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Reconnection at the Earth's magnetopause: observational evidence and outstanding questions

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Abstract. Observations suggest that solar wind energy and mass is transferred to the Earth's magnetosphere in a continuous manner. Such a constant energy transfer is at the basis of the highly dynamical state of the magnetosphere-ionosphere system. Perturbations in the near Earth space due to solar wind magnetosphere interaction are capable to influence human activities to the point that in the last years great efforts have been done in order to enhance prediction capabilities in the framework of the Space Weather discipline. Various processes have been proposed to account for the transfer of mass and energy across the Earth's magnetopause, but it is thought that the greater part of this energy is transferred through the magnetic reconnection process. Also, theoretical models for this process have been developed that permit to test its occurrence at the Earth's magnetopause by in situ measurements. Nevertheless, severe questions remain open both on the microphysics of the process and on the large scale configuration of its occurrence at the terrestrial magnetopause. Here we discuss the observational evidence of the reconnection at the magnetopause, the outstanding questions about this process and the future perspective as far as its complete comprehension is concerned.

Key words. Magnetic Reconnection; Magnetopause

1. Magnetic Reconnection

Collisionless space plasmas behaviour can be described by MHD theory, so that the induction equation holds: $\partial\mathbf{B}/\partial t=\nabla\mathrm{x}(\mathbf{U}\mathrm{x}\mathbf{B})+D_B\nabla^2\mathbf{B}$. Here $\mathbf{U}$ is the plasma bulk velocity and D_B is the *magnetic diffusion coefficient* ($D_B=\eta/\mu_0$, where η is the plasma resistivity). The relative importance between the convection term, $\nabla\mathrm{x}(\mathbf{U}\mathrm{x}\mathbf{B})$, and the diffusion term $D_B\nabla^2\mathbf{B}$, is expressed by the *magnetic Reynolds number*, $R_m\sim\mathrm{L}\mathbf{U}/D_B$ where L is the characteristic length of the variation of the magnetic field. Being R_m generally very large for space plasmas, the frozen-in-flux condition holds to a very high accuracy: plasma cannot mix across

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different flux tubes, but only along them. Two interacting plasmas, characterized by different magnetic topology, cannot diffuse into each other and a thin current sheet will develop, across which the magnetic field topology changes. When the solar wind plasma, carrying the interplanetary magnetic field (IMF), arrives in the vicinity of the Earth, the geomagnetic field deflects it and a thin current sheet, separating the dense and cold solar wind from the tenuous magnetospheric plasma dominated by the geomagnetic field, is formed: the terrestrial *magnetopause*. Solar wind cannot freely enter the magnetosphere across the magnetopause and this is generally true, apart from two narrow regions where the magnetic field topology resembles a throat (the magnetospheric *cusps*). Even if the majority of solar wind plasma does not enter the magnetosphere, observations show that a boundary layer of magnetosheath like plasma can be found just inside all regions of the magnetopause. On the other hand magnetospheric particle are often observed in the magnetosheath outside the magnetosphere. This means that solar wind mass, momentum and energy are constantly being transferred to the Earth magnetosphere, across the magnetopause, through some process taking place right at the magnetopause. Actually, in a narrow current sheet, like the Earth's magnetopause, can be places where L is small. There, R_m becomes small and the magnetic diffusion becomes important; the geomagnetic field and the interplanetary magnetic field loose their identity in this *diffusion* region and can merge or reconnect. Then, there will be a class of magnetic field lines connected to the Earth at one end and to the distant interplanetary magnetic field at the other so that, along them, plasma can flow across regions with different magnetic field topology: this is the magnetic reconnection process (Vasyliunas , 1975). The intersection between the surfaces separating the interplanetary fields lines, the reconnected field lines and the closed field lines is the reconnection X line. All the reconnection models presume the existence of a diffusion region where the frozen-in condition breaks down and magnetic field reconfigures. Outside the diffusion region MHD holds. Due to the conservation of mass and momentum balance, the efficiency of the reconnection depends on the efficiency with which the plasma is ejected from the diffusion region. The effectiveness of the process is expressed by the reconnection rate, defined as the Alfvén Mach-number $M_A = v_{in}/v_A$ in the inflow region. In the Sweet-Parker model (Parker, 1957) the length of the diffusion region corresponds to the total system size. For this model, all the plasma involved in the reconnection process has to go through the diffusion region and the reconnection rate is rather low, in contrast with the observations. According to the Petschek (1964) model, instead, the diffusion region, where the actual process of reconnection takes place, is vanishingly small, two slow mode shock waves connected to the diffusion region accomplish the rotation of the magnetic field across the separation surface and most of the plasma involved in the reconnection is accelerated out through these shock waves, without entering the diffusion region. Priest & Forbes (1986) developed the general solution for steady state MHD reconnection in which boundary conditions are generalized. The most appropriate model for the reconnection at the subsolar magnetopause is the asymmetric model of Levy et al. (1964). It is a steady, two-dimensional model similar to the Petschek model, but it takes into account the very different upstream (dense, cold plasma, weak magnetic field) and downstream (hot, dilute plasma, strong magnetic field) conditions. In the next sections the observational facts supporting the occurrence of the reconnection process at the magnetopause will be described and afterwards a review of the still unresolved issues on this subject will be given. Much of this material has been drawn from Sibeck et al. (1999) and Haerendel &

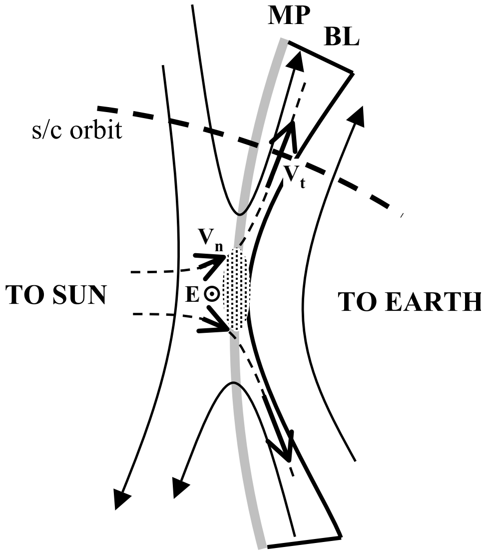

Fig. 1. Schematic meridional view of reconnection at the subsolar magnetopause (adapted from Paschmann et al. (1979).

Paschmann (1982) to which the reader is referred for further details.

2. Observational evidence

Different plasma transfer processes have been proposed to take place at the magnetopause. The reconnection process differs from the others because, although it occurs at a very narrow region in the magnetopause surface, once the interplanetary and geomagnetic fields become interconnected, global effects are produced in the magnetosphere-ionosphere system. On the other hand, the reconnection model has been developed to the point that several testable predictions can be done as far as in situ measurements are concerned. Here, we will first describe evidences of reconnection which are observed right at the magnetopause and next the ones which are considered indirect evidences, relating to the large-scale magnetospheric phenomena caused by reconnection.

In 1 the spot at the subsolar magnetopause where reconnection is occurring in case of southward IMF is illustrated according to the Levy et al. (1964) model. Five discontinuities (not shown) are introduced in the model to match the upstream and downstream conditions. The magnetopause (light grey region) is the outermost of the five and can be described as a rotational discontinuity (RD): a current layer across which the tangential field changes direction by an arbitrary angle, with a normal magnetic field component across it and a finite mass flux along its normal. The diffusion region is evidenced. Plasma of solar wind origin flows across the magnetopause and forms a boundary layer on the magnetospheric side of the magnetopause; the bent in the newly interconnected field lines leads to the acceleration of these plasma along the magnetopause. Therefore evidence for reconnection would be: the existence a normal component of the magnetic field, B_n, across the magnetopause (positive if observations are made north of the diffusion region, negative south of it); the existence of an inward directed plasma flow V_n; the existence of a tangential electric field, $\boldsymbol{E}_t$, consistent with the motion of the plasma towards and across the magnetopause; plasma acceleration along the magnetopause in the boundary layer. The normal components B_n and V_n and the tangential electric field $\boldsymbol{E}_t$ are usually too small to be measured reliably, so the only mark of reconnection remains the plasma jets which, in general, are expected to be quite large. As a results of tangential Maxwell stress at a one-dimensional, steady rotational discontinuity, the tangential momentum of the plasma changes, from one side to the other, according to a strict quantitative relationship (Hudson, 1970):

$$\Delta \mathbf{V} = \pm \Delta \mathbf{V}_A \tag{1}$$

where $\mathbf{V}_A$ is the Alfvén velocity and the ± sign depends on whether the observations are made north or south the reconnection point. Therefore, in situ evidence of reconnection comes from the observations of accelerated flows which obey the above re-

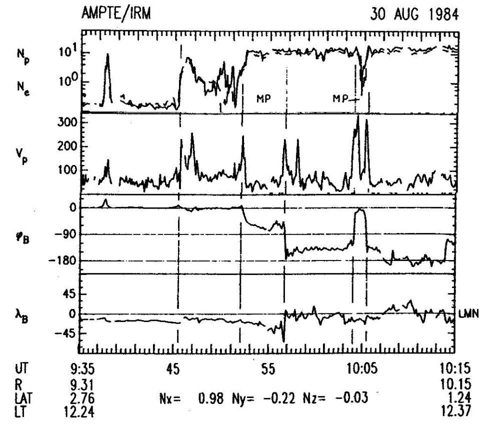

Fig. 2. Outbound crossing of the terrestrial magnetopause by AMPTE spacecraft (adapted from Paschmann et al. (1986). At each magnetopause crossing, identified by magnetic field rotation from northward ($\phi_B \sim 0$, in the magnetosphere) to southward ($\phi_B \sim 180$, in the magnetosheath) accelerated flows are observed.

lation, referred to as the Walén test. The first observations of high speed flows which could unambiguously be attributed to magnetic reconnection at the magnetopause, were made by Paschmann et al. (1979) with ISEE spacecraft. As an example, in 2 the proton density and bulk velocity together with magnetic field orientation, expressed by the azimuthal and elevation angles, are shown for an outbound magnetopause crossing of the AMPTE satellite: at every magnetopause crossing accelerated flows are observed (Paschmann et al., 1986). Since then, several other observations of plasma jets due to reconnection have been made at the dayside magnetopause.

Another signature of magnetic reconnection can be found in the particle distribution functions. During reconnection particles enter the boundary layer along magnetic field lines, because of the flux-tube motion along the magnetopause imposed by reconnection only those particles with velocities greater than the flux-tube velocity will be able to enter the boundary layer.

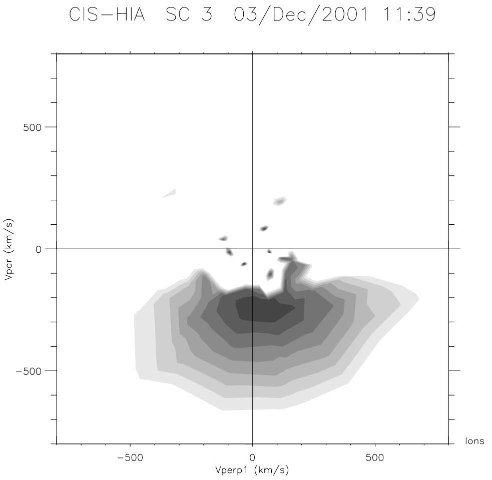

Fig. 3. Cut of the ions three dimensional distribution function in the B-V plane as measured by s/c 3 of the Cluster mission during a reconnection event.

This results in the so called 'D'-shaped distribution functions (Cowley, 1982; Fuselier et al., 1991). An example of such a distribution is shown in 3 where the proton distribution function as measured by one of the Cluster spacecrafts is plotted in the plane containing the magnetic field vector and proton bulk velocity during a reconnection event. It is evident that the velocity parallel to the magnetic field shows a threshold at about 150 km/s.

Even if the actual spatial configuration of the reconnection at the magnetopause and its temporal evolution is still a matter of debate (see section 3), once the IMF and geomagnetic field lines become interconnected the solar wind is able to communicate its momentum through the magnetosphere and down to the ionosphere and energetic particles get direct access to low altitudes. Uniform bombardment by solar energetic electrons of the polar cap region strongly support the hypothesis that all the polar cap field lines extend in the solar wind, otherwise solar electrons could access these field lines by cross-field diffusion resulting in a depleted central polar cap precipitation. Once the reconnection has occurred, the newly interconnected field lines remain in a highly bended configuration, so they begin to move over the magnetopause under the combined action of magnetic curvature force and pressure-gradient force that pushes solar wind past the magnetosphere. The motion of the interconnected lines does depend on the orientation of the IMF. This motion is transmitted down to the ionosphere through field aligned currents and results in the ionospheric plasma convection. Even if the observed anti-sunward ionospheric convection could be explained also by a viscous-type interaction between the solar wind and the magnetosphere, the magnetic curvature force which arises from reconnection is responsible for dawn-dusk convection asymmetries related to the IMF B_y component. This predicted asymmetries have been observed both in subsolar flow directions and at the field line footprints in the ionosphere (Gosling et al., 1990; Heppner & Maynard, 1987). The energy transferred from the solar wind to the magnetosphere, be it done by magnetic reconnection or not, is stored in the geomagnetic tail and released in an explosive manner during geomagnetic storm. It is thought that reconnection in the tail is once again the process for the release of this energy, but how the release process is initiated is still unknown. Historically the observational fact that geomagnetic activity depends on the IMF orientation (Fairfield & Cahill, 1966; Perrault & Akasofu, 1978) was considered the first evidence of reconnection at the magnetopause and gave for the first time strong support to the prediction of an open magnetosphere previously given by Dungey (1961).

3. Outstanding questions

Although a lot of different observations seems to support the occurrence of reconnection in the magnetosphere, the debate on whether this process actually exist or not is still vigorous. This is probably due to the fact that both theoretically and observationally it has not been found what really happens in the posited diffusion region. It can be considered as a sort of short-scale 'black box' where reconfiguration of the magnetic field takes place in some way we do not know. Nevertheless, it must be stressed that observations confirm that at some times the magnetopause is an RD, therefore somewhere reconnection has occurred or is occurring.

For reconnection to occur the frozen-in condition must be broken. In a two fluid quasy-neutral plasma the generalized Ohm's law holds:

$$\mathbf{E} + \mathbf{V} \times \mathbf{B} = \frac{1}{en}\mathbf{j} \times \mathbf{B} - \frac{1}{en}\nabla \cdot P_e + \frac{1}{\epsilon_0 \omega_{pe}^2}\frac{d\mathbf{j}}{dt} + \eta \mathbf{j} \qquad (2)$$

Here $\mathbf{V}$ is the ions bulk velocity, P_e is the full electron pressure tensor, n is the number density of both ions and electron and ω_{pe} is the electron plasma frequency. The left-hand side of this equation describes the frozen-in state. Each term on the right-hand side, usually neglected, describes a different process which could in principle be responsible for the breaking of the frozen-in condition and each of them have associated different scale length. The process with the largest scale length will dominate the breaking process (Sibeck et al. , 1999; Drake, 1995). The last term on the right-hand side is the resistive term. In collisionless plasma anomalous resistivity could be provided by instability processes. As far as the other terms are concerned they become more and more important as smaller length scales are considered. The first term on the right-hand side is the Hall term and becomes important on scale length smaller than the ion inertial length λ_i (for nominal magnetopause values $\lambda_i \sim 40$ km). At this scale the magnetic field remains frozen into the electron fluid only. If reconnection is accomplished by resistive or collisionless mechanism is still an important and unresolved issue. It seems that the Hall term in the generalized Ohm's law is anyway an

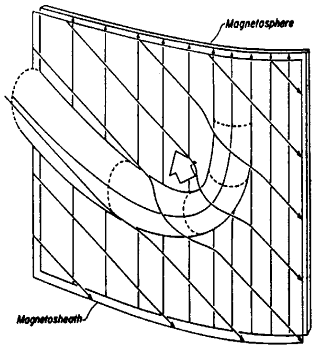

Fig. 4. Scheme of a *flux transfer events*: a bundle of interconnected field lines moves, under the magnetic tension, on the magnetopause surface.

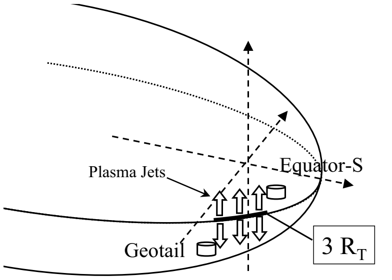

Fig. 5. Geotail and Equator-S satellites observed reconnection jets in opposite directions as they were skimming at the equatorial magnetopause.

important one: its inclusion in the simulations models seems to enable acceptable reconnection rates, irrespective of the specific mechanism which initiate reconnection (Birn et al., 2001). The scale size of the diffusion region will depend on the scale size of the reconnection mechanism: for collisionless reconnection it will be shorter than the ion inertial length, for resistive reconnection this length is not constrained a-priori. Only recently some observations have been claimed to pertain right to the diffusion region and seem to give evidence for collisionless reconnection (Oieroset et al., 2001).

Not knowing which is the actual process of reconnection, it follows that it is not possible to predict how it occurs at the Earth's magnetopause. Questions concern whether, depending on large-scale configuration at the magnetopause, it takes place in a quasi-stationary manner along an extended reconnection line, or, being controlled by local plasma conditions, is intrinsically transient and occurs in reconnection patches randomly distributed on the magnetopause surface. Both these two behaviour have been observed at the magnetopause. Evidence for sporadic small scale reconnection derives from in situ observations of bipolar signature in the B_n component. These are interpreted as the passage through the s/c of an isolated flux tube of interconnected field lines (see 4) which sweep the magnetosheath lines outside the magnetopause and the magnetospheric field lines inside it. These signatures are referred to as *flux transfer events* (FTEs) and were first observed by Russel & Elphic (1979). Sometimes, due to magnetopause motion, satellites experience multiple magnetopause crossings: they cross the magnetopause surface several times in a short period whilst they are moving on their outbound or inbound orbits. The persistence of plasma jets observed at every magnetopause crossing leads Paschmann et al. (1979) to conclude that reconnection was going on in a quasy-steady manner in that case. Of course single point measurements are intrinsically limited. Phan et al. (2000) revealed for the first time the presence of a rather stable and extended reconnection line along the equatorial magnetopause. The Geotail and Equator-S satellites simultaneously observed reconnection jets each time they crossed the magnetopause for a long time interval. Their position with respect the equatorial magnetopause (see 5) permits to infer that the reconnection line extended for at least 3 Earth radii.

Another unresolved issue is whether reconnection occurs only in case of strictly antiparallel magnetic fields or not. In the 'antiparallel merging' model (Crooker,

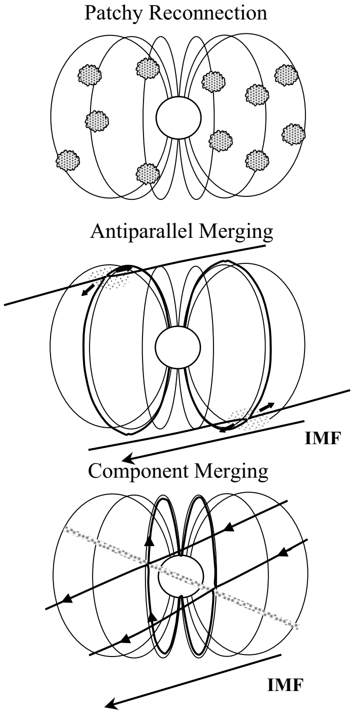

Fig. 6. Different predictions of reconnection locations at the dayside magnetopause.

1979; Luhmann et al., 1984) the magnetospheric and IMF magnetic fields can merge only if they are perfectly antiparallel. This model predicts an extended reconnection line along the dayside equatorial magnetopause only when the IMF is southward; if it has a large B_y component or is northward the predicted reconnection location moves to higher latitudes, equatorward or tailward of the cusps respectively. In the 'component merging' model (Gonzales & Mozer, 1974; Sonnerup, 1974) reconnection can occur even if the two magnetic field are not strictly antiparallel: as the IMF rotates northward the subsolar reconnection line will rotate depending on the sign of the B_y component. The different models predictions of the reconnection sites at the magnetopause are sketched in 6. To summarize, according to the observations reconnection can occur both sporadically, in localized reconnection sites sparse on the magnetopause surface, supposedly when local plasma conditions dominate, even when the IMF is northward (Nishida et al., 1989), or along reconnection lines whose orientation and extent depend on the orientation of the IMF magnetic field. Actually the relation between large and very small scale is still controversial, does the large scale boundary conditions determine the occurrence and rate of reconnection or the micro-processes affect the entire system? The study of a subset of Equator-S data gave evidence, for the first time, of a long lasting reconnection at the dawn flank magnetopause in which reconnection site moved readily following a rotation of the IMF magnetic field (Marcucci et al., 2000). In this case the reconnection occurrence was controlled by large scale conditions. Nevertheless, there have been observations of a locally closed magnetopause, even if the IMF magnetic field and the magnetospheric field were antiparallel (Papamastorakis, 1984). More efforts have to be done to clarify all these issues, both in theoretical predictions and in observations. Multispacecraft missions as Cluster promise to highlight on still unknown fundamental magnetospheric processes. The final goal would be to understand if there is a preferred way in which reconnection occurs at the magnetopause and therefore to give an estimate of the overall reconnection rate. Such an estimate is the major improvement towards a better understanding of the solar wind forcing of the magnetosphere system.

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