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Reconnection

The reconnection of magnetic fields in a conducting fluid or gas is one of the most important processes in cosmical plasmas. It converts energy stored in magnetic fields into kinetic energy, transforms magnetic configurations, and enables interactions between two magnetized plasma regimes which otherwise would be much weaker. The recognition of the existence of this process grew half a century ago out of the attempt to understand the dramatic energy releases in the solar corona and chromosphere during flares. Processes on the Sun on all scales of energy release have the been targets of reconnection studies ever since. With the beginning of space research and the discovery of the magnetosphere it soon became clear that the fundamental process underlying solar wind–magnetosphere interactions and the ensuing internal dynamics of the magnetosphere must be reconnection. Furthermore, there was the chance to explore the process by extensive *in situ* and global response studies.

Reconnection is a process that breaks the magnetic connection of plasma elements in situations in which the magnetic field can be generally considered as frozen in. It requires high current densities which are concentrated in thin sheets or filaments and are thus exceptional regions in a much larger quasi-inert environment. The formation of reconnection regions – that is, of the necessary thin current sheets – may occur over long build-up times. The onset of reconnection can thus have a quasi-explosive character and lead to a rapid release of magnetic energy stored during the preparatory process. However, in some situations reconnection can also be essentially stationary. Since cosmic plasmas outside stellar interiors, dense atmospheres, and dense molecular clouds are essentially collisionless and highly conducting, reconnection is the most striking transformation process of magnetic configurations and the most powerful conversion process of magnetic into kinetic energy in the magnetic regimes around stars and in interstellar space. Magnetic reconnection is, however, also a necessary ingredient of the dynamos that act in the slow plasma flows in stellar interiors.

Reconnection is conceptually not a difficult process. The main controversy has been not so much its existence in highly conducting fluids, but its speed or efficiency. Postulated in the late 1940s, it took three decades to verify its existence in space and two decades more to derive an understanding of the microphysical origin of its efficiency. Although it was first proposed in an attempt to explain the sudden energy release in solar flares, it was the direct access to reconnection situations in the laboratory and in space that laid the foundations of its acceptance by the wider community of plasma physicists and astrophysicists, and it was thanks to the rapidly developing art of computer simulations during the last two decades of the twentieth century that led to a deeper understanding of the microprocesses involved. Reconnection is fundamental to the energetics and dynamics of the solar corona, which is the source of the plasma and magnetic fields that fill the heliosphere. Reconnection also plays a key role in transferring energy from the solar wind flow to planetary magnetospheres and atmospheres. It is thus the most important ingredient of solar–terrestrial physics. Although it is most familiar in the high-beta plasmas of corona, magnetopause, and magnetotail, a modified form of reconnection occurs in the very low-beta plasmas ($\leq 10^{-4}$) at the bottom of the corona or planetary magnetospheres. However, in this context the term "reconnection" has been mostly avoided: although magnetic connections are broken and magnetic energy is released, terms such as "auroral acceleration," "thawing" of field lines, and "magnetic fractures" tend to be used instead.

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This chapter attempts to trace the evolution of the understanding of the concept of reconnection from the first conjectures, via the growing body of evidence, to the present-day analysis of the relevant microprocesses. After looking at the early history and the development of basic reconnection configurations on the Sun and in the magnetosphere, we turn to the growth of indirect and direct evidence of its existence and to the insights gained from specifically designed reconnection experiments in the laboratory and from numerical simulations. Finally, we return to our point of origin, the application to the Sun. There are still many unanswered questions, and controversies are still debated. However, the foundations for a successful interpretation of some of the most striking phenomena on the Sun and in near-Earth space have become increasingly solid, and applications to distant cosmic phenomena are gaining credibility. The author is grateful for having been an observer and participant, although not in the front row, of the exciting quest for a thorough understanding of this powerful and yet elusive process.

THE EARLY HISTORY: FROM GIOVANELLI TO PETSCHEK

In a *Nature* article of 1946, Donald G. Giovanelli (1946) proposed a theory of solar flares according to which electrons accelerated by induction electric fields near magnetic neutral points excite the optical emissions of chromospheric atoms. He assumed that a discharge takes place because, with increasing energy, the electrons undergo fewer collisions. Consequently, he proposed the existence of very high current densities. Cowling (1953) heavily criticized Giovanelli's and Hoyle's (1949) subsequently developed ideas on the grounds that this implied current sheets a few meters in width "which cannot by any stretch of

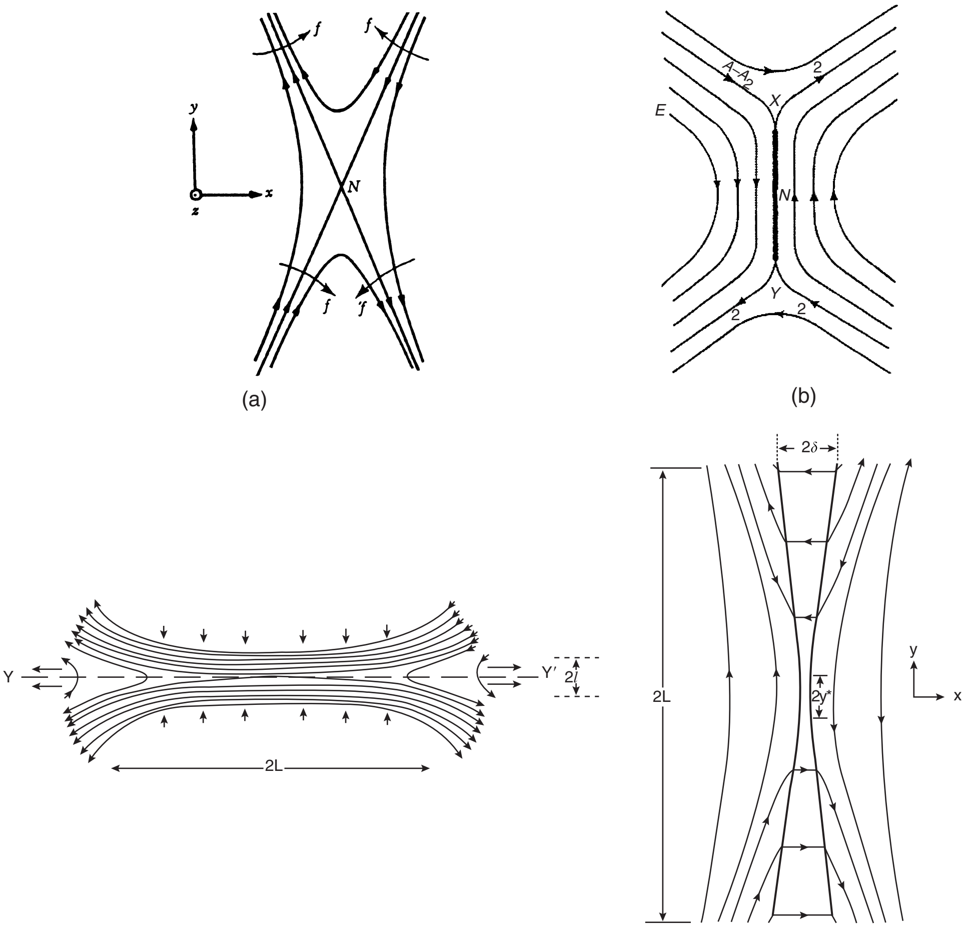

Figure 1 (a) The direction of the magnetic force, *f*, near a neutral point, N. (After Dungey 1958.) (b) The collision layer. (After Sweet 1958.) (c) Schematic of a reconnection configuration. (After Parker 1963.) (d) Petschek's solution: a small diffusion region with standing slow shocks attached. (After Petschek 1964.)

imagination be regarded as a possible thickness of a flare layer." He further concluded that "the discharge is not a regular one, but an irregular dissipation of energy in a violently twisted field." He then asked how the field can become so heavily twisted. The electromagnetic forces may well be there. "But induced currents, whose effect is always to oppose the changes to which they are due, smother the effect which was sought and leave only an unsatisfactory vestige of it remaining." This argument of Cowling, in which he invoked Lenz's law, was disputed by Hoyle's student Jim Dungey (1958), who showed that near neutral points Lenz's law is reversed: that the magnetic force density, $\boldsymbol{f} = \mathbf{j} \times \mathbf{B}$ (Figure 1), "tends to compress the material and field in the x-direction and stretch them in the y-direction. Since this motion reduces the acute angle between the limiting lines of force at N, it seems probable that it increases the current density." He added, "While a rigorous investigation is lacking, then, the indications are that the pressure gradient cannot prevent the discharge."

Dungey's ideas were taken up by Sweet (1958), who concluded that the magnetic forces would flatten the field and form a thin "collision layer," as shown in Figure 1b. In analogy to the hydromagnetic situation, he considered two plates being forced together, calculated correctly the outflow velocity, and investigated the dissipation of magnetic energy by Joule heating in the current layer of decreasing thickness. It was Parker (1957, 1963) who, inspired by Sweet's work, posed the reconnection problem in the simplest possible terms, at the same time drawing attention to the fact that none of the then "known mechanisms are sufficiently rapid to account for the solar flare from the annihilation of magnetic fields." And he was concerned that "there appears to be some popular belief that the necessary annihilation of magnetic fields has been accounted for by quantitative theory." In his papers he elaborated quantitatively on the existing difficulties, the most striking of which was the *rate* of reconnection. This can be derived immediately from Parker's famous set of relations. With $2l$ as the width of the current sheet in Figure 1c and $2L$ its length, conservation of mass yields

$$v L = V l \tag{1}$$

where v is the speed of magnetic field merging and V the efflux velocity, which from pressure equilibrium across the neutral sheet must be the Alfvén speed:

$$V = \frac{B_0}{\sqrt{\mu_0 \rho}} = V_{\mathrm{A}} \tag{2}$$

where B_0 is the upstream magnetic field. According to Sweet and Parker, magnetic diffusion controls the merging speed v:

$$v = \frac{D_{\mathrm{m}}}{l} \tag{3}$$

where D_{m} is the magnetic diffusivity,

$$D_{\mathrm{m}} = \frac{\eta}{\mu_0} \tag{4}$$

and η is the electrical resistivity. Combining eqns (1)–(4) provides an expression for the merging or reconnection rate in terms of the Alfvénic Mach number:

$$M_{\mathrm{A}} = \frac{v}{V_{\mathrm{A}}} = R_{\mathrm{m}}^{-1/2} \tag{5}$$

where $R_{\mathrm{m}} = V_{\mathrm{A}} L / D_{\mathrm{m}}$ is the magnetic Reynolds or Lundquist number. The difficulty, which Parker pointed out and which exists still today (see, e.g., Biskamp 1993), is that for current sheets of macroscopic length L, R_{m} tends to be a very large number in space and solar plasmas, and the reconnection rate v or M_{A} is very small, much too small to account for the fast energy release in solar flares.

The solution came from Petschek (1964), in a paper he presented at the AAS–NASA symposium on the physics of solar flares in 1963. As shown in Figure 1d, he attached standing hydromagnetic waves to a diffusion region of length y^*, much shorter than the length L of the overall reconnection situation. He determined y^* to be

$$y^* = \frac{D_{\mathrm{m}}}{v_{\mathrm{A}} M_{\mathrm{A}}^2} \tag{6}$$

whereby the merging rate, M_{A}, is considered as an externally controlled parameter. His theory then provides a maximum possible flow rate, which (with a correction by a factor of $\frac{1}{2}$, found by Vasyliunas (1975)) is

$$M_{\mathrm{A,max}} = \frac{\pi}{8 \ln(2 M_{\mathrm{A,max}}^2 R_{\mathrm{m}})} \tag{7}$$

So, Parker's merging rate, which depends inversely on the square root of R_{m}, has now been replaced by a logarithmic dependence. Even with $R_{\mathrm{m}} = 10^{10}$, maximum merging rates of 0.05 appear to be possible. "The principal effect of including the wave propagation mechanism is to reduce the length over which the diffusion mechanism must operate," wrote Petschek. With this reduced length, Parker's relation (eqn (3)) is still valid.

The two waves attached to the diffusion region are slow mode shocks which nearly switch off the tangential field component. They propagate with the Alfvén speed based on the normal magnetic field component. Thus

$$\frac{B_{\mathrm{n}}}{B_0} = M_{\mathrm{A}} \tag{8}$$

These waves are dissipative, and the pressure increases across the shock so as to maintain continuity of the total (gas plus magnetic) pressure.

As pointed out by Vasyliunas (1975), Petschek's solution requires a convergent flow toward the diffusion region (Figure 2). The magnetic field strength is thus lowered in the region immediately upstream of the diffusion region. Here the Alfvén speed is lower than it is farther away. Since the Alfvén Mach number must not exceed unity just outside the diffusion region, it follows that the merging rate must be less than unity. This conclusion, however, depends on Petschek's assumption that the magnetic field far upstream is homogeneous. Other boundary conditions can produce even higher merging rates.

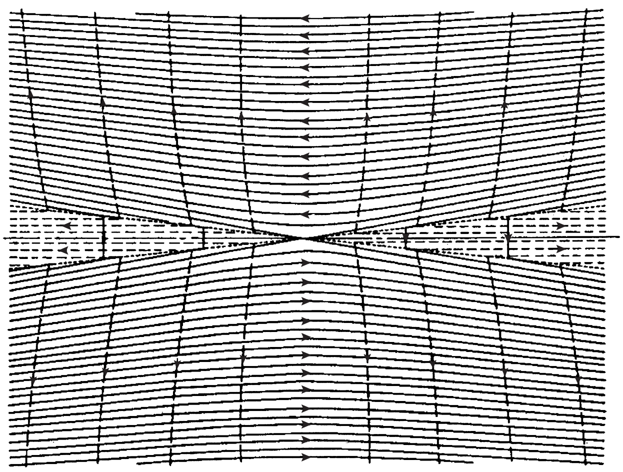

Figure 2 Convergent flows in the Petschek solution. (After Vasyliunas 1975.)

Petschek's (1964) paper constituted a major breakthrough in the theory of reconnection and in plasma astrophysics generally. Several alternate models producing even higher reconnection rates were subsequently presented, for instance by Sonnerup (1970) and Yeh and Axford (1970). Their solutions are basically similarity solutions in that, at scales between that of the diffusion region (considered to be nearly zero) and the external scale L, the magnetic field and flow velocity depend only on the ratio x/y of the two relevant coordinates. These and other models have been critically analyzed by Vasyliunas (1975). The outcome was:

> Neither Petschek's model nor the similarity model predicts a definite merging rate. In both models the speed of plasma inflow (v) is, within limits, a free parameter whose value is assumed to be determined by the boundary conditions; the merging rate fixes the dimensions of the diffusion region in terms of the appropriate microscopic length scale, but neither resistivity nor inertial effects have any influence upon the models outside the reconnection region.

The microscopic length scales Vasyliunas was referring to arise from the various terms of the generalized Ohm's law and are the resistive length, D_m/v_A, and the ion inertial length, c/ω_{pi}, or the electron inertial length, c/ω_{pe}. In a later section we return to the role of these scales in the so-called diffusion region according to present-day understanding.

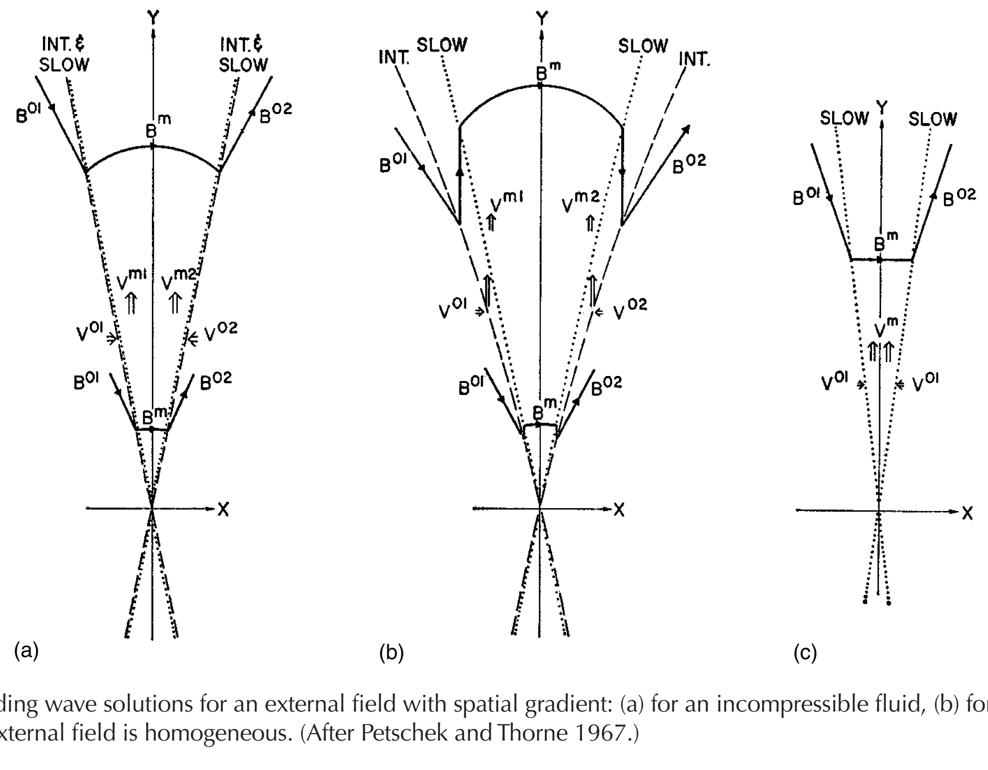

Figure 3 Standing wave solutions for an external field with spatial gradient: (a) for an incompressible fluid, (b) for a compressible one. In (c) the external field is homogeneous. (After Petschek and Thorne 1967.)

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