Magnetic Reconnection and Physical Concepts

Michel Roth
Institut d'Aéronomie Spatiale de Belgique, Bruxelles, Belgium

Abstract:

This report is an attempt to clarify the physical concepts on which fluid magnetic reconnection is based. It appears that the theoretical structure is not built on a solid foundation. The concept of Magneto-Fluid-Dynamic does not give rise to a unique physical process but leads to different models of magnetic reconnection resulting from the fine-tuning of the Generalized Ohm's law.

1. Introduction

Magnetic reconnection is widely admitted by most space researchers as an important *plasma process* capable of expeditiously converting enormous amounts of magnetic energy to both thermal energy and bulk acceleration of the plasma, and also for changing the global topology of the magnetic field (e.g., *Parnell* [2000]).

A precise *definition* of magnetic reconnection is not easy to give. But do we actually have to define what most space researchers consider as a *physical process*? The term *definition* by itself means that we are looking for an enumeration of characteristics, which helps the mind to construct a mental representation of an abstract object or process. A definition tells us nothing about the *realness* of the object or process we try to characterize (after all we can give a enumeration of characteristics to define a little green man living on Mars). We can however define *physical concepts* on which *physical processes* are based (for instance the physical process of *Joule heating* is based, amongst others, on the physical concept of *energy*). The characteristics of a physical concept confer it a *scale of usefulness*. The physical concepts with the highest scale of usefulness in physics are also the most fundamental ones: mass, space-time, energy, … As the quest for an understanding of the physical world is a difficult task it is not surprising that misleading physical and astronomical concepts were often introduced in science to explain observations of the real world: the erroneous concept of geocentrism dominated astronomy for more than a millennium while the concept of ether did not resist to the accurate observations made by Michelson and Morley in order to measure speed of the ether relative to Earth. Quite often these misleading concepts led to more and more complex models like those developed by Ptolemy to explain the motion of the planets. Ptolemaic astronomy was based on combinations of epicycles whose complexity increased each time a new observation contradicted the predominated model. When these erroneous concepts were abandoned the observations were not only correctly explained but the new models used to describe the underlying physical processes appeared simpler and aesthetically more elegant.

2. The physical concepts on which magnetic reconnection is based

To describe magnetic reconnection as a physical process one should clearly define the physical concepts on which reconnection is based. As there are only a limited number of concepts in physics one should avoid introducing new ones, or at least avoid introducing new ones with a weak value in the scale of usefulness.

Although there exists a kinetic approach to magnetic reconnection (e.g., *Hill* [1975], *Galeev et al.*, [1986]), most of the reconnection models are based on the concept that space plasmas behave like regular fluids and are well described under the Magneto-Fluid-Dynamic approximation. In this approximation the state of the plasma is represented by local macroscopic properties, which depend on position in space **r**, and on time *t*.

Magnetic reconnection also relies on the concept of magnetic field lines. It is useful to recall that field lines were used by Faraday to assist visualization of the magnetic force on small magnets (this is why these lines are sometimes improperly called *magnetic lines of force*). Nowadays field lines are used as a support to visualize the direction and strength of the magnetic field in space *under time independent conditions*. In space plasmas the *mathematical concept of field line motion* relies on its association with a flow field [*Newcomb*, 1958]. The time rate of change of the magnetic flux Φ piercing the closed curve $C(t)$ with local normal **n**, linked to a set of fluid elements moving with the velocity field **u** (which transports $C(t)$) is [*Scudder*, 1997]:

$$\frac{d\Phi}{dt}\Big|C = -\iint_S \nabla \times (\mathbf{E} + \mathbf{u} \times \mathbf{B}) \cdot \mathbf{n}\, dS$$

When the magnetic flux through any circuit "attached" to the fluid and moving with it remains constant in time, the flow field of the fluid is said to be *magnetic flux preserving*. Flow fields $\mathbf{V_1}$ are magnetic flux preserving if:

$$\nabla \times (\mathbf{E} + \mathbf{V_1} \times \mathbf{B}) = 0 \qquad (1)$$

while flow fields $\mathbf{V_2}$ satisfying the more restrictive condition

$$\mathbf{E} + \mathbf{V_2} \times \mathbf{B} = 0 \qquad (2)$$

are said to be *field line preserving*. In flows that are field line preserving fluid elements connected by a field line at some time remain so later on. Flows that are field line preserving are also magnetic flux preserving. Flow fields that are line preserving or only magnetic flux preserving are not necessarily the center of mass flow of the plasma ($\mathbf{U}$). Ideal MHD is a fluid representation of the plasma where the center of mass flow, $\mathbf{U}$, obeys equation (2). In this representation $\mathbf{U}$ is then a type of flow, which is both magnetic flux and magnetic line preserving. In ideal MHD it is possible to ascribe a velocity to the magnetic field lines since the velocity in equation (2) is field line preserving. In the real world the velocity of a magnetic field line can not be unambiguously defined and, therefore *is not a measurable quantity, so that it is, strictly speaking, meaningless to talk about it* (citation from *Newcomb* [1958], page 348).

Equation (2) represents only a portion of the difference between the ion and electron momentum equations. The generalized Ohm's law results from this difference and is obtained in the Magneto-Fluid-Dynamic approximation by treating electrons and protons as two independent fluids with their own number density (n_e and n_i) and own species-velocity ($\mathbf{V_e}$ and $\mathbf{V_i}$). These two fluids are coupled by a friction force equals to $-n_e m_e \nu (\mathbf{V_e} - \mathbf{V_i})$ for the electrons and, by action-reaction, to an opposite force for the ions [*Heyvaerts*, 2000]. Neglecting gravity the equations of motion of electrons (of charge -*e* and mass m_e) and protons (of charge *e* and mass m_i) can be written in the following form:

$$\mathbf{E} + \mathbf{V_e} \times \mathbf{B} = -\frac{\nabla \cdot \mathbf{P_e}}{e n_e}$$

$$-\frac{m_e}{en_e}\left(\frac{\partial n_e\mathbf{V_e}}{\partial t}+\nabla\cdot(n_e\mathrm{V_e V_e})\right)+\frac{m_e\nu}{n_e e^2}\mathbf{j} \quad (3)$$

$$\mathbf{E}+\mathbf{V_i}\times\mathbf{B}=+\frac{\nabla\cdot\mathbf{P_i}}{en_i}$$

$$+\frac{m_i}{en_i}\left(\frac{\partial n_i\mathbf{V}_i}{\partial t}+\nabla\cdot(n_i\mathrm{V_i V_i})\right)+\frac{m_e\nu}{n_i e^2}\mathbf{j} \quad (4)$$

where $\mathbf{P_e}$ and $\mathbf{P_i}$ are ordinary pressure tensors, $m_e n_e\mathbf{V_e V_e}$ and $m_i n_i\mathbf{V_i V_i}$ are dynamic-pressure tensors, and $\mathbf{j}$ is the electric current density, $\mathbf{j}=-n_e e(\mathbf{V_e}-\mathbf{V_i})$, in the quasi-neutrality approximation.

The Generalized Ohm's law, which relates the electric field in the plasma to other field and plasma quantities, can be obtained with different levels of approximations (for details see chapter 12 in *Rossi and Olbert* [1970]). An approximate form is obtained by multiplying equation (3) by $-e/m_e$ and equation (4) by e/m_i and subtract. It simplifies in the limit of infinitely heavy protons ($m_e/m_i \to 0$) and in the quasi-neutrality approximation:

$$\mathbf{E}+\mathbf{U}\times\mathbf{B}\approx$$

$$\frac{\mathbf{j}\times\mathbf{B}}{en_e}-\frac{\nabla\cdot\mathbf{P_e}}{en_e}+\frac{m_e}{m_i}\frac{\nabla\cdot\mathbf{P_i}}{en_i}+$$

$$\frac{m_e}{n_e e^2}\left(\frac{\partial\mathbf{j}}{\partial t}+\nabla\cdot(\mathbf{Uj}+\mathbf{jU})\right)+\frac{m_e\nu}{n_i e^2}\mathbf{j} \quad (5)$$

The last term of the second member of equation (5) can be written to contain the "ordinary" Ohm's conductivity $\sigma=n_i e^2/m_e\nu$ as $\mathbf{j}/\sigma$. The phenomenological frictional parameter ν is usually calculated by the Fokker-Planck method of treating Coulomb collisions in a plasma. This approach is only valid when restricted to large-scale properties of the plasma larger than the Debye length and assumes 1) an infinitesimal smallness of the Coulomb interaction time Δt and, 2) a certain conditional smallness of the velocity changes occurring as a result of collisions in the time interval Δt. Because of the screening effect of the plasma the Coulomb interaction between two particles is actually limited to a range of the order of the Debye length, typically 1 m at the magnetopause, with typical particle velocities of 100 km/s, $\Delta t \approx 10^{-5}$ s, which is small enough in comparison with the various relaxation times of the system. The second condition is equivalent to the neglect of close Coulomb collisions. This condition is also satisfied since multiple scattering in the Coulomb interaction is much more important than single scattering. Besides the ohmic $\mathbf{j}/\sigma$ term there are additional contributions to the momentum exchange between protons and electrons called the thermal force emf that can be present even in the absence of a current density (for details see *Scudder*, [1997], page 251). These contributions are usually ignored.

The Magneto-Fluid concept implies that flow fields satisfying equation (2) describe super-conductor plasmas, in the electric sense of absolute zero resistivity (or infinite conductivity): this is the ideal MHD representation, a limiting case of the usual Ohm's law of MHD ($\mathbf{u}$ being the velocity field of the "fluid"):

$$\mathbf{E}+\mathbf{u}\times\mathbf{B}=\frac{\mathbf{j}}{\sigma} \quad (6)$$

The ideal MHD equation (2) also implies that there is no electric field component along the magnetic field direction. The generalized Ohm's law [equation (5)] shows that the preserving character of magnetic field line and magnetic flux not only requires the neglect of the ordinary ohmic dissipation term ($\mathbf{j}/\sigma$), but also implies that the contributions of the Hall electric field, pressure gradients and inertial terms cancel out. Broadly speaking magnetic reconnection involves loss of the line or flux preserving character of the plasma flow [*Scudder*, 1997] and may occur at places where the magnetized plasma locally develops strong field gradients and associated dissipative MHD motions. In the framework of the Magneto-Fluid-Dynamic magnetic reconnection may appear as a physical process with multiple facets. The physical process may differ from one situation to another depending on which term in the generalized Ohm's law plays the most important role in breaking down the ideal MHD condition. This is a situation quite similar to the Ptolemaic system: an additional epicycle (additional term in the Generalized Ohm's law) is added each time an observation contradicts a predominated model. The excellent review paper by Scudder [*Scudder*, 1997] shows that frequently the approximations made in Ohm's law are more those of convenience than physically justified. Furthermore the breakdown of ideal MHD is not a sufficient condition for magnetic reconnection to occur. For instance ideal MHD is obviously broken along auroral magnetic field lines where parallel pressure gradients and the unbalanced mirror force lead to the formation of parallel electric fields.

3. Open questions

For more than 40 years an extensive research has been made on magnetic reconnection. Despite the tremendous existing amount of literature on the subject many questions remain:

1. Most of the reconnection models assume the existence of a *diffusive region* where ideal MHD breaks down. The physical processes in this region are different for electrons and for ions. The microphysics in this region remains poorly understood.
2. The role of plasma beta is not clearly identified.
3. We know little about the *spark* that ignites magnetic reconnection [*Drake*, 2001]. Many mysteries persist, as for instance, the fact that in solar active regions the magnetic field can remain quiescent for a long time before releasing its energy (it is believed that magnetic reconnection is a universal physical process, therefore occurring also in the solar corona).
4. Does the magnetic shear play a role in the ignition process?
5. Steady-state models of magnetic reconnection at the dayside magnetopause have been developed in a 2-D geometry. They imply a uniform reconnection electric field, $\mathbf{E}$, aligned along a X-type magnetic neutral line, but also along the magnetopause current to allow for the heating and acceleration of the plasma. The question of maintaining such a $\mathbf{E}$-field remains open. Models of 3-D reconnection require the existence of *magnetic neutral points* and are still under debate [*Parnell*, 2000].
6. Transient magnetic reconnection must include the energy input from the time-dependent terms in the energy equation by appealing to Poynting's theorem, where $\mathbf{E}\cdot\mathbf{j}$ describes the net effect on or by the plasma [*Heikkila*, 1998].
7. Models for transient reconnection are still under development.

4. Signatures of magnetic reconnection

It is outside the diffusion region where ideal MHD is believed to hold that, until recently, signatures of magnetic reconnection have been looked for. This inquiry is based on tests to verify the Walén relation for a rotational discontinuity. It is important to note that the identification of a rotational discontinuity (RD) does not necessarily provide evidence for ongoing reconnection. RDs are frequently observed in the solar wind as one of possible MHD discontinuities without resorting to the context of reconnection. Furthermore WIND observations of directional discontinuities (DDs) in the solar wind have shown that DDs with small normal magnetic field can be regarded as the limiting case of tangential discontinuities (TDs) [*De Keyser et al.*, 1998]. Using a kinetic model of TDs [*Roth et al.*, 1996], *De Keyser and Roth* [1997, 1998a, 1998b] have demonstrated that, contrary to the general belief, plasma flows on both sides of a TD are not unconstrained. Indeed these authors have shown that, at the TD magnetopause, not all configurations of magnetic field vectors and magnetosheath velocity allow an equilibrium to exist and that there is a preference for a particular magnetic field rotation sense across the magnetopause. This study has demonstrated a north-south asymmetry of the rotation sense for high magnetic shear TDs: large positive (negative) rotations occurring predominantly in the northern (southern) hemisphere. It is interesting to note that the north-south asymmetry of the rotation sense for high magnetic shear TDs is the same as the one predicted by the electron whistler polarization theory for wide RDs [*Su and Sonnerup*, 1968]. Two other important conclusions of this study are worth emphasizing: the first is a better understanding of satellite observations showing that the magnetopause sometimes is in a TD state even in configurations where one would expect reconnection to occur, for instance in ≈180° magnetic shear cases; the second one is a demonstration that high-speed flows, regarded as the signature of magnetic reconnection, are also required for high magnetic shear TD equilibria.

5. Conclusions

When trying to clarify the physical concepts on which magnetic reconnection are based it appears that Magneto-Fluid-Dynamic is not the best framework for studying reconnection. One can attribute to this concept a weak *scale of usefulness* that may invalidate the whole theoretical structure. Fluid description of magnetic reconnection is like the Ptolemaic system where one hopelessly tries to fine-tune the Generalized Ohm's law to correctly explain puzzling observations. Space researchers have often disregarded early laboratory experiments showing that plasma streams injected perpendicularly to a magnetic field can cross the field by setting up a polarization electric field (e.g., *Baker and Hammel* [1965]). This polarization effect was explained theoretically by *Schmidt* [1960]. Schmidt's work is the basis of the model of impulsive penetration (IP) introduced by *Lemaire and Roth* [1978] and ultimately developed by *Lemaire* [1985]. Isolated magnetosheath-like plasma blobs have been observed in the boundary layer but a definitive experimental confirmation of the IP scenario requires at least two satellites. Favorable configurations of Cluster satellites could happen where the trajectory of the penetrating plasma blob would be "recorded" using a method developed by *De Keyser et al.* [2002].

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