flow regimes within the four separate magnetic cells. A description is given in the text.

Most notable is the strong correlation between 1) earthward jetting plasmas and energetic particles coupled with northward magnetic field, and 2) tailward jetting plasmas and energetic particles coupled with southward magnetic field. This occurs near the center plane of the tail as pictured in Figure 3.

Recent measurements of the deep geomagnetic tail have confirmed this picture. They have also allowed a quantitative comparison with the Petschek model. In particular, dynamical changes in the deep geomagnetic tail have been observed to correlate closely with those occurring in the near tail as predicted by magnetic reconnection.⁴⁸ This near-Earth activity was also shown to correlate closely with the detection in the distant magnetotail of 1) tailward jetting plasmoids,^{39,40} 2) tailward propagating energetic particles,^{41,49,50,51} and 3) standing slow-mode shocks forming a semi-permanent boundary between plasma sheet and lobe plasma populations.^{52,53}

The semi-permanent feature of slow-mode shocks observed in the distant geomagnetic tail has allowed the best quantitative comparison with Petschek's simple model of symmetric reconnection since the theory assumes time stationarity. Most important in this

regard is the inflow Alfvén Mach number discussed previously. The comparison is excellent. The average inflow Alfvén Mach number observed just upstream of 26 of the least ambiguous examples of slow-mode shocks observed by ISEE 3 near 200 R_E downstream of the earth is $M_A = 0.19 \pm 0.08$.⁴²

SUMMARY AND CONCLUSIONS

A host of in situ observations lend support to the Petschek¹ model of magnetic reconnection in the terrestrial magnetosphere.^{15,47} Because of the time- and spatially-varying orientation of the solar wind magnetic field and the generally large-amplitude turbulence of the magnetosheath flow, magnetic reconnection at the sunward face of the magnetopause proceeds by way of a standing rotational discontinuity followed by a slow-mode expansion fan.¹⁷ However, a significant fraction of magnetic reconnection at the magnetopause proceeds in discreet events, called flux transfer events,¹⁸ having a distinct scale size of about 1 R_E .

Magnetic reconnection in the geomagnetic tail is, in two major respects, simpler to understand than that which proceeds at the sunward magnetopause. This simplicity stems from the closely equal magnitude yet antiparallel orientations of magnetic fields in the north and south lobes of the magnetotail. This topology is fixed by the interaction between the supersonically streaming solar wind and the terrestrial magnetic dipole. In consequence, there is no need for a rotational discontinuity to match boundary conditions. All that remains is a slow-mode compression fan which steepens to form four slow-mode shocks intersecting along a magnetic neutral line. Most of the transformation of magnetic energy in the form of a Poynting flux, to plasma convection and enthalpy flux, occurs in a quasi-steady state fashion at these shocks.⁴² The rest occurs in a time-dependent fashion at the onset of reconnection to form earthward jetting plasmas and energetic particles^{15,15,46,47} leading to a host of related near-earth phenomena,³⁶ as well as tailward jetting plasmoids^{39,40} embedded within a sheet of magnetically open, jetting wake plasma.⁴²

Although quantitative analyses of reconnection at the sunward magnetopause^{35,36,37,38,43,44} yield rates consistent with the Levy et al.²⁰ analysis of the Petschek¹ mechanism, they are not precisely comparable. The strong time and spatial variations of conditions at the magnetopause resulting from inherent variations in the solar wind flow are difficult to account for in detail. This situation is not the case in the deep geomagnetic tail. Here the terrestrial dipole imposes an order to the lobe plasma topology not present at the magnetopause. In consequence, magnetic reconnection in the deep geomagnetic tail occurs in a more geometrically simple fashion. In addition, because of the distance from the neutral line, it occurs in a more time stationary fashion. A quantitative comparison shows that the measured reconnection

rates⁴² are in excellent agreement with theoretical predictions,²⁰ both giving an Alfvénic inflow Mach number, $M_A = 0.2 \pm 0.1$.

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