Magnetic Reconnection in Space Plasmas

Cluster Spacecraft Observations

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Abstract

Magnetic reconnection is a universal process occurring at boundaries between magnetized plasmas, where changes in the topology of the magnetic field lead to the transport of charged particles across the boundaries and to the conversion of electromagnetic energy into kinetic and thermal energy of the particles. Reconnection occurs in laboratory plasmas, in solar system plasmas and it is considered to play a key role in many other space environments such as magnetized stars and accretion disks around stars and planets under formation. Magnetic reconnection is a multi-scale plasma process where the small spatial and temporal scales are strongly coupled to the large scales. Reconnection is initiated rapidly in small regions by microphysical processes but it affects very large volumes of space for long times. The best laboratory to experimentally study magnetic reconnection at different scales is the near-Earth space, the so-called Geospace, where Cluster spacecraft in situ measurements are available. The European Space Agency Cluster mission is composed of four-spacecraft flying in a formation and this allows, for the first time, simultaneous four-point measurements at different scales, thanks to the changeable spacecraft separation. In this thesis Cluster observations of magnetic reconnection in Geospace are presented both at large and at small scales.

At large temporal (a few hours) and spatial (several thousands km) scales, both fluid and kinetic evidence of reconnection is provided. The evidence consist of ions accelerated and transmitted across the Earth’s magnetopause. The observations show that component reconnection occurs at the magnetopause and that reconnection is continuous in time.

The microphysics of reconnection is investigated at smaller temporal (a few ion gyroperiods) and spatial (a few ion gyroradii) scales. Two regions are important for the microphysics: the X-region, around the X-line, where reconnection is initiated and the separatix region, away from the X-line, where most of the energy conversion occurs. Observations of a separatix region at the magnetopause are shown and the microphysics is described in detail. The separatix region is shown to be highly structured and dynamic even away from the X-line.

Finally the discovery of magnetic reconnection in turbulent plasma is presented by showing, for the first time, in situ evidence of reconnection in a thin current sheet found in the turbulent plasma downstream of the quasi-parallel Earth’s bow shock. It is shown that turbulent reconnection is fast and that electromagnetic energy is converted into heating and acceleration of particles in turbulent plasma. It is also shown that reconnecting current sheets are abundant in turbulent plasma and that reconnection can be an efficient energy dissipation mechanism.

Keywords: space physics, plasma astrophysics, plasma physics, transport processes, boundary layers, magnetic reconnection, turbulence, particle acceleration, solar system, magnetospheres

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List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

Cluster multispacecraft observations at the high-latitude duskside magnetopause: implications for continuous and component magnetic reconnection

Kinetic signatures during a quasi-continuous lobe reconnection event: Cluster Ion Spectrometer (CIS) observations

III A. Vaivads, A. Retinò, M. André
Microphysics of reconnection

The structure of the separatrix region close to a magnetic reconnection X-line: Cluster observations

V A. Retinò, D. Sundkvist, A. Vaivads, F. Mozer, M. André, C. J. Owen
In situ evidence of magnetic reconnection in turbulent plasma

VI D. Sundkvist, A. Retinò, A. Vaivads, S. Bale
Dissipation in turbulent plasma due to reconnection in thin current sheets

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Papers not included in the thesis

1. F. S. Mozer, A. Retinò
   Quantitative magnetic field reconnection from electric and magnetic field measurements

   Multi-point observations of the Hall electro-magnetic field and secondary island formation during magnetic reconnection

   Ion kinetic features around a lobe reconnection site

   Ionospheric convection observed by SuperDARN during ongoing lobe reconnection revealed by Cluster

   Formation of Inner Structure of a Reconnection Separatrix Region

   Cluster observation of continuous reconnection at dayside magnetopause around cusp

   Structure of the Magnetic Reconnection Diffusion Region from Four-Spacecraft Observations
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1. Introduction

Thus is magnified the excellence of God, is manifested the greatness of His kingdom:
He is glorified not in one, but in countless suns:
not in a single earth, a single world, but in ten-hundred-thousands, I say in an infinity of worlds.

From “De l'infinito, universo et mundi” by Giordano Bruno (1584)
G.B. was executed by the Inquisition in 1600. A statue commemorates him in Campo dei Fiori, Roma.

The goal of space physicists as well as of astrophysicists is, in a broad sense, to explain the physical phenomena which happen in space.

The majority of the visible matter in space is in the plasma state, often called the fourth fundamental state of matter. A plasma is a gas of charged particles, which can be thought to be produced by heating an ordinary gas to very high temperatures. An important property of plasmas is to be, on average, electrically neutral. This property is called quasi-neutrality. However since a plasma is composed by charged particles, the role of the electromagnetic fields is fundamental. The motion of each charged particle is in fact due to the electric and magnetic fields produced by all the other particles and these fields are continuously modified by particle motions in a self-consistent way. This property of plasmas is sometimes referred to as collective behavior.

Space plasmas are ubiquitous in stars, galaxies and interplanetary and interstellar media. Plasmas are also present on the Earth, though not in a dominant way, e.g. in flames or lightning discharges or in laboratories where plasmas are artificially created, e.g. for nuclear fusion studies. In this thesis we will not discuss much laboratory plasmas, but it is important to mention that the study of space plasmas is often relevant for laboratory plasmas and viceversa.

Due to the large distance to most of the objects in the plasma Universe, the majority of space plasmas can be studied only remotely. This is done e.g. by measuring photon or particle fluxes from stars using telescopes and then interpreting those observables using theoretical models and/or numerical simulations. These observations deal with integrated quantities which provide average information on those plasmas but cannot give a very detailed description of the processes locally occurring in the plasmas. On the other end, there is a class of space plasmas which are relatively close to us and therefore can be studied in situ, that is, by flying a spacecraft and measuring directly observ-
ables such as electromagnetic fields and particle distribution functions. Examples are plasmas in the solar system, such as the outermost solar atmosphere, the solar wind and planetary magnetospheres. Remote and in situ observations can be considered as mutually complementary tools for studying space plasmas. In situ measurements in the solar system can help to understand in detail the fundamental plasma processes occurring e.g. in distant stars while remote observations can be obtained, on the other end, for a much larger number of plasma objects. In other words, we can use the solar system as a natural laboratory to study the plasma Universe.

There is a variety of very interesting research problems related to the study of space plasmas, which of course cannot be all discussed here. One fundamental question is how energy is converted in a plasma from electromagnetic fields to charged particles. This energy conversion is connected to other important issues such as the transport of mass, momentum and energy across boundaries and the acceleration of charged particles to very high energies. In this thesis we will consider one mechanism which explains such conversion, magnetic reconnection, and we will present in situ observations of reconnection in the near-Earth space plasmas, the so-called Geospace.

The thesis is divided in two main parts: a comprehensive summary, including six more chapters, and a series of papers. The chapters are aimed to provide the overall information which is needed for reading the papers. Chapter 2 briefly presents space plasmas and the Cluster spacecraft. Chapter 3 presents the basics of magnetic reconnection together with a few examples of reconnection in space and laboratory plasmas. Chapter 4 deals with in situ observations of reconnection in Geospace. In this chapter the main results from the papers are presented, together with a few examples from previous other studies. Observations both at large scales and at small scales are shown, focusing on a few scientific questions. Also the discovery of magnetic reconnection in turbulent plasma is presented, together with a discussion on the importance of this new type of reconnection for space and laboratory plasmas. Chapter 5 presents a summary of the papers included in the thesis. Chapter 6 is a summary of the thesis in Swedish. Chapter 7 is a summary of the main conclusions of the thesis together with an outlook on future work. The chapters are aimed for an audience of physicists with a basic background in plasma physics. Those readers who are interested in more details on plasmas and in particular on space plasmas are referred to textbooks such as [10] and [20].
2. Space plasmas

In this chapter we present a few examples of space plasmas. In particular we focus on plasmas in Geospace where four-point measurements are possible, for the first time, by using the Cluster spacecraft. The main features of Cluster are also briefly outlined.

2.1 Examples of space plasmas

Observations in space have been traditionally carried out by using optical instruments, which have given a picture of a quiet Universe where stars are stable objects and their interaction is mainly gravitational. However, recent measurements from x and γ rays telescopes, from major optical, infrared and radio telescopes as well as from spacecraft in situ measurements have revealed an active plasma Universe, populated by very dynamical objects such as flaring stars, disks, winds and jets. The behavior of these objects is determined by the combination of gravitational and plasma interactions, where the role of magnetic fields is often fundamental, as shown in Fig. 2.1.

Figure 2.1: The relation between gravity, magnetic fields and plasmas. Adapted from [84]
In this thesis we will concentrate on one particular process among those in Fig. 2.1, magnetic reconnection, that is a process during which energy stored in magnetic fields is converted into kinetic and thermal energy of charged particles. Reconnection is likely to be ubiquitous in the plasma Universe, since magnetic fields are basically everywhere as indicated in Fig. 2.2. Reconnection will be discussed in detail in chapters 3 and 4.

![Figure 2.2: Magnetic fields in various space plasmas. Adapted from [84]](image)

Space plasmas can be grouped into a few categories with respect to the role played by the magnetic field [84], as shown in figures 2.3, 2.4 and 2.5.

In some space plasmas, such as those in regions around forming stars shown in Fig. 2.3, the gravitational contraction plays a major role and magnetic fields are strongly influenced by the gravitational motions. These *non-equilibrium* space plasmas are usually young and extremely dynamic objects, where reconnection is very likely to play an important role. A typical example is a star under formation.

In other space plasmas in *quasi-hydrostatic equilibrium*, typically older than the previous ones, the gravitational contraction is much less important while still there are relevant free energy sources in their interiors. Typically these sources are internal plasma motions, which generate magnetic fields by dynamo effects and lead to a series of magnetic activity phenomena such as flares on stars and accretion disks, as shown in Fig. 2.4. A typical example is the Sun. Magnetic reconnection occurs also in these plasmas, e.g. it plays a fundamental role in solar flares.
For the last group of space plasmas in *quasi-magnetostatic equilibrium*, the main source of energy is external. Examples are planetary magnetospheres in the solar system, sketched in Fig. 2.5, for which the source of energy is the solar activity. In the next section we will discuss in more detail plasmas in Geospace as examples of such space plasmas. Magnetic reconnection widely occurs in Geospace, as it will be discussed in detail in chapter 4.

*Figure 2.3*: (a) Schematic diagram of non-equilibrium objects. Adapted from [84]. (b) Jets from young stars as observed by the Hubble Space Telescope. Adapted from [1]

*Figure 2.4*: (a) Schematic diagram of quasi-hydrostatic equilibrium objects. Adapted from [84]. (b) A flare on the Sun as observed by the SOHO spacecraft. Adapted from [5]
2.2 Geospace plasmas

The solar wind is a plasma blowing from the Sun into the solar system. The solar magnetic field, generated at the Sun, is carried along by the solar wind into the interplanetary space, where it is usually referred to as the interplanetary magnetic field IMF.

Figure 2.5: (a) Schematic diagram of quasi-magnetostatic equilibrium objects. Adapted from [84]. (b) Aurora on Saturn as observed by the Hubble Space Telescope. Adapted from [2]

Figure 2.6: Schematic diagram representing Geospace at 1 AU. The Geocentric Solar Ecliptic coordinate system GSE is indicated in the left bottom corner. Adapted from [10]
At a distance of about 150 million kilometers (1 AU, astronomical unity) from the Sun, the solar wind and the IMF interact with the Earth and its magnetic field in a region called Geospace, as showed in the schematic diagram in Fig. 2.6. The Earth, as other objects in the solar system, acts as an obstacle to the supersonic solar wind which must decelerate to be able to flow around the obstacle. Due to this interaction a standing shock wave, the **bow shock**, forms in front of the Earth. Downstream of the bow shock, in the **magnetosheath**, the shocked solar wind plasma decelerates to subsonic velocity and it flows around the Earth. The compressed and heated plasma in the magnetosheath is in a turbulent state. The turbulence is particularly strong in the magnetosheath downstream of the so-called **quasi-parallel** shock, where the IMF is parallel to the normal direction to the shock. In this region fluctuations in plasma parameters and magnetic field are usually much stronger than in the magnetosheath downstream of the **quasi-perpendicular** shock, as indicated by Fig. 2.7.

![Figure 2.7](image)

*Figure 2.7*: The quasi-perpendicular and quasi-parallel bow-shock as seen in a numerical simulation. Lengths on the $X$ and $Y$ axes are expressed in ion inertial lengths $\lambda_i$. The ion temperature is color coded. Note that the plane in the figure is the same as in the previous Fig. 2.6 while the relative position of the quasi-perpendicular and quasi-parallel shocks is reversed. Adapted from [57]
The magnetopause is the boundary which separates the Earth’s magnetic field from the IMF transported in the magnetosheath. Due to the dynamic pressure of the solar wind, the terrestrial magnetic field is confined in the anti-sunward direction into a comet-like cavity, the magnetosphere, whose tail is referred to as magnetotail and extends far way from the Earth (not shown in Fig. 2.6). The cusps are the two magnetic funnels in the magnetosphere at polar latitudes, where solar wind plasma has direct access to the magnetosphere and flows down towards the Earth’s atmosphere.

The magnetopause is a surface whose location and shape are determined by the balance between solar wind and magnetospheric pressures. The magnetopause is a current layer since the magnetic field changes orientation and magnitude across it, as indicated in the schematic diagram in Fig. 2.8. In this very simple model the typical thickness of the current layer at equilibrium is approximately one ion gyroradius $\rho_i$.

![Figure 2.8: A schematic diagram of the magnetopause current layer. Electrons and ions perform half a gyration around the magnetospheric field in opposite directions producing the current. The typical thickness of the magnetopause at equilibrium is one ion gyroradius $\rho_i$. Adapted from [20]](image)

Plasmas in Geospace are examples of space plasmas in quasi-magnetostatic equilibrium, whose behavior is determined mainly by the solar wind and IMF dynamics. One important property of many of Geospace plasmas is that they are collisionless. A collisionless plasma is a plasma where collisions are negligible. As an example, the mean free path for collisions in the solar wind is about 1 AU, which is much larger than any characteristic spatial scale in Geospace. In other Geospace plasmas, such as the Earth’s ionosphere below a few hundred kilometers altitude, the collisions are instead important. The fact that plasmas are collisionless has important consequences. Charged particles which are moving along a given magnetic field line at one time, will
continue to move along the same field at later times since they cannot move across the magnetic field lines due to the lack of collisions. This property is called the *frozen-in* condition for a collisionless plasma [6] and it will be discussed in more detail in the next chapter 3. Due to the frozen-in condition, when two different magnetized plasmas come into contact they cannot mix. This situation happens in Geospace e.g. at the magnetopause, where the plasma and magnetic field in the magnetosheath come into contact with those of the magnetosphere. In this model the magnetopause is thus an impenetrable boundary separating solar and terrestrial plasmas and magnetic fields. However, the frozen-in condition can be violated at the magnetopause in small regions where the interplanetary and terrestrial magnetic fields become interconnected and solar and magnetospheric plasmas can mix. This happens during magnetic reconnection, as is discussed in detail in chapters 3 and 4.

2.3 Cluster: first four-point measurements in space

The plasmas in Geospace described in the previous section are examples of space plasmas which can be studied *in situ* by flying a spacecraft through them. The European Space Agency cornerstone mission Cluster [28] is the first scientific space mission ever with four identical spacecraft flying in formation (Fig. 2.9).

![Figure 2.9: Artist’s impression of the Cluster spacecraft. From [4].](image_url)

The Cluster spacecraft move in a polar orbit around the Earth, as indicated in the schematic diagram in Fig. 2.10. For all the events studied in this thesis, the spacecraft have been in a tetrahedral configuration with a inter-spacecraft separation from hundred to a few thousands km.
Each spacecraft is equipped with the same set of eleven instruments which can simultaneously measure plasma quantities and electromagnetic fields at four different points in space. This allows, for the first time, to separate spatial from temporal variations. Furthermore, thanks to the possibility to vary the spacecraft separation, Cluster allows the unique opportunity to study space plasmas at different spatial scales. Due to its polar orbit, Cluster is particularly suited to study high-latitude regions such as the high latitude magnetopause and the magnetospheric cusps.

*Figure 2.10:* Cluster orbit in two different periods of the year. From [3].
3. Magnetic reconnection

This chapter is a brief overview on magnetic reconnection. We provide the main ideas behind the reconnection process and the basic equations. We also present a few examples of magnetic reconnection in laboratory and space plasmas. Those readers interested in more details are referred to [88], [79], [66], [12] and references therein.

3.1 Basics of magnetic reconnection

Magnetic reconnection was first proposed in 1946 by Giovanelli [30] as a possible mechanism of particle acceleration in space plasmas. In 1961 Dungey [27] applied this mechanism to the Earth’s magnetosphere and the first direct evidence of magnetic reconnection was obtained in 1979 at the Earth’s magnetopause [60].

Magnetic reconnection, as anticipated in chapter 2, is a process occurring at the boundary between two magnetized plasmas where the frozen-in condition for the magnetic field breaks down.

The frozen-in condition for the magnetic field can be illustrated within the framework of the so-called magnetohydrodynamic (MHD) approximation. In the MHD approximation the plasma is described as a conductive fluid and no distinction is made between the dynamics of ions and electrons. The MHD approximation is valid for scales larger than one ion gyroradius. In presence of a finite plasma conductivity $\sigma$ the equation governing the magnetic field $\mathbf{B}$ is the induction equation:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \frac{1}{\mu_0 \sigma} \nabla^2 \mathbf{B}$$  \hspace{1cm} (3.1)

where $\mathbf{u}$ is the plasma velocity and $\mu_0$ is the vacuum permeability. The first term on the right hand side of Eq. 3.1 is called the convective term while the second one the diffusive term. The ratio (as order of magnitude) between the convective term and the diffusive term is the magnetic Reynolds number:

$$R_m = \frac{\mu_0 \sigma L_x U_x}{\mu_0 \sigma L_x U_x}$$  \hspace{1cm} (3.2)

where $L_x$ and $U_x$ denote a typical length and a typical velocity, respectively, of the system.
The electric field in the MHD approximation is given by:

$$\mathbf{E} + \mathbf{u} \times \mathbf{B} = \frac{\mathbf{J}}{\sigma}$$  \hspace{1cm} (3.3)

where $\mathbf{J}$ is the electric current. In the absence of collisions, the conductivity $\sigma$ is infinite ($R_m >> 1$) and thus the diffusive term is zero. This regime is called \textit{ideal MHD} regime. The electric field is then given by:

$$\mathbf{E} + \mathbf{u} \times \mathbf{B} = 0$$  \hspace{1cm} (3.4)

and Eq. 3.1 reduces to:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B})$$  \hspace{1cm} (3.5)

These last two equations are the mathematical formulation of the frozen-in condition for the magnetic field in an infinitely conductive \textit{ideal} plasma \cite{6, 10}. The frozen-in condition states that the total magnetic flux through a surface delimited by a closed curve moving with the plasma is constant. This implies that all plasma elements and all magnetic flux contained at a given time in a magnetic flux tube (delimited by a set of magnetic field lines) will remain inside the same flux tube at all later times, independent from the motion of the flux tube. The frozen-in condition is illustrated in Fig. 3.1 (a).

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure3_1.png}
\caption{Time evolution of magnetic field lines. (a) Frozen-in field lines (b) Reconnected field lines. Adapted from [59].}
\end{figure}
The magnetic field lines in Fig. 3.1 (a) are frozen in the plasma flow, which is indicated by the blue arrows. The two plasma elements A and B, which are connected at the time $t_1$ by a magnetic field line, stay connected with the same line at later times though the magnetic field lines are deformed by the plasma flow. In this situation the velocity $\mathbf{w} = \frac{\mathbf{E} \times \mathbf{B}}{|\mathbf{E}|}$ of magnetic field lines is equal to the velocity of plasma elements $\mathbf{w} = \mathbf{u}$. A consequence of the frozen-in condition is that ideal plasma flows conserve the magnetic topology, which is defined as any property of the magnetic field that is preserved by an ideal displacement [66]. In other words, the topology of the magnetic field is conserved when it is possible to deform magnetic field lines in a continuous matter so that properties such as their mutual position and their sense (positive or negative direction) stay the same. It must be noted that, when the magnetic field is frozen into the plasma, any component of the electric field $E_\parallel$ parallel to the magnetic field direction must vanish, as implied by Eq. 3.4. When $E_\parallel = 0$ both the connectivity of plasma elements and the magnetic topology are not changed.

During magnetic reconnection, the frozen-in condition is violated in a diffusion region where plasma and magnetic fields decouple and move at different velocities, $\mathbf{w} \neq \mathbf{u}$. In the diffusion region, the earlier separated magnetic fields of the two plasmas get interconnected at an X-point, while outside the diffusion region the magnetic fields are still frozen-in. As a result, both the magnetic topology and the magnetic connectivity of plasma elements change. This process is illustrated in Fig. 3.1 (b). A new class of reconnected field lines is created from the initial red and green field lines. The topology of these reconnected magnetic field lines is different from the topology of the initial ones, as one can notice that it is not possible to come back from the magnetic configuration at time $t_3$ to the one at time $t_1$ by a simple continuous deformation of the magnetic field lines. The change in magnetic connectivity of plasma elements is illustrated in Fig. 3.1 (b) where two plasma elements initially connected to different field lines, e.g. the elements A and C, after reconnection are connected to the same field line. The change of magnetic topology and connectivity of plasma elements is due to the presence of a parallel electric field $E_\parallel$ within the diffusion region, as will be discussed in the next section 3.2. This parallel electric field is created by microscopical effects which will be discussed in section 4.3.
Figure 3.1 (b) also demonstrates that during magnetic reconnection plasma is accelerated in reconnection jets. The Lorentz force:

\[
\mathbf{J} \times \mathbf{B} = -\nabla \left( \frac{B^2}{2\mu_0} \right) + \frac{1}{\mu_0} \nabla \cdot (\mathbf{B} \mathbf{B})
\]  

(3.6)

accelerates the plasma away from the X-point. In particular the magnetic tension \( \frac{1}{\mu_0} \nabla \cdot (\mathbf{B} \mathbf{B}) \) acts to reduce the curvature of the highly bent reconnected field lines. Thus, during reconnection magnetic energy is converted into kinetic energy of the plasma. Part of the magnetic energy is also converted into thermal energy of the plasma, as it will be explained in section 3.3.

3.2 Definitions of magnetic reconnection

Despite of many theoretical and experimental studies, there is no commonly accepted definition of magnetic reconnection and the discussion is still ongoing. Here we briefly give a few possible definitions. For illustrative purposes, it is convenient to first present a two-dimensional (2D) and steady-state description of reconnection. Although it is sometimes objected that this is an oversimplified cartoon of reconnection, the 2D steady-state description provides a good physical insight and it is often consistent with the observations. The schematic diagram of 2D reconnection is shown in Fig. 3.2 (a).

Figure 3.2: (a) 2D and (b) 3D schematic diagram of magnetic reconnection. Lines are magnetic field lines while plasma elements are represented by capital letters. Adapted from [66].
In the 2D picture the opposite directed magnetic field lines in the reconnection plane get interconnected in the X-point located in the center of the diffusion region, the shaded region in Fig. 3.2 (a). The line connecting all the X-points in the direction out of the reconnection plane is referred to as the X-line. The magnetic separatrices are the surfaces separating magnetic fields with different topologies and they intersect in the X-line. The projection of the magnetic separatrices onto the reconnection plane are the magnetic field lines connected to the X-point (the dashed lines in Fig. 3.2 (a)). In 2D reconnection can be defined as the process with the following properties [66]:
1. it occurs at an X-point; during reconnection two magnetic field lines are brought towards the X-point; then they lie along the separatrices and are broken and reconnected
2. there is an electric field \( E \) that is directed along the X-line, thus perpendicularly to the reconnection plane
3. there is a change of magnetic connectivity of plasma elements due to the breaking of the frozen-in condition inside the diffusion region, such that two plasma elements initially on the same field line (A and B) after reconnection are no longer magnetically connected
4. there is a plasma flow across the separatrices

Despite of the fact that the 2D definitions are often satisfactory, magnetic reconnection is a three-dimensional and time dependent process. A 3D definition of magnetic reconnection has been given by [74] and [37]. General magnetic reconnection is defined as a breakdown of magnetic connection due to a localized non-idealness. The non-idealness is localized inside the diffusion region, shaded in Fig. 3.2 (b), and its effect is to produce a parallel electric field \( E_{||} \) inside that region. It can be shown [74, 37] that a necessary and sufficient condition for general magnetic reconnection is that:

\[
\int E_{||} ds \neq 0 \tag{3.7}
\]

where the integration is done along a set of field lines inside the diffusion region.

The 2D definitions given above are too restrictive in a way that they require the existence of X-points and separatrices, which may not exist in 3D reconnection. On the other end, the 3D definition is too wide in a way that focuses only on the change in magnetic connectivity of the plasma elements. In this thesis we prefer to adopt a phenomenological definition of magnetic reconnection which originates from the need to interpret observations in space. In Paper III we define magnetic reconnection as the process where:

1. microscopic local processes cause a macroscopic change in magnetic topology so that earlier separated plasma regions become magnetically connected
2. on macroscopic scales the system relaxes to a lower energy state converting magnetic field energy to kinetic energy of charged particles
This definition focuses both on the changes in magnetic topology and connectivity and on the conversion of energy and it is sketched for a 2D geometry in Fig. 3.3.

![Diagram of magnetic reconnection](image)

**Figure 3.3:** Schematic diagram for the definition of magnetic reconnection given in Paper III. Magnetic field lines of different topologies are labeled with different colors while the arrows indicate plasma flows. The region between the reconnecting magnetic fields is a current sheet. Adapted from Paper III.

From an *operational* point of view this definition corresponds to the simultaneous observations of the following quantities:

1. change in magnetic topology and connectivity:
   * non-zero parallel electric field at the X-line
   * non-zero component of the magnetic field perpendicular to the current sheet (in the reconnection plane)
   * plasma transport across the current sheet

2. energy conversion:
   * non-zero electric field corresponding to transport of electromagnetic energy towards the X-line
   * plasma acceleration (reconnection jets)
   * plasma heating

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3.3 Models of magnetic reconnection

Many theoretical models have been proposed to describe the process of magnetic reconnection. A detailed discussion can be found in [66]. Models of reconnection are usually divided into 2D/3D and/or steady-state/transient models, according to the approximations used. In this section we present only the 2D and steady-state models by Sweet and Parker [58, 83] and by Petschek [61], together with a generalization of Petschek’s model by Levy [44]. Though not always realistic from an observational point of view, the models discussed here are illustrative of the main properties of magnetic reconnection. These models are based on MHD equations and are thus valid at scales typically larger than one ion gyroradius. At smaller scales, where the MHD approximation is no longer valid, a more complicated description is needed to account for the different dynamics of electrons and ions. Due to the complexity of the problem, numerical simulations are mainly used in this case, as it will be discussed in section 4.3.

The basic equations used in the MHD models of reconnection are the equations 3.1 and 3.3, together with the continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$ (3.8)

and the equation of motion:

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} = -\frac{\nabla p}{\rho} + \frac{\mathbf{J} \times \mathbf{B}}{\rho}$$ (3.9)

where $\rho$ is the plasma mass density and $p$ the plasma pressure.

3.3.1 Sweet-Parker reconnection

A schematic diagram of the Sweet-Parker reconnection model is shown in Fig. 3.4 (a). The figure shows the reconnection plane $XZ$ with the antiparallel reconnecting magnetic fields in $Z$ direction and the normal to the current sheet in $X$ direction. The system has size $2L$ along the current sheet ($Z$ direction) and $2a$ across the current sheet ($X$ direction). The magnetic field vanishes in the center of the current sheet.

We now describe the basics of the Sweet-Parker model following the derivation in [66]. In the inflow region the electric field is given by:

$$E = u_0 B_0$$ (3.10)

and it is directed out of the reconnection plane, corresponding to the inflow of plasma from both sides of the current sheet at the velocity $u_0$. At the center of the diffusion region where the magnetic field is zero the electric field is:

$$E = \frac{J}{\sigma}$$ (3.11)
where the current is given by Ampère’s law across the current sheet:

$$J = \frac{B_0}{\mu_0 a}$$

(3.12)

In steady-state the electric field is constant so that:

$$u_0 = \frac{1}{\mu_0 \sigma a}$$

(3.13)

The integration of the continuity equation 3.8 across the current sheet gives:

$$Lu_0 = au_e$$

(3.14)

where $u_e$ is the outflow speed. Then eliminating the width $a$ between Eq. 3.13 and Eq. 3.14 we get:

$$u_0^2 = \frac{u_e}{\mu_0 \sigma L}$$

(3.15)
In dimensionless variables Eq. 3.15 can be written as:

$$M_0 = \frac{\sqrt{u_e}}{u_{e0}} \sqrt{R_{m0}}$$  \hspace{1cm} (3.16)

where

$$M_0 = \frac{u_0}{u_{A0}}$$  \hspace{1cm} (3.17)

is the inflow Alfvén Mach number or dimensionless reconnection rate and

$$R_{m0} = Lu_{A0} \sigma \mu_0$$  \hspace{1cm} (3.18)

is the magnetic Reynolds number based on the inflow Alfvén speed

$$u_{A0} = \frac{B_0}{\sqrt{\mu_0 \rho}}$$  \hspace{1cm} where \( \rho \) is the plasma density.

Once \( u_e \) and therefore \( u_0 \) from Eq. 3.15 are known for a given \( L \) then Eq. 3.14 determines the width \( a \) as:

$$a = L \frac{u_0}{u_e}$$  \hspace{1cm} (3.19)

The outflow magnetic field strength is obtained by magnetic flux conservation as:

$$B_e = B_0 \frac{u_0}{u_e}$$  \hspace{1cm} (3.20)

The outflow speed \( u_e \) is obtained from the equation of motion 3.9. If we neglect the effect of thermal pressure and consider steady-state situation then the Lorentz force \((J \times B)_z\) accelerates the plasma from rest to \( u_e \) over the distance \( L \) along the current sheet. Imposing balance between the Lorentz force and the inertial term \( \rho (u \cdot \nabla) u_z \) we get:

$$\rho \frac{u_e^2}{L} \approx \frac{B_0 B_e}{\mu_0 a}$$  \hspace{1cm} (3.21)

Combining Eq. 3.21 with Eq. 3.14 and Eq. 3.20 we finally get the important result:

$$u_e = \frac{B_0}{\mu_0 \rho} = u_{A0}$$  \hspace{1cm} (3.22)

implying that during reconnection the magnetic force accelerates the plasma to the Alfvén speed. The magnetic field reconnects at the speed:

$$u_0 = \frac{u_{A0}}{\sqrt{R_{m0}}}$$  \hspace{1cm} (3.23)

Due to the large value of the magnetic Reynolds number \( R_{m0} > > 1 \) we have \( u_0 << u_{A0}, B_e << B_0 \) and also \( a << L \).

A schematic diagram of the energy balance in the Sweet-Parker reconnection is shown in Fig. 3.4 (b). The inflow rate of electromagnetic (EM) energy is the flux of the Poynting vector \( \mathbf{S} = \frac{E \times B}{\mu_0} \) through the inflow region:

$$\Phi(\mathbf{S}) = \frac{E B_0}{\mu_0} L = \frac{B_0^2}{\mu_0} (u_0 L)$$  \hspace{1cm} (3.24)
The ratio between the inflow rates of kinetic (K) and EM energy is:

\[
\frac{(K)_0}{(EM)_0} = \frac{(1/2)\rho u_0^2}{\mathcal{B}_0^2/\mu_0} = \frac{u_0^2}{2u_0^2} << 1 \tag{3.25}
\]

since most of the inflowing energy is magnetic. Because of the condition \(a << L\) and \(B_e << B_0\), the outflow rate of EM energy \(E_{Be}\mu_0 a\) is much smaller than the inflow rate of EM energy. This implies that during reconnection the magnetic energy is dissipated. The ratio between the outflow rate of K energy and the inflow rate of EM energy is:

\[
\frac{(K)_e}{(EM)_0} = \frac{(1/2)\rho u_e^2(u_e a)}{\mathcal{B}_0^2/\mu_0(u_0 L)} = \frac{(1/2)u_e^2}{u_0^2} = \frac{1}{2} \tag{3.26}
\]

showing that during reconnection magnetic energy is converted half to plasma kinetic energy and half to thermal energy. Thus the effect of reconnection is to create fast and hot plasma jets.

### 3.3.2 Petschek reconnection

In Sweet-Parker reconnection the size of the reconnection region is equal to the whole size of the diffusion region and all the plasma must go through the diffusion region to be accelerated. As a consequence reconnection is quite slow and the reconnection rate estimated from Eq. 3.17 is often not realistic, e.g. it cannot account for the observations of solar flares. In Petschek reconnection model, sketched in Fig. 3.5, this problem is avoided by replacing the Sweet-Parker diffusion region with a much smaller diffusion region, which extends into two standing slow-shocks in the outflow directions.

![Figure 3.5: Schematic diagram of 2D steady-state reconnection according to the Petschek model. The size of the diffusion region is 2L* while the size of the system is 2L. The diffusion region bifurcates into two standing slow-shocks in the downstream flow. Current-carrying regions are hatched. Adapted from [18].](image)
With this configuration, only a small fraction of the inflowing plasma must go through the diffusion region while the most part of it is accelerated at the slow-shocks away from the diffusion region. The reconnection rate in the Petschek model is [66]:

\[
M_{\text{Petschek}} \approx \frac{\pi}{8 \log R_{m0}}
\]  

(3.27)

where \( R_{m0} \) is the magnetic Reynolds number calculated in the inflow region. This reconnection rate typically lies in the range \( 0.01 - 0.1 \) since \( \log R_{m0} \) is a slowly varying function of the Reynolds number. For given \( R_{m0} \), the reconnection rate in Eq. 3.27 is much higher than in the Sweet-Parker model and thus in better agreement with observations.

![Schematic diagram of 2D steady-state reconnection in the Levy’s model.](image)

*Figure 3.6: Schematic diagram of 2D steady-state reconnection in the Levy’s model. From [43].*

The Petschek model describes symmetric reconnection where the two inflow regions are identical. Although this situation is suitable for some cases, such as in the Earth’s magnetotail, in other cases such as at the Earth’s magnetopause the two inflowing regions are usually quite different. In the Levy model [44] shown in Fig. 3.6 plasma is inflowing mainly from one side (magnetosheath side at the Earth’s magnetopause). In the inflow region the density is much higher than on the other side (magnetospheric side at the Earth’s magnetopause) but the magnetic field strength is much smaller. As a result, the slow-shocks in Petschek model are substituted by a rotational discontinuity and a standing slow expansion wave. Across the rotational discontinuity, the magnetic field rotates from the magnetosheath to the magnetospheric direc-
tion while the magnitude of the magnetic field and the density stay constant. Plasma jets are accelerated within the rotational discontinuity, as we will discuss in more detail in section 4.2. Across the slow wave the strength of the magnetic field and the density change gradually to match their values on the magnetospheric side. The reconnection rate in the Levy model is similar to the one in the Petschek model.

3.4 Examples of reconnection

Magnetic reconnection is an universal process which is important both in laboratory and space plasmas. Reconnection has been observed in the Earth’s magnetosphere at the magnetopause [63] and in the magnetotail [90]. Reconnection has also been directly observed in the terrestrial magnetosheath, as discussed in Paper V where the first evidence of magnetic reconnection in turbulent plasma is presented. Reconnection in Geospace will be discussed in detail in chapter 4. In the solar system magnetic reconnection has been also observed in the solar wind [34, 33, 64], on the Sun [8, 45], in other planetary magnetospheres [39, 71] and could occur at the heliopause [55] and in cometary tails [73, 40]. Fig. 3.7 is a schematic diagram of magnetic reconnection during a solar flare. Reconnection is also thought to play an important role in other space environments e.g. in the interstellar medium [89], in accretion disks [69], in cosmic rays acceleration [42] and in astrophysical jets [91].

![Figure 3.7: Schematic diagram of magnetic reconnection in the solar corona. Adapted from [45].](image-url)
Magnetic reconnection has also been observed in several laboratory experiments such as the Princeton MRX experiment [93] and the Swarthmore SSX experiment [14]. Magnetic reconnection is considered to play a major role in magnetic field disruptions in tokamak devices during the so-called sawtooth oscillations [94]. Fig. 3.8 is a schematic diagram of magnetic reconnection in the MRX experiment.

3.5 Magnetic reconnection at different scales

One fundamental and still largely unknown aspect of reconnection is its multiscale nature. Magnetic reconnection is initiated rapidly at microscopic scales but affects very large volumes in space for long time. From an experimental point of view, reconnection can be investigated in three spatial domains: the electron scale, the ion scale and the MHD scale. The generalized Ohm’s law [10] is given by:

\[
E + u \times B = \frac{J}{\sigma} + \frac{J \times B}{ne} - \frac{\nabla \cdot P_e}{ne} + \frac{m_e}{ne^2} \frac{\partial J}{\partial t}
\]

(3.28)

where \(e\) and \(m_e\) are the electron charge and mass, \(u\) the ion velocity, \(n\) the plasma number density and \(P_e\) the electron pressure tensor. The first term on the right-hand side of Eq. 3.28 represents the contribution to the electric field due to finite conductivity \(\sigma\), the second term, often called the Hall term, the contribution due to the Lorentz force, the third term the contribution due to variations in the electron pressure tensor and the fourth term the contribution due to the electron inertia. The relative importance of these terms depends on the characteristic length scale, as discussed in detail e.g. in [76] and references therein.
At MHD scales, larger than the ion gyroradius $\rho_i$, the terms on the right hand side of equation Eq. 3.28 are all zero. Both ions and electrons are magnetized and their perpendicular velocity is equal to the field lines velocity $\mathbf{w} = \frac{\mathbf{E} \times \mathbf{B}}{B^2}$.

At ion scales, on the order of the ion inertial length $\lambda_i$, the Hall term becomes dominant. Ions are no longer magnetized while the electrons are still magnetized and their perpendicular velocity is $\mathbf{w}$.

Finally at electron scales, on the order of the electron inertial length $\lambda_e$, some or all of the remaining terms on the right side of equation Eq. 3.28 are non-zero. Both ions and electrons are no longer magnetized and parallel electric fields occur.

During reconnection all these scales are strongly coupled to each other. Therefore the experimental investigation of reconnection requires simultaneous multi-point measurements at these scales. This is possible in Geospace, for the first time, by using Cluster four-spacecraft measurements as it will be shown in chapter 4.
4. Observations of magnetic reconnection in Geospace

This chapter is an overview of Cluster observations of magnetic reconnection in Geospace. The main results of papers I-VI are summarized, focusing on observations at different spatial and temporal scales. At MHD scales, we present observations at the Earth’s magnetopause and we discuss component and antiparallel reconnection and the continuity in time of reconnection. At smaller scales, we discuss the importance of the X-region and of the separatrix region for the microphysics of reconnection and we present observations in the separatrix region. Finally we present the discovery of magnetic reconnection in turbulent plasma and discuss a few issues related to this new kind of reconnection.

4.1 Reconnection in Geospace

The Geospace is the best laboratory to study magnetic reconnection from an experimental point of view. In Geospace in situ spacecraft measurements of plasma and electromagnetic field quantities are available over a wide range of temporal and spatial scales which are characteristic of reconnection. This cannot be done in the same detail in other plasmas where reconnection occurs, e.g. in the solar atmosphere in situ measurements are not yet available while in laboratory plasmas it is not yet possible to measure quantities such ion and electron distribution functions. Furthermore in Geospace the multi-scale aspect of reconnection can be experimentally investigated, at least partially, by using simultaneous Cluster measurements at different spacecraft separation. As an example, at the magnetopause the ion gyroradius and the ion inertial length are typically $\rho_i \sim 1000 \text{ km}$ and $\lambda_i \sim 50 \text{ km}$ and thus comparable with the Cluster inter-spacecraft separation, which ranges from a few hundred to a several thousand kilometers. The electron inertial length at the magnetopause is typically $\lambda_e \sim 1 \text{ km}$ and this scale cannot be resolved by Cluster. In the magnetotail the electron inertial length is larger than at the magnetopause and the electron scales can be partially resolved.
Magnetic reconnection occurs in Geospace in two key regions, the magnetopause and the magnetotail, and in this thesis we show that it also occurs in a third key region, the magnetosheath. The locations of reconnection in Geospace are illustrated in Fig. 4.1. At the magnetopause, the change in magnetic topology due to reconnection allows the interconnection between solar and terrestrial magnetic fields and thus the transport of mass, momentum and energy from the solar wind into the magnetosphere. In the magnetotail, magnetic reconnection plays a major role in magnetic storms and is responsible for the heating of plasma to temperature up to hundred millions degrees (∼10 keV). In the magnetosheath, reconnection plays an important role in the dissipation of magnetic energy and in the heating and acceleration of turbulent plasma.

![Figure 4.1](image)

*Figure 4.1:* Magnetic reconnection in Geospace. The locations where reconnection occurs are indicated with big crosses. Adapted from [22]

Magnetic reconnection is considered to be the dominant mechanism in Geospace to explain changes in the magnetic field topology, transport of plasma across boundaries and conversion from magnetic energy to kinetic and thermal energy of the plasma. A few other mechanisms alternative to reconnection have also been proposed, as discussed in [76, 95] and references therein. Some of these processes are sketched in Fig. 4.2. During diffusion plasma is transported across the magnetic field according to the ordinary diffusion equation, in which the diffusion coefficient is due to wave-particle scattering. In the viscous-like mechanism energy and momentum are transferred by sound waves in a viscous boundary layer. In the Kelvin-Helmholtz mechanism energy and momentum are transferred through large amplitude surface waves as a consequence of the Kelvin-Helmholtz instability. During impulsive penetration plasma is transferred across the magnetic fields through blobs having momentum in excess. Plasma can also
be transported across boundaries due to \textit{finite gyroradius} effects when the particles have gyroradii larger than the boundary thickness. However none of these mechanisms is able to explain, at the same time, the change in topology, the transport and the energy conversion and the experimental evidence in favor of these alternative mechanisms is limited. In this chapter we concentrate on observations at the magnetopause and in the magnetosheath both at MHD and at smaller scales.

![Figure 4.2: Alternative mechanisms to magnetic reconnection. Adapted from [95]](image)

### 4.2 Reconnection at MHD scales

At MHD scales the magnetopause can be described as an \textit{MHD discontinuity} [10]. Figure 4.3 shows two cases of MHD discontinuities. In absence of reconnection the magnetopause can be described as a \textit{tangential discontinuity}. A tangential discontinuity (Fig. 4.3 (a)) is a boundary where the tangential components of the magnetic field $\mathbf{B}$ and of the plasma velocity $\mathbf{u}$ change arbitrarily in direction and strength. Both the magnetic field and the plasma velocity components perpendicular to the magnetopause, $B_n$ and $u_n$, are zero and there is neither mass nor magnetic flux flow across the boundary. Across a rotational discontinuity (Fig. 4.3 (b)) there is instead a finite mass and magnetic flux flow.
The normal components $B_n$ and $u_n$ are different from zero and constant across the boundary and they satisfy the following relation:

$$u_n = \pm \frac{B_n}{\sqrt{\mu_0 \rho}}$$

where the velocity $u_n$ is measured in the discontinuity reference frame.

The magnetic field rotates across a rotational discontinuity while keeping constant magnitude. The tangential components of the magnetic field $B_t$ and of the plasma velocity $u_t$ change across the boundary according to the Walén relation:

$$\Delta u_t = \pm \frac{\Delta B_t}{\sqrt{\mu_0 \rho}}$$

where $\Delta u_t$ and $\Delta B_t$ denote the difference between these quantities on the two sides of the boundary. For the more general case of an anisotropic plasma Eq. 4.2 can be written as:

$$u_{t2} - u_{t1} = \pm \left(1 - \frac{\alpha_1}{\mu_0 \rho_1}\right)^{1/2} \left[B_{t2} \left(1 - \frac{\alpha_2}{\mu_0 \rho_2}\right) - B_{t1}\right]$$

where $\alpha = \frac{\mu_0 (p || - p \perp)}{B^2}$ is the pressure anisotropy and $||, \perp$ refer to directions parallel and perpendicular to the magnetic field, respectively. The subscripts 1, 2 indicate quantities on the two sides of the rotational discontinuity.
4.2.1 Evidence of reconnection

**Fluid evidence**

When reconnection is ongoing, the magnetopause boundary can be described as a rotational discontinuity. The following conditions must hold:

\[ B_n \neq 0 \]  \hspace{1cm} (4.4)
\[ u_n \neq 0 \]  \hspace{1cm} (4.5)
\[ E_t \neq 0 \]  \hspace{1cm} (4.6)

where \( E_t \) is the electric field tangent to the magnetopause. These conditions provide evidence of ongoing reconnection and a measurement of the reconnection rate:

\[ M_n = \frac{u_n}{u_A} = \frac{B_n}{B} \]  \hspace{1cm} (4.7)

where \( u_A \) is the Alfvén velocity calculated in the inflow region. Unfortunately, a direct measurement of \( B_n, u_n \) and \( E_t \) at the magnetopause is quite difficult because these quantities are usually small compared to measurement uncertainties, as discussed in [76] and references therein. The tangential quantities instead do not usually suffer from this limitation.

**Fluid evidence** of reconnection can be obtained verifying the **tangential stress balance** prescribed by Eq. 4.3 across the magnetopause. Eq. 4.3 is evaluated between one magnetosheath reference level, label 1 in Fig. 4.4, and one interval inside the accelerated plasma jet in the magnetopause, label 2. The signs + and − in Eq. 4.3 correspond to the two sides of the X-point in Fig. 4.4 where \( B_n < 0 \) and \( B_n > 0 \), respectively, above and below the X-point. When Eq. 4.3 is satisfied then the magnetopause is a rotational discontinuity where reconnection is ongoing. This test is called the Walén test [60, 82].

An example of a successful Walén test at the magnetopause is shown in Fig. 4.5 for two reconnection jets accelerated in opposite directions with respect to the X-point (jet reversal). In Fig. 4.5 (b), (c) the equation 4.3 is verified by calculating, for each reconnection jet, the vectors \( \Delta V_{obs} \) and \( \Delta V_{th} \) corresponding to the left and right hand side of the equation, respectively, and then calculating the quantities \( R = |\Delta V_{obs}| / |\Delta V_{th}| \) and \( \theta \), which is the angle between \( \Delta V_{obs} \) and \( \Delta V_{th} \). The vectors are evaluated in the \( LM \) plane tangential to the magnetopause i.e. the plane perpendicular to Fig. 4.5 (a) and to the magnetopause normal. A perfect Walén test would give \( R = 1 \) and \( \theta = 0^\circ \) and \( \theta = 180^\circ \) for \( B_n < 0 \) and \( B_n > 0 \), respectively. Thus the results in Fig. 4.5 (b), (c) are consistent with ongoing reconnection.

Another equivalent method to test the tangential stress balance across the magnetopause is to perform the Walén test in the deHoffmann-Teller frame [80, 81]. If \( B_n \neq 0 \) across the magnetopause then magnetic field lines on both sides of the boundary must move together. Then it must exist an inertial reference frame where the flows are aligned with the magnetic field and the electric
field vanishes on both sides of the boundary. This reference frame is called the deHoffmann-Teller (HT) frame [23]. The HT frame moves at the velocity $\mathbf{u}_{HT}$, which is the velocity of the reconnected field lines along the magnetopause. The component of $\mathbf{u}_{HT}$ along the normal to the magnetopause $\mathbf{n}$ is the velocity of the magnetopause in the normal direction $u_{MP} = \mathbf{u}_{HT} \cdot \mathbf{n}$. The existence of a proper HT frame is thus a necessary (but not sufficient) condition for an open magnetopause and ongoing reconnection. In the HT frame the Walén test becomes a verification of the relation:

$$\mathbf{u} - \mathbf{u}_{HT} = \pm u_A \quad (4.8)$$

where $u_A$ is the local Alfvén velocity.

The Walén test is a powerful tool to provide evidence of reconnection at MHD scales. However this method has also several limitations e.g. it is valid only for planar and steady-state discontinuities while observations often show that the magnetopause is a three-dimensional discontinuity where time variations are important. Thus, despite of a not successful Walén test, reconnection can still be ongoing at the magnetopause, as indicated e.g. from the observation of particle distribution functions expected during reconnection [9]. This kinetic evidence of reconnection is independent from the fluid evidence and the two evidences can be considered as mutually complementary. Kinetic evidence of reconnection is discussed in the next section.
Figure 4.5: Fluid evidence for two reconnection jets at the magnetopause flowing, respectively, in sunward (+\(\hat{X}_{\text{gse}}\)) and tailward (−\(\hat{X}_{\text{gse}}\)) direction. (a) Schematic diagram of the reconnection region. MP indicates the magnetopause. The magnetospheric boundary layer (BL) and the magnetosheath boundary layer (MSBL) are the layers of mixed magnetospheric and magnetosheath plasma located on the magnetospheric and of the magnetosheath side of the magnetopause, respectively. The Walén test for (b) the sunward jet and (c) the tailward jet. The details of the Walén test are explained in the text. Adapted from Paper I.

Kinetic evidence

Quantitative evidence of reconnection can also be obtained from the analysis of particle motions in the HT frame [19]. The acceleration of a particle in the current sheet during reconnection is described in Fig. 4.6, where the motion of the particle is sketched both in the Earth’s frame and in the HT frame.

The reconnecting magnetic fields on both sides of the current sheet in Fig. 4.6 (a), (b) are antiparallel and have a common constant normal magnetic field \(B_n\). In the Earth’s frame, Fig. 4.6 (a), the particle incoming along a reconnected field line from the left has both the parallel velocity \(V_{\parallel i}\) along the magnetic field and the velocity \(V_{E1}\) perpendicular to the magnetic field due to \(E \times B\) motion toward the current sheet. The HT frame moves along the current sheet with the velocity \(V_{HT} = \frac{E_i \times B_n}{B^2}\) where \(E_i\) is the constant tangential electric field. Since in the HT frame the total electric field \(E = 0\) on both sides of the current sheet, the incident particle has only the parallel velocity \(V_{\parallel i} + V_{HT}\) and this will be also its velocity after transmission through or reflection from the current sheet.
Thus, in the Earth’s frame the field velocity of the transmitted or reflected particle will be $V_{\parallel} + 2V_{HT}$, which is equivalent to an acceleration by a perfect mirror moving at velocity $V_{HT}$ along the current sheet. These conditions set constraints on the velocity of transmitted and reflected particles, which can be observed in the distribution functions measured around the current sheet, as shown in Fig. 4.6 (c), (d). In the HT frame only particles with positive velocity can be transmitted across the current sheet thus implying that in the Earth’s frame transmitted particle must have velocity $|V_{\parallel}| > |V_{HT}|$. This situation is shown in Fig. 4.6 (d) where a cut of the ion distribution function just inside the magnetopause is shown in the magnetopause plane. The transmitted magnetosheath ions show a cut-off at a parallel velocity equal to $|V_{HT}|$. These distribution functions are often called D-shaped distribution functions. The distribution function of the reflected particles is the mirror image of the distribution function of the incident particles with respect to $|V_{HT}|$, as shown in Fig. 4.6 (c).
Fig. 4.7 shows an example of transmitted and reflected ion distribution functions during magnetopause reconnection.

The top left panel in Fig. 4.7 (b) shows the observed incident and reflected ions in the MSBL. The reflected ions correspond to the widely spaced contours below $V_{HT\parallel 1}$, which is the component of the HT velocity parallel to the magnetic field in the MSBL. The observed distribution function is in agreement with the theoretical expectation shown in the bottom left panel, where the reflected ions are the mirror image of the incident ions with respect to $V_{HT\parallel 1}$. The top right panel shows the observed transmitted ions in the BL. The observed cut-off at $V_{HT\parallel 2}$ is consistent with the theoretical expectation shown in the bottom right panel.

4.2.2 Antiparallel and component reconnection

The location where reconnection occurs at the magnetopause depends on the relative orientation between the IMF in the magnetosheath and the magnetospheric magnetic field. Different models predict different locations.

During antiparallel reconnection [21, 47] the X-line on the magnetopause is the line connecting all the X-points at which the two magnetic fields are exactly antiparallel. In this case newly reconnected field lines are highly bent and act efficiently as slingshots, accelerating solar wind plasma into the magnetosphere. As shown in Fig. 4.1, for purely southward IMF (directed along $-\hat{Z}_{gse}$) reconnection occurs in the equatorial plane sunward of the two magnetospheric cusps. In this case the X-line extends over the entire dayside magnetopause along the equator.
However when the IMF has a substantial component in the $\tilde{Y}_{gse}$ direction, then the X-line splits in two parts at the local noon ($Y_{gse} = 0$) and it is shifted towards higher latitudes, as shown in Fig. 4.8 (a).

![Figure 4.8](image)

**Figure 4.8:** The location of the X-line (in red) as seen from the Sun for IMF $B_z < 0$ and $B_y > 0$: (a) for antiparallel reconnection (adapted from [21]) (b) for component reconnection (adapted from [82]). The subscripts 1 and 2 refer to the magnetosheath and magnetosphere, respectively.

During *component* reconnection [78, 31], on the other hand, reconnection can start where the reconnecting magnetic fields are not strictly antiparallel. In this case a finite magnetic field component exists along the X-line, the so-called guide field, while the guide field is zero during antiparallel reconnection. For southward IMF this model predicts that reconnection occurs at the magnetopause where the IMF first gets into contact with the magnetospheric field lines and creates a tilted X-line as the one shown in Fig. 4.8 (b). The tilt of the X-line is determined by the relative magnitude of the IMF components $B_y$ and $B_z$. During component reconnection the newly reconnected field lines are not highly bent as in the antiparallel case and plasma acceleration is expected to be less efficient.
For purely northward IMF (directed along $\hat{Z}_{\text{gse}}$) reconnection occurs at high latitudes tailward of the cusps in the meridian $X_{\text{gse}}Z_{\text{gse}}$ plane, as shown in Fig. 4.9. The effect of the IMF component $B_y$ is to shift the X-line from the local noon towards the flanks of the magnetosphere.

![Figure 4.9: Location of magnetic reconnection in the meridian $X_{\text{gse}}Z_{\text{gse}}$ plane for purely northward IMF. Adapted from [35].](image)

The question whether reconnection at the magnetopause occurs according to the antiparallel or component model is still under debate, as well as the location of the X-line for different IMF orientations. This is an important issue for the problem of the transport of plasma across the magnetopause since component reconnection implies that solar wind plasma can enter the magnetosphere over much larger volumes than during antiparallel reconnection.

Previous observations have provided evidence both of antiparallel and of component reconnection at the magnetopause, as discussed in [63] and references therein. In particular [85] estimated the location of the X-line from ion distribution function measurements to show that both antiparallel and component reconnection occur at the high latitude magnetopause under northward IMF, as indicated in Fig. 4.10. However the evidence provided in these previous studies is only indirect. To directly distinguish between antiparallel and component reconnection it is necessary to measure the shear of the magnetic field at the X-line, where reconnection is initiated. These measurements are quite difficult, due to the fact that spacecraft crossings close to the X-line are rare. In Paper I we present in situ evidence of component reconnection at the magnetopause by measuring the magnetic shear at two reconnection jet reversals, during which one Cluster spacecraft was passing close to the X-line. Figure 4.11 (d) shows the first jet reversal from tailward (label 1) to sunward (label 2) velocities and the second reversal from sunward (label 3) to tailward (label 4) velocities, while panel (f) shows the magnetic field rotation at the two jet reversals.
Figure 4.10: The location of the X-line during northward IMF, as seen from the Sun. The squares represent the estimated location of the X-line while the magnetic shear at the magnetopause (calculated from a model) is color coded. (a) estimated X-line location where the magnetic shear is close to $180^\circ$, consistent with antiparallel reconnection (b) estimated X-line location where the magnetic shear is about $100^\circ$, consistent with component reconnection. Adapted from [85].

The magnetic shear calculated between the magnetosheath and magnetospheric fields at the first reversal is $\sim 100^\circ$ while at the second jet reversal is $\sim 160^\circ$. The observation of low magnetic shear at the first jet reversal is not consistent with antiparallel reconnection and thus provides in situ evidence of component reconnection. Panel (d) also shows that both the sunward and the tailward jet velocities during component reconnection are smaller than those observed during antiparallel reconnection, thus indicating that component reconnection is less efficient to accelerate plasma than antiparallel reconnection. This is expected since the Alfvén velocity at which ions are accelerated is smaller during component reconnection, due to the smaller magnitude of the reconnecting field.
Figure 4.11: In situ observations of component reconnection at the magnetopause under northward IMF. Panel (d) shows two reconnection jet reversals at the magnetopause where Cluster was close to the X-line. The magnetic shear calculated from panel (f) at the first reversal is \( \sim 100^\circ \) and thus consistent with component reconnection. Adapted from Paper I.

4.2.3 Continuity in time

Magnetic reconnection is \textit{continuous} in time if the reconnection rate is all the time different from zero, as sketched in Fig. 4.12. Continuous reconnection can be \textit{steady} or \textit{unsteady} depending on the fact that the reconnection rate is constant or not. Reconnection is \textit{intermittent} when it switches on and off and the reconnection rate drops to zero.

Figure 4.12: The reconnection rate during several types of reconnection.
The continuity of reconnection is important for the problem of the transport of mass, momentum and energy across the magnetopause. Continuous reconnection implies that solar wind plasma can continuously enter the Earth’s magnetosphere and this can have important consequences for the solar wind - magnetosphere coupling.

To be able to answer if reconnection is continuous or not, one should continuously measure the reconnection rate at the X-line. This is basically impossible from spacecraft measurements, since crossings close to the X-line are very rare and the residence time of spacecraft within the magnetopause is usually short. Remote observations of reconnection have provided indications of both intermittent reconnection [46] and continuous reconnection [29, 65] for a few hours. However these measurements have not been obtained directly at the magnetopause where reconnection is occurring. Previous observations at the magnetopause have been interpreted both as intermittent [72] and as continuous reconnection [32] but they were obtained by single spacecraft and only for short residence times within the magnetopause. Intermittent reconnection at the magnetopause has been associated to the observation of isolated reconnected flux tubes as the one shown in Fig. 4.13 and usually called flux transfer events (FTE).

![Figure 4.13: A schematic diagram of the reconnected magnetic flux tubes of an FTE at the subsolar magnetopause. The coordinate system is GSE. Adapted from [66]](image)

The possibility to have four simultaneous points of observation using Cluster has been used by [62] to show that magnetic reconnection is continuous at the magnetopause for about two hours, under steady southward IMF.

In Paper I we report in situ Cluster observations of continuous reconnection at the magnetopause for about four hours, under approximately steady northward IMF. The continuity in time is substantiated by the fact that, at almost all the magnetopause crossings during the four hours interval, Cluster observed accelerated flows consistent with reconnection.
The Walén test for these flows is shown in the left panel of Fig. 4.14, where each line represents an accelerated flow. A perfect Walén test corresponds to a vertical vector of unit length. Thus the observed flows were in good agreement with ongoing reconnection over four hours. This result is also confirmed in Paper II by the observations of predicted distribution functions for transmitted/reflected ions at most of the magnetopause crossings. A crucial condition for studying the continuity of reconnection in this event has been the availability of four points of observations simultaneously located at large distances. This condition, combined with the ideal trajectory of the spacecraft which were skimming the magnetopause, made it possible to have at least one spacecraft within the magnetopause over the four hours interval, thus substantially increasing the number of magnetopause crossings.

Figure 4.14: The Walén test during four hours of continuous reconnection. Each line in the left panel represents a reconnection jet at a complete (full line) and partial (dashed line) magnetopause crossing. The lines point up and down for tailward and sunward jets, respectively. Colors represent different spacecraft. The horizontal thick black bars indicate times when the all the spacecraft were far from the magnetopause and thus the occurrence of reconnection could not be tested. The orbit of the Cluster spacecraft in two different planes and the spacecraft separation are indicated on the right hand side. Adapted from Paper I.

4.3 Microphysics of reconnection

The MHD description of magnetic reconnection discussed in the previous section is no longer valid at ion $\sim \lambda_i$ and electron $\sim \lambda_e$ scales, where microphysical effects related to the dynamics of ions and electrons become important.

The microphysics is a crucial aspect of magnetic reconnection related to fundamental questions such as how reconnection is initiated, which factors determine the reconnection rate and the details of the energy conversion from the magnetic fields to charged particles. Despite of its importance, the micro-
physics of reconnection is still largely unexplored since experimental observations are few compared to those at large scales.

In Paper III we identify two regions which are important for the microphysics of reconnection: the X-region and the separatrix region, which are illustrated in Fig. 4.15.

The X-region is the region around the X-line where the major topology changes occur and reconnection starts. The separatrix region is the region between the magnetic separatrix and the reconnection jet. This region extends away from the X-line and most of the energy conversion occurs there. Each of these two regions is characterized by three nested subregions: the diffusion region, where $\int E_\parallel \neq 0$, the electron diffusion region, where $E + v_e \times B \neq 0$ and both ions and electrons are unmagnetized, and the ion diffusion region, where $E + v_i \times B \neq 0$ and ions are unmagnetized while the electrons move together with the magnetic field lines. The typical scales of the ion and electron diffusion regions are their inertial length scales or gyroradii scales. These concepts generalize the definition of diffusion regions typically used in the literature, where they are referred to as those small regions around the X-line where the frozen-in condition is broken for electrons and ions respectively. The frozen-in condition for ions and electrons is also broken inside the separatrix region away from the X-line, as it will be discussed in section 4.3.2.
4.3.1 The X region

A schematic diagram of the X-region is illustrated in Fig. 4.16.

During ongoing reconnection there is a tangential electric field $E_M$ along the X-line, as discussed in section 3.2. This electric field corresponds to the inflow of magnetic field lines and plasma towards the X-line and is a measure of the reconnection rate. The tangential electric field has been directly measured only in a few cases [53, 87] and its typical value $\sim 1\text{mV/m}$ corresponds to reconnection rates in the range 2-10%. The existence of reconnected field lines in the X-region implies a magnetic field $B_N$ perpendicular to the current sheet.

In the ion diffusion region, the condition $\mathbf{E} + v_i \times \mathbf{B} \neq 0$ has been directly verified by [53]. In this region ion and electrons move differently, since the first are unmagnetized while the latter are still magnetized and the Hall term in the generalized Ohm’s law 3.28 plays a major role. This decoupling produces a quadrupolar out-of-plane Hall magnetic field $B_M$ and a bipolar Hall electric field $E_N$ perpendicular to the current sheet. The Hall $B_M$ was first predicted by [79] and confirmed by numerical simulations [48, 75, 67, 68] and by both spacecraft [56, 53, 87, 13] and laboratory [70] observations. The Hall $E_N$ has been observed in spacecraft data [53, 87, 13]. The Hall electric field $E_N$ is much larger than the tangential electric field $E_M$ and the potential difference $\Phi$ associated to $E_N$ corresponds to ion energies $e\Phi$ consistent with the reconnection jet velocity [92]. The Hall physics within the diffusion region plays a very important role for the microphysics of reconnection and it has been suggested to be the reason for fast reconnection (rate $\sim 10\%$) in recent numerical simulations [11].
In the electron diffusion region the electrons also decouple from the magnetic field, as indicated by numerical simulations [67, 68]. The condition $\mathbf{E} + v_e \times \mathbf{B} \neq 0$ has been verified directly by [54]. However, very little is known about this region due to the small number of direct observations.

In the diffusion region $\int E_\parallel \neq 0$ and the topology of the magnetic field changes, as indicated by numerical simulations [67, 68]. The details of this region are also largely unknown due to the small number of observations. Only a few direct observations of $E_\parallel$ have been obtained in the X-region [53, 54]. Furthermore, it is not known which are the microphysical processes creating and supporting $E_\parallel$. Numerical simulations [36] suggest that the divergence of the electron pressure tensor in the generalized Ohm’s law 3.28 plays a major role.

Direct observations of the X-region at ion scales will be discussed in section 4.4 in the context of reconnection in turbulent plasma.

### 4.3.2 The separatrix region

The microphysics of the separatrix region has been recently investigated in numerical simulations [38, 25] and by using spacecraft observations [7, 16, 41]. Simulations [67, 68] indicate that parallel electric fields $E_\parallel$ extend away from the X-line in the separatrix region. Observations of bipolar $E_\parallel$ in solitary waves [49, 16] as well as unipolar $E_\parallel$ [52] have been reported. However the importance of these parallel electric fields for topology changes is not yet well understood. On the other hand, observations indicate that a large part of the energy conversion occurs in the region. Accelerated electron beams have been observed in this region [38] as well as strong electric fields [7, 52, 41].

Figure 4.17 shows an example of a separatrix region from Paper IV. The top panels show observations of density, electric and magnetic fields and waves while the schematic diagram below summarizes the main properties of the region. Observations are obtained during ongoing reconnection, which is substantiated by the evidence at MHD scales provided in Papers I and II. The separatrix region is indicated in the figure by the yellow vertical layer and it is the region between the magnetic separatrix and the reconnection jet (magenta layer). The region has the size of a few ion inertial lengths $\lambda_i$ and it contains a few subregions of typical size $\sim \lambda_i$ where strong electric fields and waves are found at scales down to the electron scale and even below. One such region, a density cavity adjacent to the magnetic separatrix, contains a strong Hall electric field perpendicular to the magnetopause, strong waves, Fig. 4.18 (a), and an accelerated electron beam, Fig. 4.18 (b), which indicates that electron energization occurs within the separatrix region.
An interesting feature is the observation within the separatrix region of short duration (~4s) magnetic bulges such as the one in Fig. 4.17 (c), which is indicated by a bipolar signature in the normal component $B_N$ of the magnetic field. These bulges are interpreted as freshly reconnected flux tubes (micro FTEs) which propagate away from the X-line and may indicate that reconnection is intermittent at short temporal scales (below a few ion gyroperiods).

![Diagram of separatrix region](image)

**Figure 4.17:** An example of separatrix region. The top panels show measurements of electric and magnetic fields and electric field waves. The schematic diagram below summarizes the main properties. Adapted from Paper IV.

The observations reported in Paper IV indicate that the separatrix region extends at a distance $\sim 50\lambda_i \sim 2500$ km from the X-line while keeping its internal structure with strong electric fields, waves and particle energization at ion scales and below. Since some of the magnetic field lines in the separatrix region are connected to the X-region, these results suggest that the microphysics of the X-region could be indirectly studied, at least partly, from observations in the separatrix region. This can be important from an experimental point of view, since spacecraft crossings of the tiny X-regions are usually rare compared with crossings of the much wider separatrix regions.
4.4 Reconnection in turbulent plasma

In this section we present the discovery by the Cluster spacecraft of magnetic reconnection in turbulent plasma.

Magnetic reconnection, as discussed in the previous sections, has been widely observed at large-scale boundaries in plasmas, such as the Earth’s magnetopause where the two large-scale interplanetary and terrestrial magnetic field get interconnected. However it has not been known whether and how reconnection occurs in small-scale boundaries such as those typically forming in turbulent plasmas. The possibility of this small-scale reconnection in turbulent plasma has been predicted by models and numerical simulations [51, 15, 24] and also suggested by laboratory [17] and solar [77] measurements. This kind of reconnection is important for the dissipation of electromagnetic energy in turbulent plasma and could be relevant for the acceleration of particles to very high energies.

In Paper V we present, for the first time, experimental evidence of reconnection in turbulent plasma by showing Cluster spacecraft measurements in a thin current sheet observed in the turbulent environment of the Earth’s magnetosheath. Figure 4.19 shows the location where reconnection occurs while Fig. 4.20 presents an overview of the turbulent environment of the magnetosheath.
Figure 4.19: The location of magnetic reconnection in the magnetosheath. The red line is the Cluster spacecraft orbit. The schematic diagram in the inset suggests how thin current sheets could form in the turbulent plasma between magnetic islands. Adapted from Paper V.

Figure 4.20 shows that the magnetosheath downstream of the quasi-parallel shock is strongly turbulent, with large amplitude fluctuations in density and magnetic field as well as accelerated and heated ions. The magnetosheath downstream of the quasi-perpendicular shock (after around 11:00 universal time) is much less turbulent. Figure 4.20 (d) shows that many thin current sheets with typical size of one ion inertial length are found only in the quasi-parallel region where the turbulence is stronger. The detailed properties of the turbulence are discussed in Paper VI.

Figure 4.21 shows the detailed evidence of reconnection in one thin current sheet. The observations are obtained in the diffusion region close to the X-line and are consistent with the schematic diagram in Fig. 4.16. The reconnection electric field $E_M \sim -0.5 mV/m$ in Fig. 4.21 (f) corresponds to plasma inflow towards the X-line, where the change in the magnetic topology is indicated by the normal component of the magnetic field $B_N \sim -1 nT$, Fig. 4.21 (c). In the current sheet energy is converted from the electromagnetic field to the plasma as indicated by $j \cdot E > 0$ in Fig. 4.21 (i). As a result electrons are accelerated away from the X-line, Fig. 4.21 (j), and their thermal energy is increased, Fig. 4.21 (m). The evidence for crossing the ion diffusion region comes from the observations of Hall magnetic field, Fig. 4.21 (b), and Hall electric field, Fig. 4.21 (g) as well as the fact that the current sheet is bifurcated, Fig. 4.21 (a), (h). The reconnection rate is approximately 10% since on both sides of the current sheet the inflow velocity in Fig. 4.21 (l) is approximately 0.1 times the Alfvén velocity. 

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Figure 4.20: Overview of the turbulent plasma environment in the terrestrial magnetosheath downstream of the quasi-parallel bow shock. Thin current sheets (color shaded in the last panel) are found only where large amplitude fluctuations in density and magnetic field as well as accelerated and heated ions are observed. Adapted from Paper V.

The observations demonstrate that fast reconnection occurs in turbulent plasma and that the turbulent plasma is heated and accelerated in the current sheet. Furthermore, the observation in Fig. 4.20 (a) of ions with energies much larger than their thermal energies suggests that particle acceleration to high energies is operating during turbulent reconnection. The acceleration to velocities higher than thermal velocities $V_{th}$ cannot be directly caused by reconnection, since the maximum velocity that particles can gain during reconnection is a few times the Alfvén velocity $V_A$ and $V_{th}$ is typically comparable with or larger than $V_A$. However, the small-scale nature of turbulent reconnection could create the conditions for the acceleration to high energies to take place in magnetic islands acting as local accelerators, as also is suggested by numerical simulations [50, 26]. In this case three-dimensional as well as time variation effects like inductive electric fields could be important.
In Paper VI we further investigate the relationship between the properties of the turbulent plasma and reconnection in thin current sheets. As a result, we find that a very large number of thin current sheets exists in the strong turbulence of the magnetosheath downstream of the quasi-parallel shock and that reconnection is ongoing in most of them. The formation of the thin current sheets is associated with the deviation from scale invariance in the turbulent plasma. This phenomena is called intermittency and means that, in a statistical sense, not all scales are equal but instead some scales are more preferred than others. Intermittency in a turbulent medium is usually associated with the presence of coherent structures at these particular scales. Figure 4.22 shows that the turbulent plasma in the magnetosheath is intermittent at scales corresponding to a few ion gyroradii, which could correspond to the size of coherent structures like magnetic islands or vortices between which the thin current sheets may form. In Paper VI we also estimate the contribution by reconnection in thin current sheets to the dissipation of electromagnetic magnetic energy in the turbulent plasma. We assume continuously ongoing dissi-
pation in all the observed thin current sheets at the measured dissipation rate \( j \cdot E \sim 1nW/m^3 \). By comparing this rate with the typical dissipation rate due to the damping of waves at ion scales, we conclude that reconnection in thin current sheets can be an efficient if not dominant energy dissipation mechanism in turbulent plasma.

\[ \frac{(B-B_0)}{\sigma} \]

\[ \text{PDF} \]

\[ 0.11s, 0.76s, 12s, 56s \]

**Figure 4.22:** Analysis of the intermittent behavior of the turbulent plasma using magnetic field data. Intermittency occurs in the left panel at temporal scales where there is a deviation from a gaussian behavior. These times correspond to spatial scales below a few ion gyroradii \( \rho_i \) as indicated in the right panel. See Paper VI for more details.

The discovery of reconnection in turbulent plasma was obtained by measurements in Geospace, but it has significant implications for laboratory and astrophysical plasmas too. In all these environments both turbulence and reconnection should be ubiquitous and thus turbulent reconnection quite common. Possible applications range from the dissipation of magnetic energy in fusion plasmas and in the solar corona to the acceleration of high-energy particles in solar flares and in cosmic rays.
5. Summary of the papers

Paper I


Cluster multispacecraft observations at the high-latitude duskside magnetopause: implications for continuous and component magnetic reconnection


This paper investigates a magnetic reconnection event at large temporal (a few hours) and spatial (a few thousands km) scales. The event occurs at the high-latitude magnetopause (MP) during mainly northward interplanetary magnetic field (IMF) conditions and sub-Alfvénic magnetosheath flow. The study uses multi-point Cluster spacecraft measurements of ion moments and distribution functions and of magnetic field. The spacecraft separation is a few thousands km. The event occurs on December 3, 2001 when the Cluster spacecraft were skimming the MP and the magnetospheric boundary layer (BL) for a period of about four hours. The orbit and the configuration of the spacecraft were such that at least one satellite was present in the MP/BL during most of that period. The paper presents evidence of reconnection in the form of tangential stress balance between the magnetosheath and the MP/BL (Walén test) and in several cases also in the form of transmitted magnetosheath ions in the MP/BL and incident/reflected magnetosheath ions in the magnetosheath boundary layer (MSBL). The observations are consistent with magnetic reconnection occurring tailward of the cusp (lobe reconnection) and being ongoing continuously for a period of about four hours since the Walén test was successful in almost all the MP crossings. The observed directions of the reconnection flows are consistent with the IMF orientation, thus indicating that reconnection is globally controlled by the IMF. Observations of a few flow reversals suggest that the spacecraft cross the MP close to the X-line. The observation of low magnetic shear across the MP during such a flow reversal is consistent with the component merging model.

My contribution to Paper I

I planned the study and analyzed the data. I wrote the paper. The other coauthors contributed to the planning of the study and to the data analysis.
Paper II

**Kinetic signatures during a quasi-continuous lobe reconnection event: Cluster Ion Spectrometer (CIS) observations**

This paper uses the same Cluster data set as in Paper I to investigate magnetic reconnection from a kinetic point of view. The study presents evidence of reconnection by showing the existence of a large number of secondary populations in the ion distribution functions i.e. ions of magnetosheath or magnetospheric origin which cross the magnetopause (MP) either way. The detailed analysis of the distribution functions shows that the X-line frequently moves relative to the spacecraft. However simultaneous measurements by two spacecraft on opposite sides of the reconnection site indicate that the spacecraft are always close to the X line, the distance from the X-line being less than 3000 km. The properties of the observed distribution functions agree with theoretical expectations on both sides of the reconnection site throughout the duration of the event (about 4 hours). This could be due to the vicinity of the spacecraft to the X-line. Moreover, the detailed analysis of the distribution functions shows evidence, during a few time intervals, of dual reconnection i.e. reconnection simultaneously going on in both hemispheres.

**My contribution to Paper II**
I contributed to the planning of the study and to analyze the data. I also contributed to the discussions in the paper.

Paper III
A. Vaivads, A. Retinò, M. André

**Microphysics of reconnection**

This paper review the basics of the microphysics of magnetic reconnection focusing on a space plasmas point of view. Magnetic reconnection is defined as a universal phenomenon where energy is converted from the magnetic field to charged particles as a result of magnetic topology changes, during which earlier separated plasma regions become magnetically connected.
Two regions are identified as important for the microphysics of magnetic reconnection: the X-region, where reconnection is initiated and most of the topology changes occur, and the separatrix region, where most of the energy conversion occur. The paper singles out the importance of the Earth magnetosphere as the best environment where the details of these two regions can be studied in situ. The main properties of the X-region and of the separatrix region are discussed, together with recent spacecraft observations.

My contribution to Paper III
I contributed to the planning of the study. I also contributed to the discussions in the paper. I wrote half of the paper.

Paper IV
The structure of the separatrix region close to a magnetic reconnection X-line: Cluster observations

This paper investigates the detailed microphysical properties of a magnetic reconnection separatrix region observed by one of the Cluster spacecraft on the magnetospheric side of the magnetopause during the same event as in Papers I and II. In particular the paper focuses on one of the reconnection jet reversals observed in Paper I. The separatrix region is the region located between the magnetic separatrix and the reconnection jet. The study uses high-time resolution measurements of electric and magnetic fields, electric field fluctuations and electron distribution functions. The separatrix region is several ion inertial lengths wide and contains a few subregions showing different features in particle and wave data. One such subregion, a density cavity adjacent to the separatrix, has strong electric fields, electron beams and intense wave turbulence. The separatrix region shows structures even at smaller scales, for example, solitary waves at Debye length scale. The paper describes in detail the wave-particle interactions in the separatrix region and compare them to a numerical simulation. The observations show that while reconnection is ongoing the separatrix region is highly structured and dynamic though the X-line is up to 50 ion inertial lengths away.

My contribution to Paper IV
I planned the study and analyzed the data. I wrote the paper. The other coauthors contributed to the planning of the study and to the data analysis.
Paper V

A. Retinò, D. Sundkvist, A. Vaivads, F. Mozer, M. André, C. J. Owen

*in situ* evidence of magnetic reconnection in turbulent plasma


This paper presents the first direct experimental evidence of magnetic reconnection in turbulent plasma. Magnetic reconnection occurs in a thin current sheet the size of about one ion inertial length. The current sheet is found in the turbulent plasma of the magnetosheath downstream of the Earth’s quasi-parallel bow shock. The occurrence of reconnection is substantiated by Cluster spacecraft measurements of key quantities such as tangential electric field, normal magnetic field, plasma flows and thermal energy of electrons which show the plasma inflow and accelerated outflow, the magnetic connection between both sides of the current sheet and the plasma heating within the current sheet. The paper shows that magnetic reconnection is fast and electromagnetic energy is converted into heating and acceleration of the turbulent plasma. The paper also indicates the presence of high-energy particles which seems to be produced during turbulent reconnection.

**My contribution to Paper V**
I planned the study and analyzed the data. I wrote the paper. The other coauthors contributed to the planning of the study and to the data analysis.

Paper VI

D. Sundkvist, A. Retinò, A. Vaivads, S. Bale

Dissipation in turbulent plasma due to reconnection in thin current sheets


This paper presents the detailed analysis of the turbulent plasma where reconnection was found in Paper V. The paper shows that a very large number of thin current sheets with a typical size of one ion inertial length exist in the plasma. The current sheets exhibit the microphysical signatures of magnetic reconnection. The plasma is strongly turbulent and shows intermittency at scales corresponding to a few ion gyroradii. The observed dissipation rates within the thin current sheets are comparable to or even dominating over collisionless damping rates of waves at ion scales, suggesting that reconnection can be a very efficient energy dissipation mechanism in turbulent plasma.

**My contribution to Paper VI**
I contributed to the planning of the study and to analyze the data. I also contributed to the discussions in the paper. I wrote some parts of the paper.
6. Sammanfattning på svenska


Magnetiska fält finns också i hela universum. Magnetfält finns runt jorden och andra planeter, såväl som på stjärnor i Vintergatan och andra galaxer, och runt hela galaxer.

transporteras från ena sidan till den andra av strömskiktet. Magnetisk återkoppling är en av de viktigaste och mest universella mekanismerna för frigörelse av energi i plasma och spelar en viktig roll i rymdplasma till exempel på solen och i plasma nära jorden.

En av de bästa platserna för studier av magnetisk återkoppling ur en observationell synpunkt är ett stort område runt jorden där plasma och magnetiska fält med ursprung på solen respektive jorden påverkar varandra. Till detta område är det möjligt att skicka rymdfarkoster och mäta in situ (på plats) både plasma och elektromagnetiska fält.

Solvinden innehåller plasma som kontinuerligt blåser från solen ut i solsystemet. Magnetfältet från solen transporteras av solvinden ut i interplanetärt område, där fältet brukar kallas för interplanetärt magnetiskt fält IMF. På ett avstånd av cirka 150 miljoner kilometer (1 AU, en astronomisk enhet) från solen växelverkar solvinden och IMF med jordens magnetiska fält, se Bild 2.6. Solvinden träffar jordens magnetfält med "överljudshastighet". Därför bildas en stationär chockväg framför jorden. Nedströms från chockvägen, i "magnetosheath" bromsas solvindens plasma till underljudshastighet och flyger runt jorden. Komprimerat och upphettat plasma i magnetosheath är väldigt turbulent, särskilt nedströms området där IMF är parallellt med normalen till chockfronten, en så kallad "quasiparallel chock".


En fundamental egenskap hos magnetisk återkoppling är att under processen kopplas små rums- och tidsskalor till motsvarande stora skalar. Återkoppling startar snabbt i små områden på grund av mikrofysikaliska processer, men den påverkar mycket stora områden i rymden under lång tid. Studier av magnetisk återkoppling på olika skalar är alltså ett viktigt forskningsområde.

I Artikel I och II har vi studerat magnetisk återkoppling på stora tids-(flera timmars) och rums- (flera tusen kilometers) skalor. Vi har visat att återkoppling kan pågå nästan utan avbrott under minst fyra timmar och alltså är en kontinuerlig process. Vi har också upptäckt att magnetisk återkoppling sker vid magnetopausen även när de återkopplande magnetiska fälten inte är strikt antiparallella.


Slutligen presenterar Artiklarna V och VI de första direkta observationerna av magnetisk återkoppling i turbulent plasma. I Artikel V presenterar vi upptäckten av magnetisk återkoppling i turbulent plasma genom att för första gången visa direkta mätningar av återkoppling i ett småskaligt strömskikt. Detta strömskikt finns i ett turbulent plasma i magnetosheath nedströms jordens quasiparallela chockvåg (Bild 2.7). I Artikel VI undersöker vi i detalj egenskaperna hos turbulent plasma. Artikeln visar att i ett turbulent plasma kan det finnas ett mycket stort antal tunna strömskiktar med pågående återkoppling. Återkoppling i turbulent plasma är alltså troligen ett vanligt fenomen. Upptäckten av återkoppling i turbulent plasma har gjorts i rymdplasma och bör vara viktig också för laboratorie- och astrofysikaliska plasma.
7. Summary and outlook

The work done in this thesis contributes to the experimental study of magnetic reconnection at different spatial and temporal scales. This has been achieved by using Cluster spacecraft observations in Geospace at different inter-spacecraft separations.

We have presented evidence of magnetic reconnection at the high latitude magnetopause at large temporal (a few hours) and spatial (several thousands km) MHD scales, by using in situ observations at large spacecraft separation (several thousands km). The two main results are the evidence of component reconnection and the continuity in time of reconnection four about four hours.

We have shown, by in situ observations of low magnetic shear at the X-line, that reconnection does not necessarily require antiparallel magnetic fields at the magnetopause. The fact that component reconnection occurs at the magnetopause, and most likely in other places, is relevant for the problem of transport across the magnetopause since it implies that solar wind plasma can enter the magnetosphere over larger volumes than in the antiparallel case. A few interesting questions arise from this result. First, is antiparallel reconnection just a very special case of component reconnection or instead the preferred way in which reconnection occurs? Second, does the reconnection rate decreases with the magnetic shear? Numerical simulations indicate that for moderate ratios between guide and reconnecting magnetic fields ($B_{guide}/B_{rec} \sim 1$) the reconnection rate does not change much while for larger guide fields ($B_{guide}/B_{rec} >> 1$) the reconnection rate decreases. Finally, a question is how much component reconnection is efficient to accelerate plasma at the magnetopause, compared with antiparallel reconnection. The observations presented here indicate that component reconnection is less efficient than antiparallel reconnection, as indicated by the smaller velocities of the ions accelerated during component reconnection with respect to the antiparallel case. To answer these questions, more measurements of the magnetic shear and of the reconnection rate in the vicinity of the X-line are needed.
We have shown, for one particular event, that magnetic reconnection is continuous for at least four hours under approximately steady interplanetary magnetic field. Reconnection may have been continuous for longer time during the event, however observations of reconnection jets were possible only during the four hours time interval when Cluster spacecraft were close to the magnetopause. This finding is important for the transport of mass, momentum and energy across the magnetopause and implies that solar wind plasma can continuously enter the Earth’s magnetosphere for long times. However some aspects of the continuity problem still require further investigation. Magnetic reconnection at the magnetopause is known to be controlled by external boundary conditions, mainly the orientation of the interplanetary magnetic field. In the case presented here, as well as in a few other similar observations, the interplanetary magnetic field was approximately constant during the four hours duration of the event. Thus it seems very likely that the time continuity at the magnetopause depends mainly on the external drivers rather than from its intrinsic nature. More observations under different boundary conditions would be necessary in the future to confirm the continuity of reconnection at large temporal scales. A crucial issue regarding the continuity problem is at which temporal scales reconnection is observed. In this study, we used measurements with a time resolution of four seconds, which is the spin period of Cluster. Higher time resolution measurements of the magnetic field during a particular magnetopause crossing have revealed the existence of short duration magnetic islands (micro-FTEs) propagating away from the X-line, which suggests that at shorter temporal scales reconnection could be intermittent. However, with measurements from only one spacecraft as for this crossing, it is hard to reach any conclusion. This is another point which would require further investigation, possibly of other events with shorter spacecraft separation, to be able to accurately reconstruct the motion of those magnetic islands.

We have investigated the microphysics of magnetic reconnection in a few examples at smaller spatial and temporal ion scales. We presented observations of a separatrix region at the magnetopause and discussed its detailed microphysical structure. The main result of this study is that the separatrix region is very dynamic and structured during ongoing reconnection even away from the X-line. In this region we found strong electric fields and waves as well as accelerated electron beams. Since the separatrix region is directly connected to the X-line through the magnetic separatrix field line, the fundamental question is how much information on the X-region that can be obtained by studying separatrix regions. Direct measurements in the X-region are difficult because of the low probability to cross this tiny region and observations are few. However, observations in the much extended separatrix regions could give indirect but still important information about the microphysics of the X-region, such as how reconnection starts at the X-line and how it develops in time. To better understand the relationship between the separatrix and the X-region we would need more observations, in particular
with different spacecraft simultaneously present in the separatrix region but at
different distances from the X-line.

We presented the discovery by the Cluster spacecraft of magnetic recon-
nection in turbulent plasma. Magnetic reconnection was widely observed at
large-scale boundaries such as the Earth’s magnetopause but it was not known
if and how reconnection occurs at small-scale boundaries such as those form-
ing in turbulent plasma, despite of the fact that models and numerical simu-
lations predicted this possibility. Our data showed, for the first time, experi-
mental evidence of magnetic reconnection in a thin current sheet found in the
turbulent plasma of the magnetosheath. Reconnection in turbulent plasmas is
fast and electromagnetic energy is converted into acceleration and heating of
the plasma. The study also indicates the presence of high-energy non-thermal
particles, which seem to be produced during turbulent reconnection. We also
analyzed in detail the properties of the turbulent plasma and we found that a
very large number of thin current sheets exist in the turbulent plasma, in most
of which reconnection is ongoing. Furthermore we showed that the dissipa-
tion of electromagnetic energy within the thin current sheets is comparable
to or even dominating over the dissipation due to ordinary waves, which sug-
gests that reconnection could be a very efficient dissipation mechanism in
turbulent plasma. The discovery of reconnection in turbulent plasma can have
significant implications for the study of laboratory and astrophysical plasmas,
where turbulent reconnection should be quite common. Possible applications
range from the dissipation of magnetic energy in fusion plasmas and in the
solar atmosphere to the acceleration of high-energy particles in solar flares
and in cosmic rays. However, further investigation is required in the future to
address a few key questions on turbulent reconnection. How common is mag-
netic reconnection in turbulent plasma and how does reconnection depend
on the properties of the turbulence? To address this point, one would need a
larger number of data sets from the magnetosheath and maybe also from other
turbulent space regions such as the magnetospheric cusps. Another relevant
question is how important reconnection is for the dissipation of electromagnetic
energy in turbulent plasmas. This question was partially addressed in
this thesis but needs further investigation. It would be also crucial to quantify
the importance of reconnection for the acceleration of particles to very high
energies. Reconnection in itself cannot accelerate charged particles to veloc-
ities higher than the Alfvén velocity, which is typically smaller or comparable
to the thermal velocity of the particles. However during turbulent reconnec-
tion particles could be accelerated to very high energies in small-scale mag-
netic islands working as local accelerators, where three-dimensional as well
as time variation effects like inductive electric fields are important. To quan-
titatively asses particle acceleration by turbulent reconnection, high-energy
particle detectors with higher sensitivity and better time resolution are re-
quired, as those planned onboard the NASA Magnetospheric Multiscale mis-
ion (MMS), whose launch is expected for 2013/2014.
The last point regards the relevance of the results presented in this thesis for future spacecraft missions. At the magnetopause we could prove that reconnection was ongoing on MHD scales because we had four points of observations located at large distances. However, the simultaneous analysis of the separatrix region at ion scales was done only with data from one spacecraft, due to the large spacecraft separation. For this region we could not distinguish between temporal and spatial variations, which is the key advantage of multi-point measurements. Furthermore no information could be obtained at the electron scales, which are crucial for the reconnection process. In the turbulent magnetosheath we could provide evidence of reconnection at ions scales because we had four-point measurements. However, no information was obtained at electron scales where reconnection starts. Furthermore, due to the lack of simultaneous measurements at MHD scales, we could not prove under which geometry the thin current sheet were formed in the turbulent plasma. Cluster observations have allowed us to only partially reveal the intricate multi-scale coupling of reconnection in these cases, and much more work is needed to get a complete picture. The detailed understanding of this multi-scale physics is a real challenge for the future. One of the lessons learnt from Cluster is that we need new space missions with a larger number of spacecraft equipped with instruments of better sensitivity and time resolution, such as the planned Cross-Scale mission which is currently being discussed as a future cooperation between ESA and the Japanese Space Agency JAXA. This mission would consist of twelve spacecraft covering simultaneously MHD, ion and electron scales and would have as a goal the study of the coupling between scales in magnetic reconnection, shocks and plasma turbulence.
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Bibliography


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