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Special Section:
Cluster 20th anniversary: results from the first 3D mission

20 Years of Cluster Observations: The Magnetopause

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Key Points:

- The magnetopause is a key region for transfer of mass, momentum and energy from the solar wind into the magnetosphere
- Cluster has probed the terrestrial magnetopause for more than 20 years
- An overview of key magnetopause results from the Cluster mission is given

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Abstract The terrestrial magnetopause forms the boundary between the solar wind plasma with its embedded interplanetary magnetic field on one side, and the terrestrial magnetosphere, dominated by Earth's dipole field, on the other side. It is therefore a key region for the transfer of mass, momentum, and energy from the solar wind to the magnetosphere. The Cluster mission, comprising a constellation of four spacecraft flying in formation was launched more than 20 years ago to study boundaries in space. During its lifetime, Cluster has provided a wealth of new knowledge about the magnetopause. In this paper, we give an overview of Cluster-based studies of this boundary, and highlight a selection of interesting results.

1. Introduction and History

When the solar wind plasma, with its embedded interplanetary magnetic field (IMF), encounters Earth's magnetic field, it slows down and is diverted around it, forming a magnetic cavity–the magnetosphere. The region of shocked and thermalized solar wind plasma just outside the the magnetosphere is known as the magnetosheath. Between that region and the magnetosphere itself, an electric current sheet, shaped as a paraboloid, is formed, with its sub-solar vertex at about 10–12 R_E (R_E = Earth radius ≃ 6371 *km*) upstream of Earth. This current sheet is what we call the magnetopause. It represents the outer boundary of the terrestrial magnetosphere. The constantly changing solar wind, causes the magnetopause to move back and forth by substantial amounts.

Boundaries in space, including the terrestrial magnetopause were among the primary science objectives of the Cluster mission (see e.g., Escoubet, 2021; Escoubet et al., 1997, 2001). Since launch in 2000, Cluster has been in operation for more than 20 years, and has provided a wealth of new knowledge about the magnetopause. As the first dedicated four-spacecraft mission, Cluster also paved the way for new multi-spacecraft methods to explore boundaries and discontinuities in space. But Cluster was not the first mission to have a focus on the magnetopause. Due to the key importance of the transfer of mass, momentum, and energy from the solar wind into the magnetosphere, transport across it has received a lot of attention and has been extensively studied during the past several decades.

One of the first descriptions of a sharp boundary between the solar wind and Earth's geomagnetic field can be found in Chapman and Ferraro (1930). Although that paper never uses the word "magnetopause," it describes how the solar wind ("a highly conductive stream") encounters the geomagnetic field, causing electrical currents in "surface layers" to be induced. Chapman and Ferraro envisaged this boundary to be within a few Earth radii of the center of Earth as shown in Figure 1a). Today, more than 90 years later, we know that the magnetopause is further away from Earth, and that the solar wind changes from supersonic to subsonic speeds at a bow shock, located upstream of the magnetopause. The region between the shock and the magnetopause is called the magnetosheath. Therefore, the interaction is not with the pristine solar wind, but with the plasma and field in this intervening region. However, the basic concept of a concentrated electric current flowing on a surface is still valid. Even today, these currents are often referred to as the Chapman-Ferraro currents.

With the advent of the space age in the late 50'es and early 60'es, in-situ observations of geospace became possible, and a new era of space research began. The first, unambiguous, in-situ observations of the magnetopause were reported by Cahill and Amazeen (1963), using field measurements from the Explorer 12 spacecraft. Figure 1b) shows a reproduction of one of their figures. In it, the magnetopause encounter is

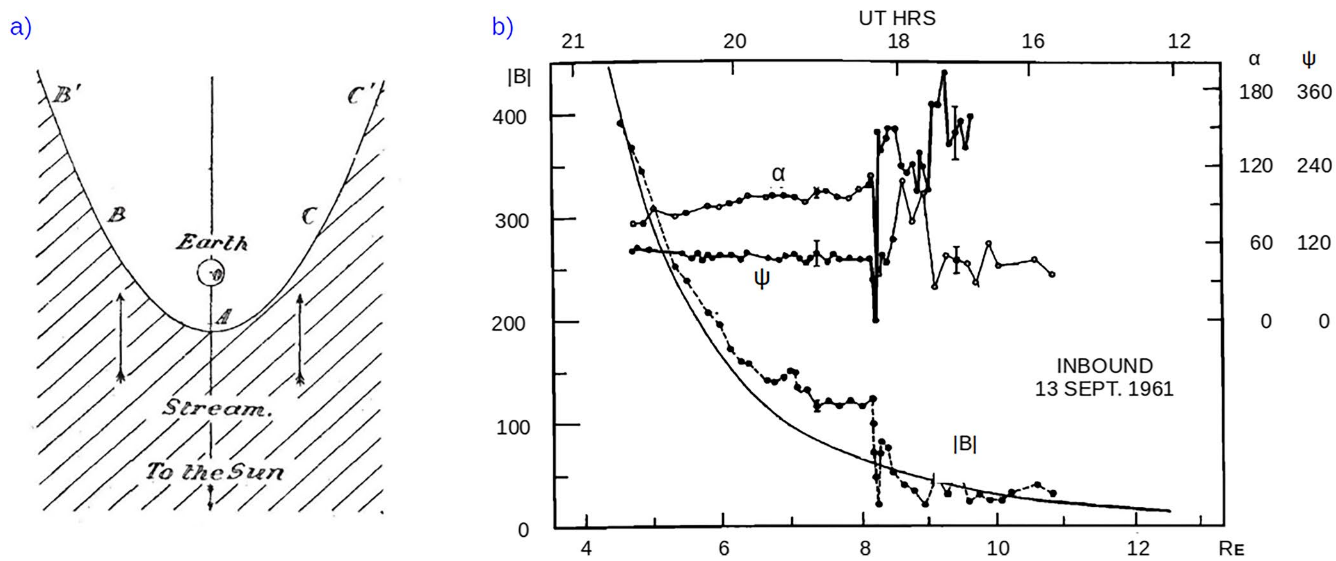

Figure 1. Panel (a) The magnetopause as envisaged in Chapman and Ferraro (1930). The '*Stream*' is what we today know as the solar wind. Note that they placed the magnetopause only '*a few Earth radii*' from the Earth. Panel (b) Magnetopause crossing in September 1961, observed by the Explorer 12 spacecraft and providing the first unambiguous evidence of this boundary. (After Cahill & Amazeen, 1963).

characterized by a distinct field rotation and a change in field magnitude, as the satellite crossed the dayside magnetopause around 8.3 R_E on an outward pass near local noon. Inside the magnetosphere (on the left in the figure), the magnetic field is nearly stable, with direction dominated by that of the geomagnetic field. In the magnetosheath (on the right), the field is highly variable. Earthward of the magnetopause but close to it, the measured magnetospheric field magnitude is seen to be about twice that expected from a pure dipole field. This enhancement was attributed to the magnetopause surface currents inducing a magnetic field that adds to the dipole field. Crossings of the magnetopause were also indicated by abrupt changes in energetic particle flux measured by the Explorer 12 energetic particle detector (Davis & Williamson, 1962; Freeman et al., 1963).

Explorer 12 data was also used by Sonnerup and Cahill (1967) in the first attempt to estimate the orientation of the magnetopause using minimum variance analysis (MVA) of the magnetic field measurements across the magnetopause. This technique and variants thereof are still used to estimate the orientation of current sheets, also in other regions of space. In Section 3.1 of our paper, we show how this technique can be expanded to utilize observations from multiple spacecraft and use combinations of plasma and field measurements.

A second major advancement in magnetopause physics came with the experimental verification of magnetic reconnection - a fundamental process in a magnetized plasma, involving conversion of magnetic energy into plasma kinetic energy. On a microscopic scale, magnetic reconnection involves a local decoupling between particles and the magnetic field. For ions and electrons, this occurs, respectively, at the ion and electron inertial length and gyroradius. At the magnetopause, reconnection allows for transfer of plasma mass, momentum, and energy across the magnetopause into the magnetosphere. Reconnection is regarded as the primary driver of magnetospheric and ionospheric dynamics, including space weather effects such as geomagnetic storms, magnetospheric substorms and aurora. Whereas the theoretical foundations of magnetic reconnection and application to space plasma had been worked out over several decades from the 40'es to the early 70'es (e.g., Cowley, 1974; Dungey, 1961; Giovanelli, 1947; Levy et al., 1964; Parker, 1963; Petschek, 1964; B. U. Ö. Sonnerup, 1974; Sweet, 1958; Vasyliunas, 1975), the first unambiguous in-situ observations of the process at the magnetopause were reported by Paschmann et al. (1979). They investigated ion and electron distributions from the ISEE-1 and 2 spacecraft during magnetopause crossings, and found flow speeds in the magnetopause layer that were much higher than in the adjacent magnetosheath and magnetosphere regions, and were correlated with the changes in the magnetic field, more precisely with the Alfvén velocity. The fast Alfveénic flows - now often referred to as *jetting* - are the most pronounced manifestation of the energy conversion. Jetting is now the most frequently used signature to identify reconnection events.

In terms of characterization and understanding of macroscopic properties of the magnetopause, the statistical study by Berchem and Russell (1982a); Berchem and Russell (1982b) brought further advancement in our understanding of the magnetopause. This was also one of the first systematic multi-spacecraft investigations of the magnetopause, in the sense that they utilized the two closely separated ISEE 1 and ISEE 2 spacecraft to calculate velocities and thicknesses for a large number of low latitude magnetopause crossings. The study revealed a highly dynamic magnetopause motion with back-and-forth velocities ranging from a few km/s up to several 100 km/s, presumably in response to changes in the solar wind pressure. Reported thicknesses were in the range 200–1,800 km, and the average across all local times was about 900 km, corresponding to about 10 ion gyro radii. For comparison, early theoretical considerations about the boundary between the solar wind and geomagnetic field (see discussions in e.g., Chapman & Ferraro, 1930; Dungey, 1958, 1963) initially stipulated the thickness of the magnetopause current sheet to be of the order of a solar wind proton Larmor radius.

The Magnetospheric Multiscale mission (MMS) (see Burch et al., 2016), launched in 2015 also targeted the magnetopause during the first mission phase. MMS builds on the success of the Cluster mission. Its primary science objective is to study magnetic reconnection, with particular emphasis on kinetic processes and the electron diffusion region (Phan et al., 2016; Torbert et al., 2018; Webster et al., 2018). Like Cluster, MMS is also a four spacecraft constellation flying in formation, but the focus on the electron diffusion region means that spacecraft separation distances were at times chosen to be very small (below 10 km at times). Much of the methodology (see e.g., Paschmann & Daly, 1998, 2008; Shi et al., 2019) originally developed for the Cluster mission has also been suitable for the MMS mission.

The purpose of the present paper is to provide an overview of Cluster's contribution to magnetopause research over the last two decades, and to highlight some of the most interesting results, a choice naturally biased by the authors' preference. We primarily focus on the current sheet constituting the magnetopause itself, and less about the adjacent boundary layers and possible consequences of magnetopause processes.

This paper is organized as follows: In Section 2 we start with an overview of Cluster's contributions to magnetopause research and provide a summary of scientific literature in which Cluster and magnetopause studies are the key elements. In Section 3 we focus on the novelty and specific advantages of the four spacecraft Cluster mission for magnetopause research. In Section 4 we highlight a few studies demonstrating some of the new results from the Cluster mission. Finally, Section 5 provides a summary of the paper.

2. Cluster Contributions to Magnetopause Research — An Overview

Cluster was launched in 2000 and started science operations in early 2001. The four Cluster satellites fly in formation with varying separation distance. Unlike many of the earlier and existing space mission mentioned in the above introduction, Cluster has a high inclination polar orbit. Initial apogee was around 19.4 R_E and initial perigee around 4 R_E, but during the more than 20 years in orbit, the line of apsides has moved down and there have also been maneuvers and changes in separation between the spacecraft to address different science questions.

2.1. Magnetopause Regions Probed by Cluster

Figure 2 shows ecliptic and meridional views of the magnetospheric regions traversed by Cluster. Apogee is in the tail around September equinox, but by November apogee has moved over to dusk and Cluster starts encountering the dusk magnetopause as shown in panel a). From around December until June, it traverses the magnetopause twice per orbit. At least in the initial years, apogee was near the ecliptic plane (apogee moves down with time - see orbit evolution in Escoubet, 2021), so magnetopause crossing near the flanks were typically at low latitudes. In Sections 4.4.2 and 4.4.1 we will highlight two Cluster magnetopause studies from the flank region.

Figure 2b shows the corresponding noon-midnight view of the northern hemisphere dayside magnetosphere. Cluster has its apogee near noon (12 magnetic local time ((MLT) around March equinox and crosses

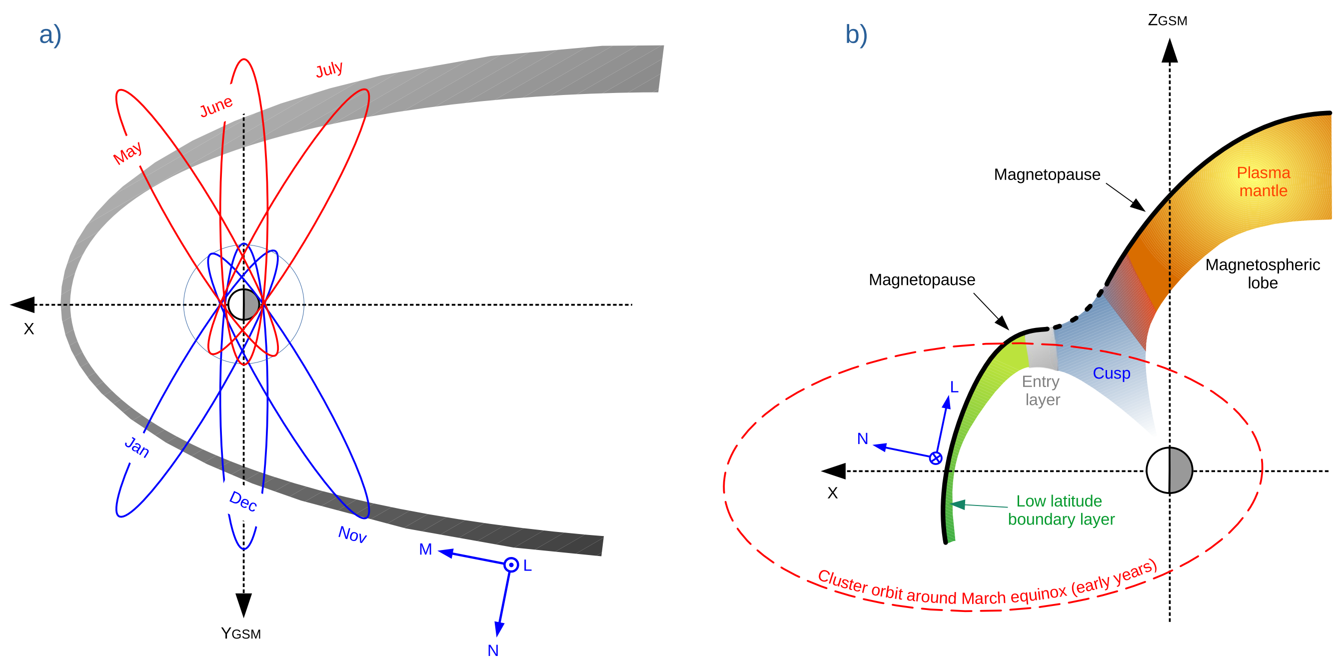

Figure 2. Key regions for Cluster magnetopause research and illustration of the LMN coordinate system. Panel (a) shows an XY view of Cluster's approximately 19×4 R_E orbit. The dawn flank is covered during the months May to July, and the dusk flank from November to early January. An example of a local LMN coordinate system is shown at dusk. Panel (b), adapted from Panov et al. (2008), shows a noon meridian view of the northern hemisphere dayside magnetosphere. The magnetopause is the thick black line, and colors show adjacent boundary regions. Depending on year, season, orbit and the prevailing configuration of the magnetosphere, Cluster can cross the high latitude dayside magnetopause either equatorward or poleward of the cusp, and/or through the cusp and its boundary regions. The red dashed curve in panel (b) shows an example of an orbit around March equinox for early years of operation, with magnetopause crossing equatorward of the cusp.

the magnetopause at high latitudes. Due to the orbit evolution over time, and configuration of the magnetosphere, crossings in a given hemisphere can be either poleward of the cusp, or equatorward of the cusp. In Section 4.1.2, we will highlight a Cluster case study from the high latitude magnetopause poleward of the cusp, and in Section 4.1.1 we highlight a study characterizing the high latitude magnetopause, using observations from both equatorward and poleward of the cusp.

When describing macroscopic features of the magnetopause, it is common to use a boundary normal system rather than a geocentric solar ecliptic (GSE) or geocentric solar magnetic (GSM) system as the one used in Figure 2. A commonly used coordinate system is the LMN system as described by for example, Russell and Elphic (1979). At the magnetopause, the convention is to let the **N** axis point outward (i.e., typically sunward at the dayside magnetopause), and the **L** axis along the tangent of the magnetopause, pointing northward. **M** completes the coordinate system so that LMN forms a right hand system. The LMN system is typically established by performing a minimum variance analysis of the magnetic field across the magnetopause, and flipped to meet the convention. As illustrated in Figure 2 this coordinate system is only locally valid; at dusk **N** will point along the Y_{GSM} or Y_{GSE} axis, while at dawn it will point almost in the opposite direction.

Likewise, when discussing internal structures and processes, a frame transformation is often used, and measurements are discussed in a frame co-moving with the magnetopause normal velocity. Often, a deHoffmann-Teller (e.g., Khrabrov & Sonnerup, 1998a) frame is used for this purpose.

2.2. Overview of Cluster Magnetopause Publications

Investigation of boundaries, including the magnetopause was a prime objective of the Cluster mission, and Cluster has provided a wealth of information about both macroscopic features of the magnetopause as well as small scale features and processes in the magnetopause. Initial results from the Cluster mission were published in a special issue of Annales Geophysicae in 2001 (see introduction in Escoubet et al., 2001), and scientific results from the first years of boundary studies were published in the volume 'Outer Magnetospheric

Boundaries: Cluster Results' in 2005 (Paschmann, Schwartz, et al., 2005). Since then, a number of additional Cluster-based studies of the magnetopause and its properties have been undertaken.

There is no single metrics for measuring the impact or knowledge gained from a project, but the number of publications in scientific journals as well as citations to these papers provide some insight. Fortunately, the archiving team at the European Space Agency (ESA) maintains a database of all Cluster related publications. At the time of writing, this database can be accessed from the Cluster Science Archives (CSA see Laakso, 2021) web pages via the URL https://sci.esa.int/web/cluster/-/39766-cluster-and-double-star-refereed-publications. Most of the papers in this database are also indexed using one or more keywords or index terms, and by searching this database (and consulting and cross checking with other on-line databases), and reading the abstracts, we found around 200 peer-reviewed papers with Cluster as the main data source and main focus on the magnetopause. (There are far more papers mentioning the magnetopause in either abstract or title, but the main focus is often another region, or the primary data are from other sources than Cluster. There are also a large number of non-refereed Cluster papers with focus on magnetopause physics in proceedings and reports).

Together, these studies and publications have addressed a number of aspects of the magnetopause, from small scale kinetic effects and processes via macroscopic properties such as orientation and motion to global scale properties like hemispheric and dawn-dusk asymmetries of the magnetopause. Many of the studies have also driven the development of new methodology, in particular methods utilizing multi-spacecraft observations, and have provided inputs to numerical simulations and modeling of the magnetopause and processes therein.

Figure 3 is an attempt to visualize in histogram form the large number of topics addressed in Cluster publications focusing on the magnetopause. Colors indicate topic and the length of each bar indicates the number of publications within that topic. A detailed list of Cluster magnetopause publications used as basis for this plot can be found in tabular form in Appendix A.

A large number of Cluster studies focus on macroscopic features, such as the magnetopause location, thickness and motion. Many of the studies deal with dynamic aspects of the magnetopause such as surface waves. As we shall see in Section 4.4.1, Cluster skims the flank magnetopause at low latitudes for extended time periods, thus providing an excellent platform for studying the evolution of Kelvin-Helmholtz waves as they travel down-tail along the flanks.

Another large number of papers are concerned with magnetic reconnection, which is a key process for the transfer of energy, mass and momentum from the solar wind into the magnetosphere. At the magnetopause, reconnection is typically observed either as a transient event (flux transfer events (FTE) see e.g., Fear et al., 2017) or as a continuous process over longer time intervals. We will highlight an example of the latter in Section 4.1.2. But observations from Cluster have also been used to argue for diffusion across the magnetopause (e.g., Gunell et al., 2012; Lundin et al., 2003; Panov, Büchner, Fränz, Korth, Khotyaintsev, et al., 2006).

Having been in space for more than 20 years, Cluster overlaps in time with other magnetospheric missions such as Geotail, THEMIS, DoubleStar and MMS, as well as a large number of low-Earth orbit satellites and ground based observations. Constellations of spacecraft from two or more missions have made it possible to study large scale phenomena such as the effects of geomagnetic storms simultaneously at several locations, or to follow their evolution and progress as they propagate through space. A recent example is the study by (Escoubet et al., 2020), in which the impact of a solar wind high stream jet (HSJ) on the magnetopause was observed simultaneously by Cluster at high latitudes and by MMS at low latitudes.

As the first space mission consisting of four spacecraft flying in formation, Cluster has also paved the way for new analysis methods. A narrow, current carrying boundary like the magnetopause provides an excellent platform to benchmark multi-spacecraft methods. In particular, the possibility to triangulate between several observation points, and the ability to derive gradients in plasma and field observations have been benchmarked using Cluster observations. This will be further discussed in the next Section.

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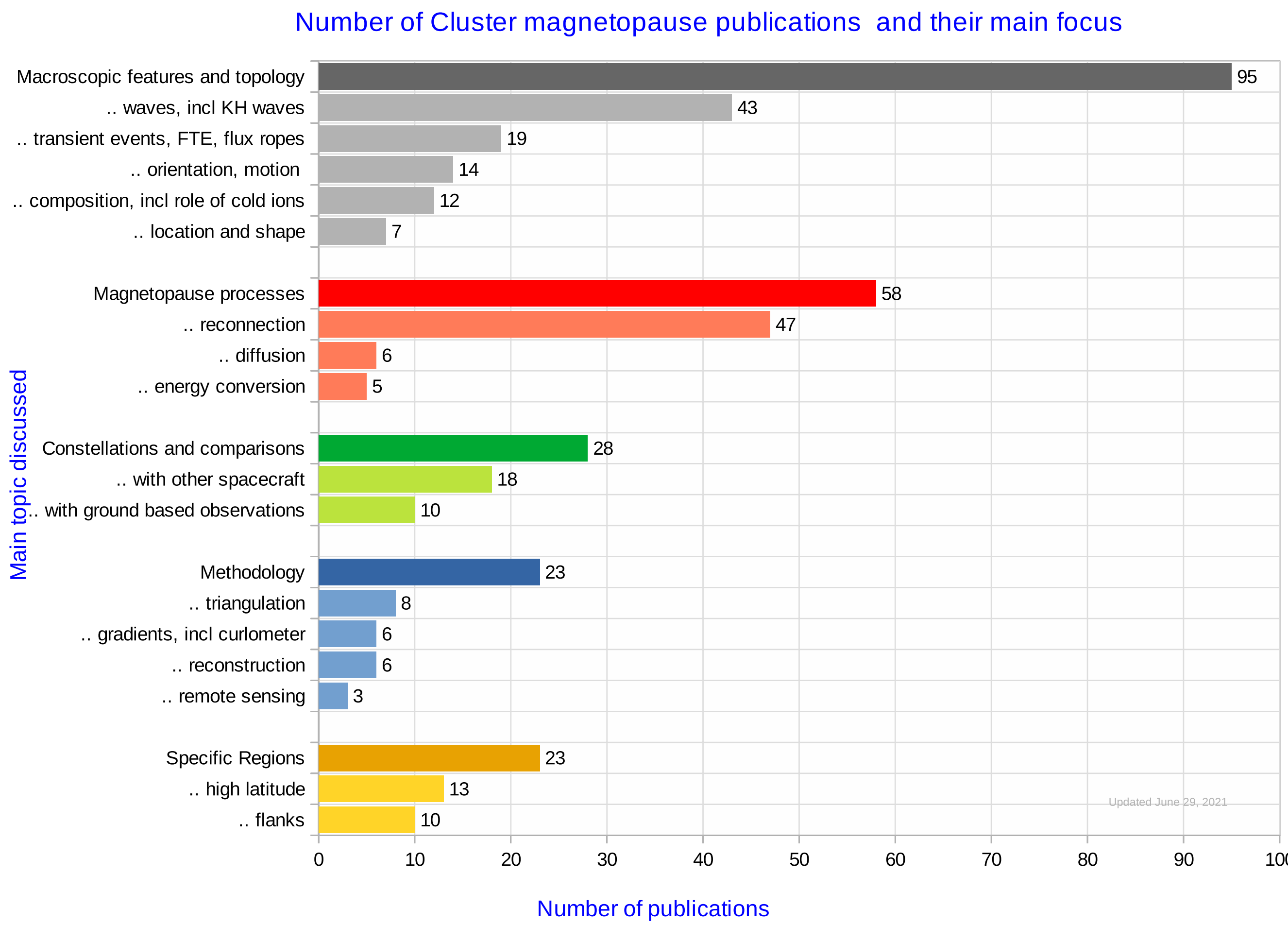

Figure 3. Graphical overview of magnetopause topics covered by Cluster publications during the period 2000–2020. Colors/groups indicate topics and length of the bars indicate number of publications. Some papers are listed in several categories.

3. Cluster Advantages for Magnetopause Research

A key feature of Cluster's success was the employment of four spacecraft flying in a tetrahedron-like formation in a polar orbit. With only one spacecraft, it was not possible to separate time variations from spatial variations. The ISEE, AMPTE and Interball-Tail missions each included two spacecraft (ISEE-1 and -2, launched in 1977; AMPTE-IRM and -UKS, launched in 1984; Interball 1 and Magion 4, launched in 1995), the members in each pair flying in nearly the same orbit. Those missions could already separate spatial from temporal variations in a limited sense. Cluster, with its four spacecraft flying in formation, provided the first opportunity to obtain fully three-dimensional measurements, thereby allowing unambiguous separation of time and space effects.

In the following subsections, we will use Cluster observations from a magnetopause crossing on June 16, 2002 to demonstrate some of these advantages.

3.1. Example of Cluster Observations at the Magnetopause

Figure 4 shows key observations from the magnetopause crossing on June 16, 2002. In this event, Cluster was initially in the magnetosheath, the region of plasma earthward of the bow shock, as manifested by the high ion density and temperatures around 1–2 MK in the left part of the figure. The flow speed is high, as expected at the flanks of the magnetopause. At around 01:43:40 UT, an abrupt change in plasma and field parameters takes place as the spacecraft cross the magnetopause into the magnetosphere, with its low density and hot plasma. The traversal of the magnetopause is manifested by a sharp rotation in the magnetic field

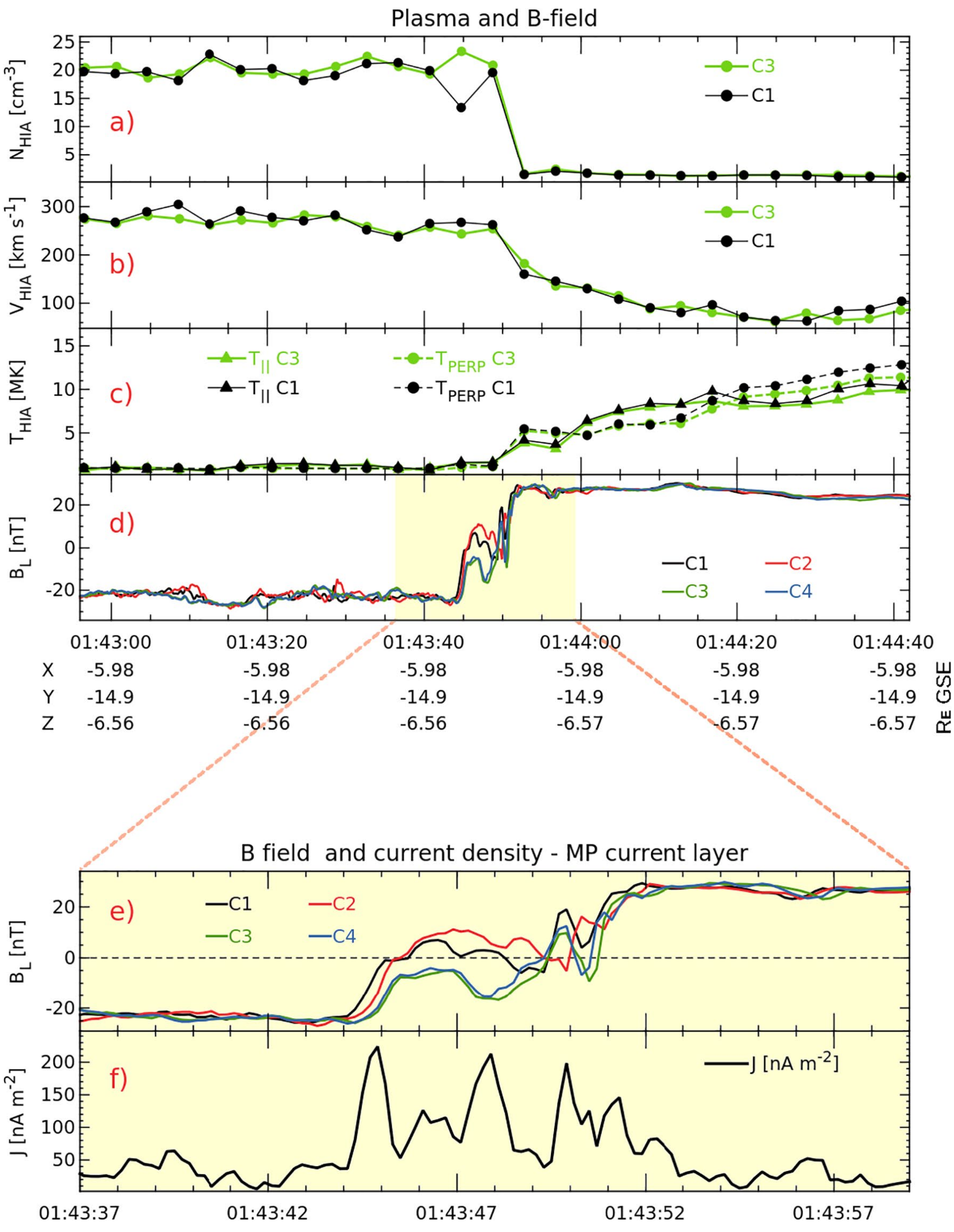

Figure 4. Cluster observations during a magnetopause crossing on June 16, 2002. Panels (a), (b), and (c), ion density, ion flow velocity, and ion temperature, from the CIS-HIA instruments on C1 and C3; Panel (d) Magnetic field, B_L component, for all f spacecraft. Panel (e) B_L component zoomed in around the current sheet. Panel (f) Current density as calculated from the curlometer method. From an event studied by Haaland et al. (2014).

as seen in panel (d). The magnetic field magnitude in the magnetosheath is typically (but not always) lower and more turbulent than the magnetospheric field, which is dominated by Earth's dipole field.

The magnetopause current sheet that produces the field rotation is observed only for about 9 s and thus is not resolved in the plasma moments with their cadence determined by the spacecraft spin period (≈4 s). Still, combined with the magnetic field, it is possible to derive the orientation and motion of the magnetopause. The boundary normal (in GSE coordinates) was determined to be $\boldsymbol{n} = [0.29–0.74–0.61]$, and its normal velocity as $V_n = 28$ km/s. With a crossing duration of approximately 9 s, the magnetopause current sheet thickness is therefore around 260 km. The peak current density (panel f), calculated with the curlometer method (see below), is just above 200 nAm^{-2} near the outer (magnetosheath) edge of the current sheet.

3.2. Analysis Methods

In preparation of the Cluster mission, analysis methods were developed that allowed to extract the most out of the 4-point measurements. They were described in several workshop proceedings, culminating in an International Space Science Institute (ISSI) book (Paschmann & Daly, 1998), with a follow-up once the methods had been tested on the actual Cluster data (Paschmann & Daly, 2008).

Of particular relevance for magnetopause studies are:

- the ability to use triangulation to determine orientation and motion of structures;
- calculation of spatial gradients, for example, to directly calculate the current density and to determine dimensionality and motion of plasma structures;
- the possibility to combine measurements from 2, 3, or 4 spacecraft to improve accuracy of the orientation and motion of discontinuities.

Details of triangulation and gradient calculations are discussed extensively in the above mentioned ISSI volumes about multi-spacecraft methods. They are also the focus of several papers in this special issue (Chanteur, 2021; Dunlop, 2021; Robert, 2021). Quantitative assessment of the errors for boundary analysis is discussed in Vogt et al. (2008); Vogt et al. (2011). The use of less than four spacecraft is described in Vogt et al. (2008).

Below we will discuss some of the methods.

3.2.1. Determination of Normal Direction, Velocity and Thickness

The quoted current sheet normal was determined from minimum variance analysis of the magnetic field data (MVAB) see e.g., Sonnerup & Cahill, 1967; B. Sonnerup & Scheible, 1998). For the case at hand, a variant of MVAB was applied, constrained so that the average $\boldsymbol{B} \cdot \boldsymbol{n}$ is zero. In fact, the quoted normal is a composite of the MVAB normals obtained for each of the four separately.

Once $\boldsymbol{n}$ is known, the boundary motion can be determined by dotting the plasma velocity, $\boldsymbol{V}$, as measured by the CIS instrument, for example, into the normal, that is, $V_n = \boldsymbol{V} \cdot \boldsymbol{n}$. A better method is to use the deHoffmann-Teller (HT) velocity (3.2.4) dotted into the normal vector, as discussed in Section 3.2.4.

Another method, referred to as Minimum Faraday Residue (MFR), (see Khrabrov & Sonnerup, 1998b), which determines both the normal direction and the velocity of a boundary. It is based on the property that in a co-moving frame the tangential electric field is continuous across a boundary.

With the advent of having four spacecraft flying in a tetrahedron-like formation, the boundary normal and motion can be determined from the timing of the crossings by the four spacecraft and their known positions, under the assumption that the velocity of the boundary is constant (Dunlop & Woodward, 1998; Harvey, 1998; Schwartz, 1998). Alternatively, one can assume that the boundary maintains a constant thickness when crossing the four spacecraft (Haaland, Sonnerup, Dunlop, Balogh, et al., 2004). The latter paper includes a comparison of the existing single-spacecraft techniques with those based on multi-spacecraft timing.

Once the velocity and duration of a boundary is known, its thickness directly follows. This way the thickness of the sample magnetopause quoted above was obtained.

3.2.2. Current Determination

Once the thickness, d, and the jump in magnetic field, ΔB, across the boundary are known, the average current density can be obtained from $j = \Delta B / \mu_0 d$. But with four spacecraft, one can apply a technique, commonly referred as the curlometer, where the current density is computed, for each time step, from Ampère's law (e.g., Dunlop et al., 1988; Robert et al., 1998), using a difference approximation to the curl of the magnetic field, that is, to $\nabla \times \boldsymbol{B}$.

Due to the close separation distance between the spacecraft in our example, all spacecraft are located inside the current sheet nearly at the same time. This makes it possible to calculate the current density, with the curlometer method, obtaining the time series shown in panel (f) of the figure, with peak values up to about 200 nA/m^2. For comparison, the values obtained from $\Delta B / \mu_0 d$ were about 150 nA/m^2.

3.2.3. Other Gradient Methods

The curlometer is one of the many gradient estimation methods made possible by the availability of four-point measurements. Another such method is the minimum directional derivative (MDD) method of Shi et al. (2005), which utilizes magnetic gradients to assess the dimensionality of a magnetic structure as well as its orientation. An extension of the method, termed Spatio Temporal Difference (STD) (see Shi et al., 2006), applied on the magnetic field can also provide the motion of the structure. An advantage of the MDD and STD methods is that the dimensionality, direction and velocity can be determined for each sample of a time series, and can thus provide information about the time evolution of the structure. An overview of applications of these methods can be found in Shi et al. (2019).

Magnetic curvature is yet another property based on gradient estimation applied to four-point magnetic field data (Shen et al., 2003). A general treatment of the errors associated with the gradient methods is provided by Vogt et al. (2008)

3.2.4. deHoffmann-Teller and Walén Analysis

The deHoffmann-Teller (HT) frame is a moving reference frame in which the convection electric field is minimized in the plasma, so that the plasma flow is optimally aligned with the magnetic field. The transformation velocity, $\boldsymbol{V}_{\mathrm{HT}}$, is obtained as described by Khrabrov and Sonnerup (1998a). Since the HT frame velocity is moving with the boundary, its normal component, $\boldsymbol{V}_{\mathrm{HT}} \cdot \boldsymbol{n}$, is a measure of the normal motion of the boundary at hand. The normal velocity $V_n = 28$ km/s quoted in Section 3.1 was obtained this way. The normal velocity calculated as $\boldsymbol{V} \cdot \boldsymbol{n}$, mentioned in Section 3.2.1, will include any exiting flow across the boundary.

Once an HT frame has been found, one can determine how close the plasma velocity, after transformation to the HT frame, is to ± the local Alfvén velocity, with the + sign for parallel flow along $\boldsymbol{B}$ and the – sign for antiparallel flow. Good agreement is usually taken as evidence for ongoing reconnection at the magnetopause, where a rotational discontinuity (RD) should be present to adjust the field direction from that in the magnetosheath to that in the magnetosphere (e.g., Levy et al., 1964).

3.2.5. Generic Residue Analysis

The combination of high quality field and plasma measurements also opens up new possibilities for single-spacecraft methods to study magnetopause properties. In particular, the availability of well-calibrated plasma moments with high time resolution led Sonnerup, Haaland, et al. (2006) to develop a unified minimum-residue approach for the calculation of boundary normals and motion of a discontinuity. Their approach is based on the fact that many key parameters, for example, mass, momentum, energy, charge, and magnetic flux are conserved in space - also across boundaries.

In addition to the benchmark testing by Sonnerup, Haaland, et al. (2006), the generic residue method has been applied on Cluster data and magnetopause crossings by for example, Palmroth et al. (2011); Anekallu et al. (2011, 2013); Dorville, Belmont, Rezeau, Aunai, and Retinò (2014); Dorville et al. (2015). A special case of generic residue, minimum variance analysis of current density (MVAJ), which combines gradient

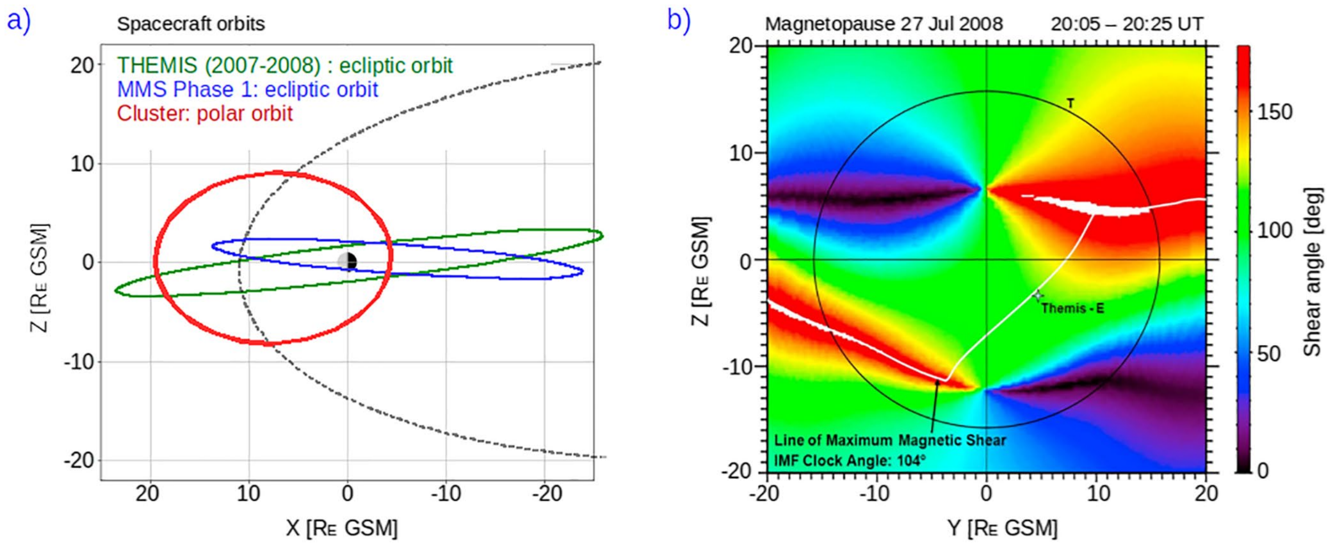

Figure 5. Panel (a): Cluster polar orbit (red color) compared with orbits of other multi-spacecraft missions in ecliptic orbits. Panel (b): Color coded magnetic shear during interplanetary magnetic field B_y dominated conditions. The region of maximum shear (white line/area) is shifted well above the equator on the dusk side, and well below the equator on the dawn side in this example. Spacecraft in ecliptic orbits (e.g., the indicated THEMIS-E spacecraft) would not be able to probe the region around a reconnection X-line located at high magnetic shear. (After Trattner et al., 2012).

calculations described above and residue analysis, was tested with Cluster data by Haaland et al. (2004) and Xiao, Pu, Huang, et al. (2004).

4. Cluster Magnetopause Highlights

Selecting highlights from a very successful mission with more than 20 years of observations is not an easy task, and any such selection will inevitably be biased by the author's interest. Still, in the next subsections, we present some of magnetopause studies which we think have contributed to significant advances in our understanding of the terrestrial magnetopause:

- High-latitude magnetopause reconnection with an optical signature
- Characteristics of the high latitude magnetopause
- Structure of the magnetic reconnection diffusion region
- Reconstruction of internal structures of the magnetopause current sheet
- Characteristics of Kelvin-Helmholtz waves at the flank magnetopause
- Large scale dawn-dusk asymmetries in magnetopause properties

4.1. The High Latitude Magnetopause

Cluster, with its high inclination polar orbit and constellation of four spacecraft, provides a new and unique possibility to investigate the high latitude magnetopause. Prior to Cluster, only the Interball-Magion two-spacecraft mission (see e.g., Sibeck & Kudela, 1999) had conducted systematic observations of the magnetopause in this region (e.g., Šafránková et al., 2005; Verigin et al., 2009).

Throughout its lifetime, Cluster has traversed the high latitude magnetopause both equatorward and poleward of the cusp. Properties and processes in the cusp itself have been addressed by for example, Cargill et al. (2005) and by Pitout (2021). Figure 5 illustrates the importance of the high latitude magnetopause and the advantage of Cluster to study this region. The right part of this figure shows a model of the magnetic shear (i.e., the rotation angle of the field) on the dayside magnetopause under a chosen positive IMF B_y condition. Solar wind-magnetosphere coupling through reconnection is expected to take place in regions where the magnetic shear is highest. In Figure 5b), the region of maximum shear is shifted northward on dusk and southward at dawn for this IMF By orientation (the IMF clock angle is 104° in this example).

Other multi-spacecraft missions like MMS or THEMIS would only cover up to approximately 35° magnetic latitude and would not be able to probe the central reconnection area for this common IMF direction, but only observe effects of reconnections remotely.

We note that the question of the actual location of a reconnection line on the magnetopause surface remains an open one. There are numerous theoretical and numerical studies of what has been called 'component merging', in which a finite magnetic field component is present along the reconnection line.

To illustrate Cluster's contribution to the investigation of the high-latitude magnetopause, we first present key results from a Cluster study by Panov et al. (2008) showing characteristics of the high latitude magnetopause. We thereafter highlight a study by Phan et al. (2003) showing reconnection poleward of the cusp, with a direct optical signature of the reconnection process.

4.1.1. Characteristics of the High-Latitude Magnetopause

For a few months around March equinox, Cluster has its apogee in the upstream solar wind and crosses the high latitude magnetopause and cusp region. Panov et al. (2008) used this opportunity to study characteristics of this region. Figure 2b) shown in Section 2.1 above is adapted from their paper, and shows a noon-meridian slice of the dayside magnetosphere with the magnetopause as a black line, and various magnetospheric boundary layers as color coded areas.

Depending on season (i.e., MLT), Cluster can cross the high latitude both poleward of the cusp or equatorward of the cusp (and obviously through the cusp itself). Also, both the magnetopause and cusp region move and change shape (and size for the cusp) in response to changes in the solar wind.

The study of Panov et al. (2008) contained 52 "proper" high-latitude magnetopause crossings, that is, crossings showing a magnetic field rotation where a clear magnetopause current sheet could be detected and characterized. Figure 6 shows an overview of the key parameters: magnetopause thickness, motion speed and current density similar to Figure 10. Colors now indicate crossings through the regions illustrated in Figure 2. Of the 52 crossings, 38 were equatorward of the cusp through the low latitude boundary layer and 11 crossings were poleward of the cusp from/to the plasma mantle.

In their summary, Panov et al. (2008) noted some distinct differences from earlier low latitude dayside studies, for example, by Berchem and Russell (1982b), and also noted different characteristics of the magnetopause current sheet poleward of the cusp compared to the high latitude magnetopause current sheet equatorward of the cusp. Among these are:

- The flapping motion (normal speed) at the high latitude magnetopause is approximately 30% slower than at the low latitude dayside magnetopause.
- The high latitude magnetopause is thicker than at the low latitude dayside.
- The high latitude magnetopause equatorward of the cusp was twice as thick and had half the current density of the magnetopause poleward of the cusp.

These observations suggests that the macroscopic nature of the magnetopause depends significantly on the geomagnetic latitude. Similar conclusions were also drawn already from preliminary analysis of Interball-Magion data reported in Šafránková et al. (1997).

4.1.2. A High Latitude Footprint of Magnetopause Reconnection

Magnetic reconnection enables transfer of mass, energy and momentum across the magnetopause. Prominent signatures of reconnection are fast plasma flow and mixture of plasma across regions. At the magnetopause, the presence of ionospheric material in the magnetosheath, or a presence of solar wind plasma inside the magnetosphere, is an indication of magnetic reconnection.

An illustrative event, demonstrating key signatures of reconnection is presented in Figure 7. On March 18, 2002, Cluster was traveling outward from the magnetotail lobe into the magnetosheath, and encountered the high latitude magnetopause poleward of the Cusp. As Cluster enters the magnetopause current layer around 14:54:52 UT, it observes strong plasma flows (top left panel), first in the tailward, that is, negative x-direction and then, at around 14:56:10 in the sunward (positive x) direction, before exiting into the the magnetosheath around 15:03:52 UT (Phan et al., 2003).

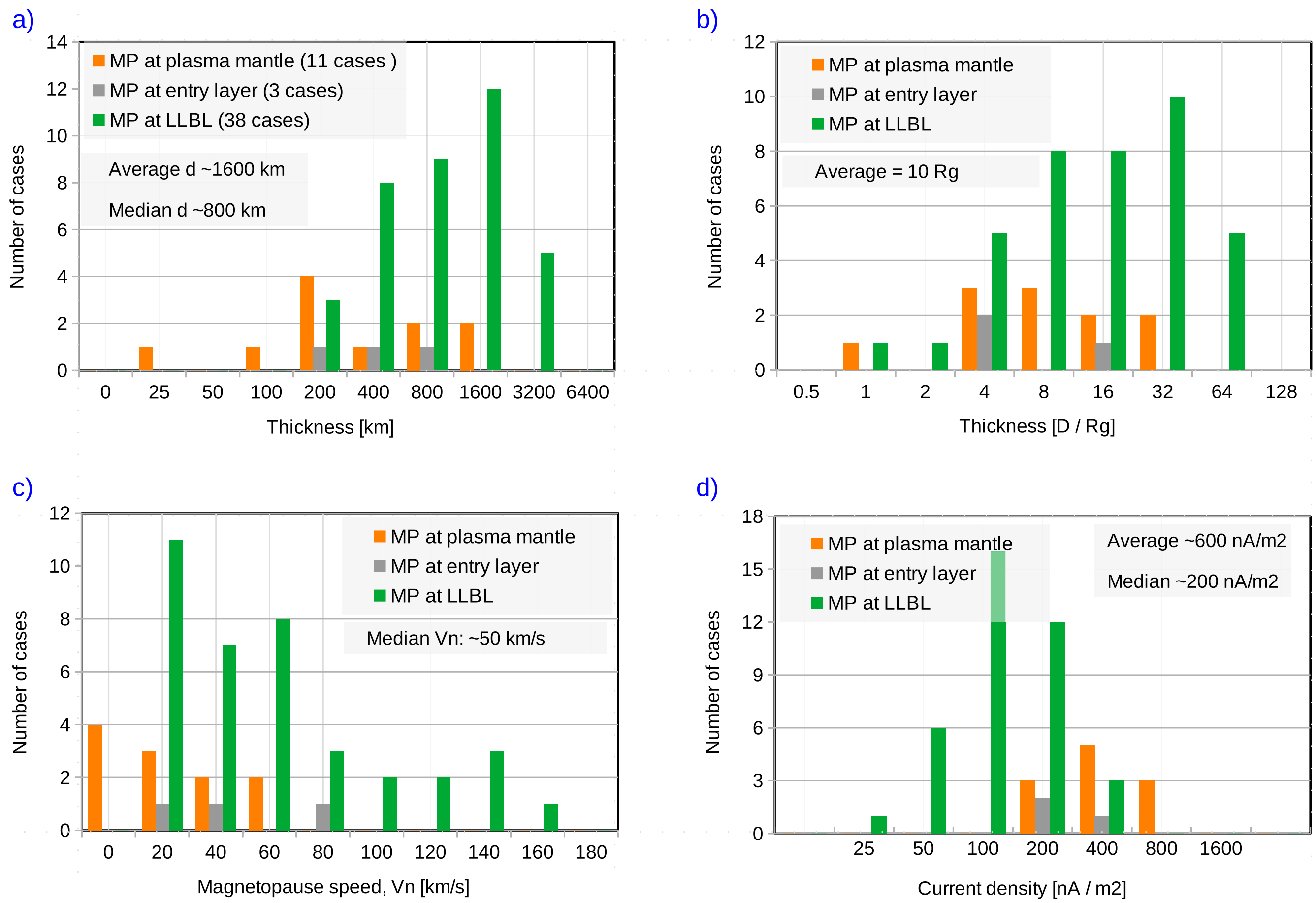

Figure 6. Histograms of magnetopause parameters from a set of 52 magnetopause current sheet crossings at high latitudes discussed in Panov et al. (2008). Colors indicate regions of the high latitude illustrated in Figure 2; green colors for crossings in/out of the low latitude boundary layer; orange color for crossings poleward of the cusp, and gray for crossings in/out through the entry layer (e.g., Paschmann et al., 1976). Panel (a) Distribution of thicknesses in units of km. Panel (b) Distribution of thicknesses in units of ion gyro radii (Rg). Panel (c) Distribution of magnetopause normal speeds. Panel (d) Distribution of current based on the curlometer technique.

The interpretation of the Cluster observations is given in the sketch at the top right of the figure. Reconnection is ongoing in a region poleward of the cusp due to the high magnetic shear there, between the IMF and the geomagnetic field. The observed flow reversal happened when the reconnection site (X-line) moved tailward across Cluster from the marked 1 to the region marked 2. As the sketch illustrates, Cluster was on magnetic field lines connected to the ionosphere, when the flow is directed sunward, while no such connection existed when the flow was directed tailward. Consistent with this topology, singly ionized oxygen ions of ionospheric origin were observed streaming along field lines while Cluster was on field lines connected to the ionosphere.

The reconnection jets were observed on field lines that are linked to a proton auroral spot observed by the Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) spacecraft in the ionosphere at the same time (Frey et al., 2003). The spot itself is a result of precipitation of protons accelerated in the reconnection region, traveling down the magnetic field lines until they precipitate in the ionosphere creating the auroral displays. Although Cluster could only observe reconnection for about 5 min, IMAGE observed the presence of the proton auroral spot over 4 h, as shown in the bottom panel of Figure 7, which implies continuous reconnection over this entire time interval.

As in the example just discussed, spacecraft stay in the magnetopause region only briefly, and that has often been taken as evidence that the process itself is intermittent. But in one encounter by Cluster of reconnection equatorward of the cusp (not shown here), it so happened that the plasma jetting, the most convincing

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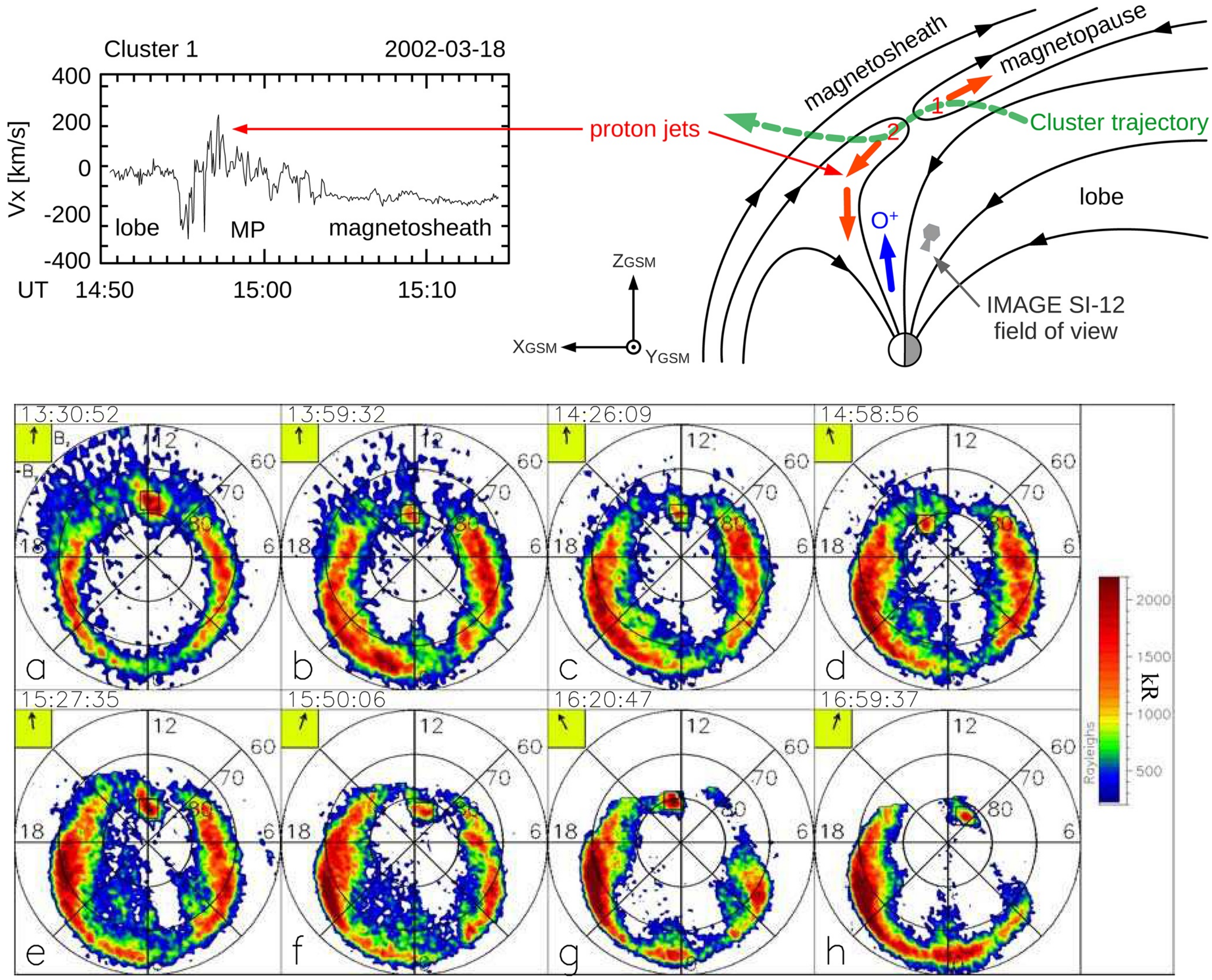

Figure 7. IMAGE-Cluster observations of continuous reconnection poleward-of-the-cusp magnetopause during northward interplanetary magnetic field. Cluster observations of reconnection jets at the high-latitude magnetopause on March 18, 2002, (top left panel) and a series of images of a proton auroral spot by IMAGE (bottom panel) on the same field lines. The sketch at the upper right shows, by red arrows, the jets created by reconnection, and by a blue arrow the upward streaming O^+ ions. The dashed green line shows Cluster's effective path through the magnetopause. After Phan et al. (2003); Frey et al. (2003).

evidence for reconnection signature, plasma jetting, while observed by each Cluster spacecraft only intermittently, due to the constant motion of the boundary, there was always one spacecraft immersed in the jetting plasma, consistent with a continuous operation of the reconnection process (Phan et al., 2004).

4.2. Structure of the Reconnection Diffusion Region

Magnetic reconnection is initiated in a small region, referred to as the diffusion region, where ions and electrons are no longer magnetized. The ions will demagnetize at the ion scale, due to the $\frac{1}{ne}\boldsymbol{j} \times \boldsymbol{B}$ (Hall) term in the generalized Ohm's law, while the electrons will remain magnetized. The ion and electron separation in the diffusion region leads to a pattern of Hall currents, which generate the quadrupolar Hall magnetic fields (Sonnerup, 1979), as first observed by Mozer et al. (2002).

Figure 8 shows a fortuitous encounter of the diffusion region at the dayside magnetopause by Cluster on February 20, 2002 showing measured out-of-plane magnetic fields that are consistent with the Hall magnetic field directions. In this encounter, two Cluster spacecraft observed oppositely directed Hall magnetic

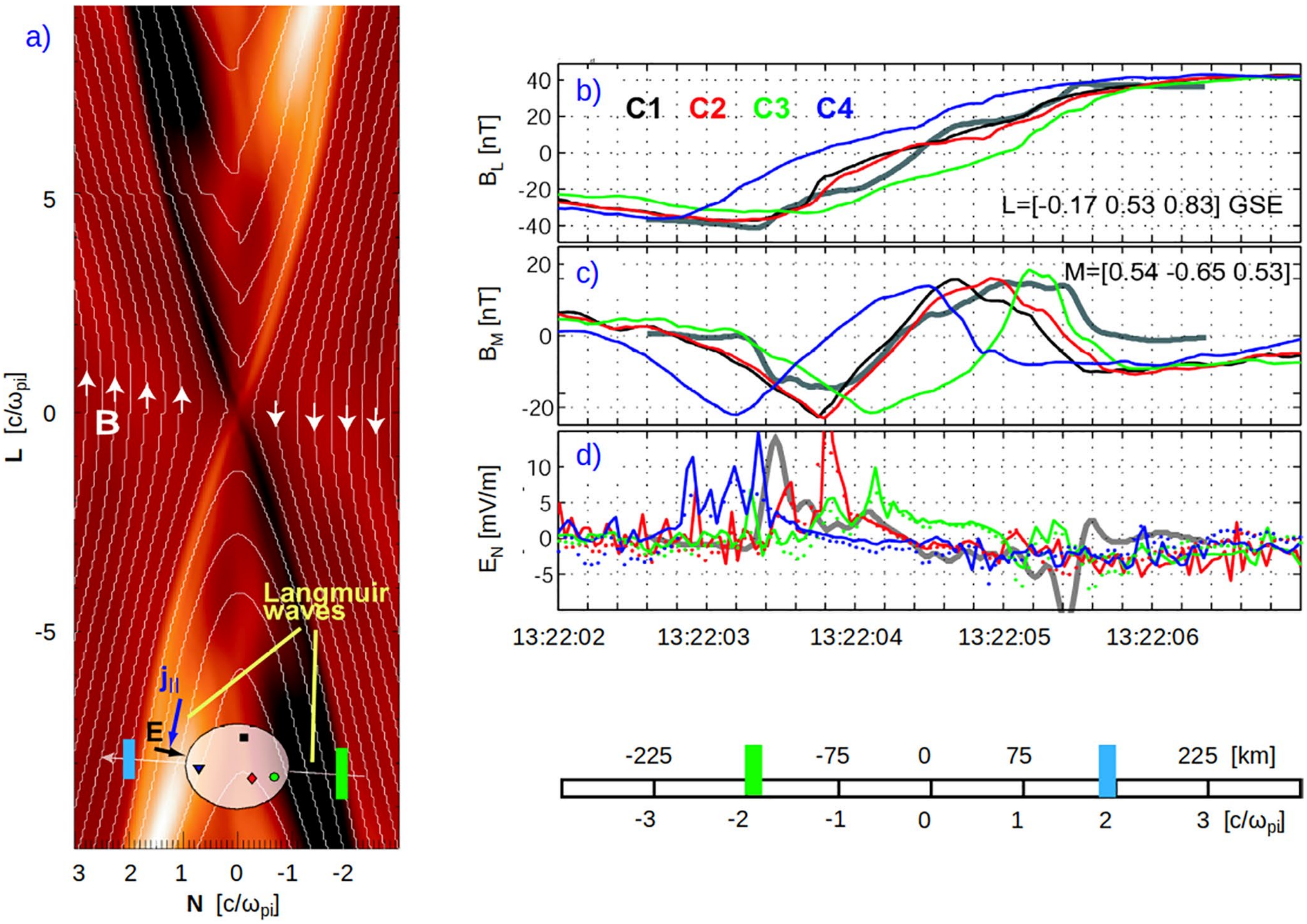

Figure 8. Panel (a): Structure of the diffusion region from a numerical simulation (Rogers et al., 2003) of a magnetopause crossing on February 20, 2002. Magnetic field lines are shown as thin white lines, the out-of-plane magnetic field component is color coded with white (black) indicating directions out of (into) the plane. Also shown is the Cluster configuration at his time, Right: Cluster observations: Panel (b): Reconnecting magnetic field component. Panel (c): Out-of-plane magnetic field component. Panel (d): measured electric field component normal to the magnetopause (solid lines), compared with the Hall term $\boldsymbol{j} \times \boldsymbol{B} / ne$ (dotted lines). Simulation results are overplotted in gray. The spatial scale is given along the bottom; green and blue markers refer to spatial positions indicated in panel (a) After Vaivads, Khotyaintsev, et al. (2004).

fields simultaneously, thus proving that the observed structure really had a spatial, not a temporal origin. This was possible only because the Cluster spacecraft were spaced about 100 km apart. In contrast, MMS, with its much smaller separation distances, while ideally suited for resolving the electron diffusion region, would not have been able to have two spacecraft on opposite sides of the underlying structure.

The spatial scale given along the bottom of the figure, inferred from the magnetopause velocity estimate based on four-spacecraft timing, with the result that the current layer thickness is a few ion inertial lengths.

4.3. Internal Structures in the Magnetopause Current Sheet

Four-spacecraft measurements by Cluster allowed to reveal internal structures of approximately one- or two-dimensional magnetopause current layers with reconstruction methods that can convert time series data recorded by spacecraft into spatial information on the structure. The assumption underlying the reconstruction is time independence of the structures, so that temporal variations of physical quantities seen by an observing probe can be interpreted as being due to spatial structures as they move past the spacecraft. There are two approaches for such a reconstruction, one only weakly constrained by physical models (De Keyser, 2005; De Keyser et al., 2004) and one constrained by models but better suited for specific plasma structures (B. Sonnerup, Hasegawa, et al., 2006). Here we summarize Cluster results from the physics-based

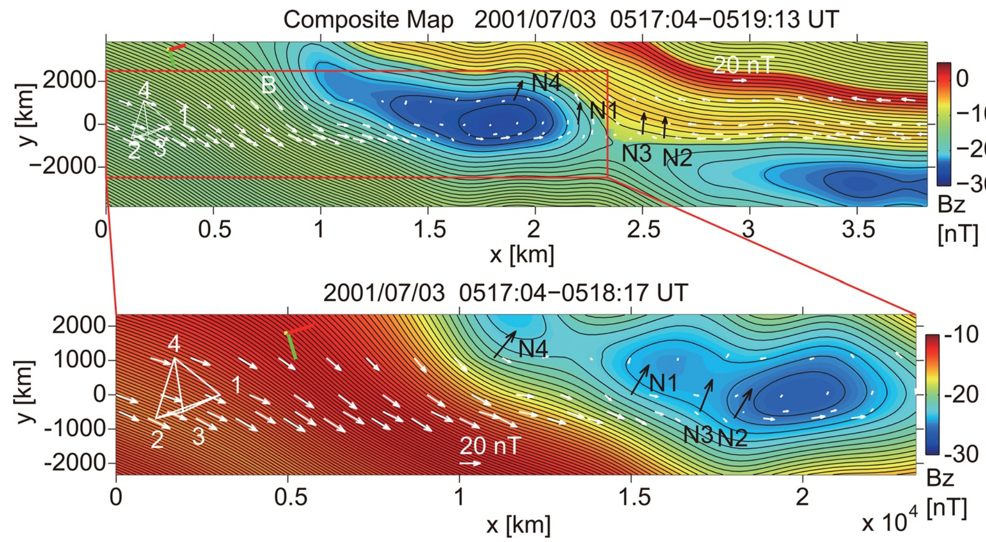

Figure 9. Magnetic field structure of the dawn-flank magnetopause recovered by the Grad-Shafranov reconstruction technique applied to Cluster data (Hasegawa et al., 2005). The white arrows show projections onto the reconstruction plane of the measured magnetic fields, black arrows are those of the current sheet normal directions from MVAB, and the red, green, and yellow bars in the upper-left part are those of the unit vectors of the GSE *x*, *y*, and *z* axes.

reconstruction, known as Grad-Shafranov (GS) and MHD reconstruction (Teh et al., 2007; B. Sonnerup et al., 2008), of the magnetopause and its internal sub-structures.

A basic concept of the GS and MHD reconstructions is that the fundamental equations believed to govern space plasma structures, such as the GS or MHD equation, can be solved as a spatial initial value (Cauchy) problem in which measurements are used to set the initial conditions at points along the spacecraft path. This contrasts with standard numerical simulations in which the governing equations are solved in time to investigate temporal evolution of physical quantities in a defined spatial domain. Theoretical details of the GS reconstruction and its variants were fully described by B. Sonnerup, Hasegawa, et al. (2006), and an overview of both the GS and MHD reconstructions was given by B. Sonnerup et al. (2008) and Hasegawa (2012). Essential parts of these reconstructions are single-spacecraft techniques. Nonetheless, multi-spacecraft information from Cluster has been crucial to validate the techniques, check whether the model assumptions are well satisfied for a chosen interval, and determine a proper coordinate system for the reconstruction.

Figure 9 shows an example of the GS reconstruction applied to a Cluster traversal of the dawn-flank magnetopause on July 3, 2001 (Hasegawa et al., 2005). Since the GS equation describes the balance between magnetic tension and the force from total pressure gradient, the successful reconstruction indicates that the island was in an approximate magnetohydrostatic equilibrium. Cluster data for the same interval were analyzed by Nykyri et al. (2006) in the context of magnetic reconnection induced by the Kelvin-Helmholtz (KH) instability. The reconstructed structure indicating a large-scale magnetic island embedded in an undulating magnetopause current layer is consistent with their suggested scenario of reconnection at the KH-perturbed magnetopause.

The GS and MHD reconstructions have been successfully applied to the magnetopause current sheets of tangential and rotational discontinuity-types (Hasegawa, Sonnerup, et al., 2004; Teh & Sonnerup, 2008; Teh et al., 2007), flux transfer events (FTEs) (Hasegawa et al., 2006; Sonnerup, Haaland, et al., 2004) and KH vortices (Hasegawa et al., 2009). These results show that the magnetopause can evolve from tangential discontinuity-type to rotational discontinuity-type, consistent with the growth of magnetopause reconnection (Hasegawa, Sonnerup, et al., 2004). Flux transfer events (FTEs - see e.g., Russell & Elphic, 1978) are often composed of non-force-free flux ropes with sizes of order 1 R_E and significant core field, consistent with component merging (Sonnerup, Hasegawa, & Paschmann, 2004).

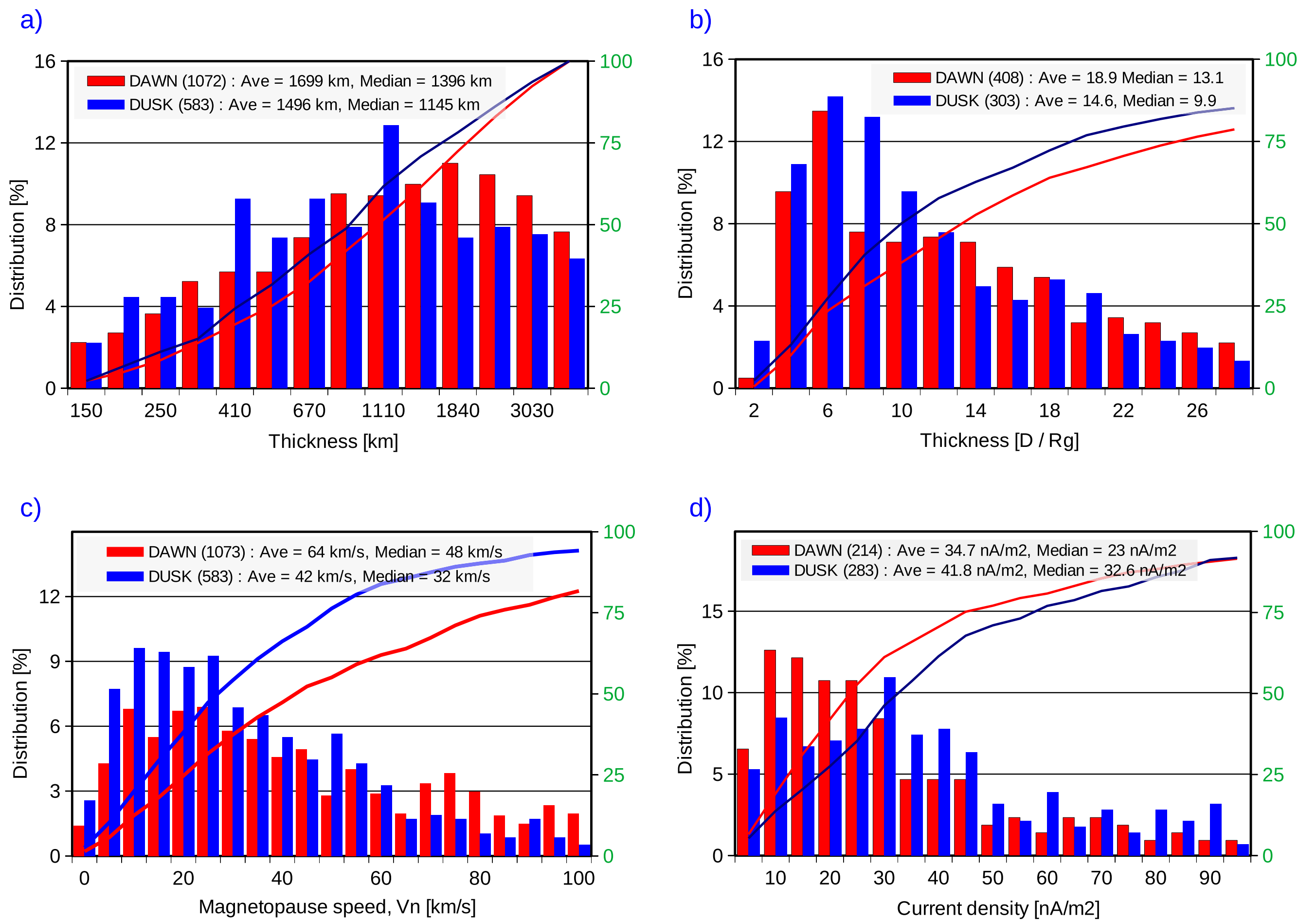

Figure 10. Similar to Figure 6, but now showing characteristics of the flank magnetopause. Red colors indicate dawn crossings, blue color indicate dusk crossings. The distributions show: Panel (a): thickness in units of [km]. Panel (b): thickness normalized to ion gyro radius. Panel (c) magnetopause normal motion. Panel (d) magnetopause current density. Lines, associated with the green scale at the right of each frame shows accumulated values (0.. 100%). After Haaland et al. (2014).

4.4. The Flank Magnetopause

With its near 20 R_E apogee, Cluster skims the dawn and dusk flank magnetopause for long time periods around May to July (dawn flank) and November to January (dusk flank) as illustrated in Figure 2a). During these intervals, Cluster spend extensive time in or near the continuously moving magnetopause. This provides opportunities to conduct studies of magnetopause waves on both flanks, and also to characterize the flank magnetopause and assess any large dawn dusk asymmetries in magnetopause properties.

Already the first published Cluster magnetopause crossing results by Dunlop, Balogh, Cargill, et al. (2001) noted how dynamic the flank magnetopause can be. They analyzed Cluster magnetic field observations from the first year of dusk crossings during the commissioning phase in November, 2000, (i.e., before the official Cluster science operations began). Despite small spacecraft separation distances they noted that the magnetic field profile changed over the sequence of spacecraft crossings, suggesting strong accelerations of the magnetopause. While these initial results were associated with a coronal mass ejection and strong compressions of the magnetosphere, subsequent Cluster observations, also during less disturbed conditions, suggest that the flank magnetopause is very dynamic with significant wave motion present much of the time.

A systematic study of a large number of magnetopause crossings at the dawn flank of the magnetopause was reported in Paschmann, Haaland, et al. (2005). Their study, consisting of a total of 96 dawnside magnetopause crossings during a 20 h period on July 4 and 5, 2001, also revealed a highly dynamic magnetopause, but with average motion, thickness and current densities very similar to earlier results by for example, Berchem and Russell (1982b) from the dayside magnetopause. Paschmann, Haaland, et al. (2005) applied the Walén test to a total of 60 of the dawn crossings, and have classified 19 cases as rotational discontinuities (RDs), of which 12 and 7 were crossings sunward and tailward of an X-line, respectively.

4.4.1. Kelvin-Helmholtz Waves at the Magnetopause Flanks

Prior to Cluster, it was difficult, if not impossible, to unambiguously identify complex two- or three-dimensional structures, such as Kelvin-Helmholtz (KH) waves in the nonlinear stage, which were suggested to be the key to efficient entry of solar wind plasma into the magnetosphere under northward IMF conditions Fairfield et al. (2000). But with the four spacecraft properly separated (inter-spacecraft separation ≃ 2,000 km), Cluster detected rolled-up KH vortices with a size of order 1 R_E at the dusk-flank magnetopause under northward IMF (Hasegawa, Fujimoto, et al., 2004). Ever since, the Cluster observations have been useful to better establish the methodology to identify vortices at the magnetopause (Cai et al., 2018; Hasegawa et al., 2006). A review of single- and multi-spacecraft methods for identifying and analyzing KH waves/vortices can be found in Hasegawa (2012).

Major results on the magnetopause KH instability from the Cluster mission can be summarized as follows. Cluster

- revealed the conditions under which and locations on the magnetopause where KH waves/vortices can be excited
- observed KH waves at the flank magnetopause under southward as well as northward IMF conditions (Hwang et al., 2011), and at the high-latitude magnetopause but equator-ward of the cusp for B_y-dominated IMF conditions (J & et al., 2021)
- identified signatures of kinetic processes likely induced by the growth of the KH instability, suggesting that cross-scale energy transport is at work at the KH-perturbed magnetopause
- observed signatures of reconnection, the most promising mechanism for the solar wind entry, in and at the trailing edge of KH vortices (Hasegawa et al., 2009; Nykyri et al., 2006).
- observed Kinetic Alfven waves, an agent for diffusive plasma transport across the magnetopause, in KH vortices, consistent with their excitation through mode conversion from KH surface waves (Chaston et al., 2007).
- observed ion-scale waves such as fast magnetosonic mode, which may heat ions, and which had more power in boundary layers earthward of the KH-active magnetopause than in those without KH-activity (Moore et al., 2016, 2017)
- provided observations consistent with the excitation of Pc5 ultra-low-frequency waves in the magnetosphere via the KH instability (Rae et al., 2005)

These Cluster results have been corroborated by new observations by the Double Star TC1 (Taylor et al., 2012), THEMIS (Kavosi & Raeder, 2015), and MMS spacecraft (Eriksson et al., 2016; Nakamura et al., 2017).

We refer to papers by for example, Johnson et al. (2014) and Masson and Nykyri (2018) for more details about observations of the KH instability in planetary magnetospheres, and J and et al. (2021) in this special issue for a full overview of Cluster results on KH waves/vortices in the terrestrial magnetosphere.

4.4.2. Global Dawn-Dusk Asymmetries in Magnetopause Properties

A comprehensive study and comparison of the low latitude dawn and dusk magnetopause flanks was conducted by Haaland and Gjerloev (2013); Haaland et al. (2014) using Cluster observations. They started out with observations from about 5,800 magnetopause crossings to characterize the dawn and dusk magnetopause. For a large number of these crossings, it was possible to calculate reliable orientation, motion and current densities from the methods in Section 3.2.

Figure 10 shows a summary of the results of Haaland et al. (2014) in the form of histograms of key parameters for the magnetopause at dusk (blue color) and dawn (red color). A systematic dawn-dusk asymmetry can be found in many of the parameters: The magnetopause at dusk moves slower, is thinner and has a higher current density than at dawn.

With Cluster observation alone, one could perhaps argue that the observed asymmetries are seasonal rather than true dawn-dusk asymmetries. However, similar studies (Haaland et al., 2019, 2020) were later conducted with THEMIS and MMS, which have different orbital phasing from Cluster. Both these studies also show similar dawn-dusk asymmetries. There is still no consensus about explanations for the large scale dawn-dusk asymmetry in magnetopause properties (or many other dawn-dusk asymmetries in geospace - see e.g., Haaland et al., 2017). It is likely that upstream factors such as shock geometry and the predominantly ± By orientation of the IMF (Parker-spiral) play a role.

5. Summary and Outlook

At the time of writing, the four-spacecraft Cluster constellation has been in operation for more than 20 years. With an orbital period of approximately 57 h, and each orbit involving two traversals through the magnetopause, each Cluster spacecraft has therefore flown through the region of the magnetopause close to 2,500 times. Due to the oscillatory motion of the magnetopause in response to changes in the solar wind, many passes comprise multiple crossings, so that the real number of magnetopause crossings is far higher.

The large number of Cluster observations of the magnetopause has provided a wealth of new information about properties of the magnetopause and processes inside the magnetopause current sheet. As the first constellation of four spacecraft flying in formation, Cluster was the first mission to utilize 3D-triangulation to determined determine orientation and motion of the magnetopause. Cluster was also the first mission able to calculate 3D gradients. Throughout the 20 years of operation, this ability has been used extensively to calculate current densities using the curlometer method - an implementation of Ampeére's law. As shown in Section 4.1.2, observations from Cluster have also been used to establish a direct link between magnetopause reconnection and auroral emissions.

Having more than one spacecraft has also enabled far better opportunities to verify and check results from single spacecraft observations and methodology. In particular, reconstruction of internal structures of the magnetopause using Grad-Shafranov or MHD reconstruction techniques enabled a glimpse of internal structures of the magnetopause, including X-lines and magnetic islands as shown in Section 4.3. The variable spacecraft separation distance has also enabled an unambiguous identification of Hall currents in the diffusion region of a reconnection region, as shown in Section 4.2.

The Cluster mission has also driven the development of new methods to explore multi spacecraft measurements. These methods are also being utilized by newer missions like THEMIS, MMS and low orbit constellations like SWARM and CHAMP.

Only a fraction of the magnetopause crossings by Cluster have been investigated in detail. While statistical studies using a large number of Cluster magnetopause crossings have addressed macroscopic features such as large scale dawn-dusk asymmetries and Kelvin-Helmholtz waves along the magnetopause flanks, Cluster observations from the dayside, high latitude regions are still underutilized.

Cluster is still in operation, and the large data set will be valuable also in the future. Upcoming missions like SMILE (e.g., Raab et al., 2016) and planned missions like STORMS (https://stormmission.com) will also target the magnetopause and solar wind - magnetosphere interaction. 20 years of observations from Cluster will provide valuable inputs for the planning and science operation of these missions-even after the Cluster satellites themselves eventually cease operation and reenter the atmosphere in a few years.

Appendix A: Cluster Magnetopause Publications

Table A1 contains a list of Cluster papers with main focus on the magnetopause, and organized by topic. Note that some papers cover two or more topics, and will be listed under two categories.

Table A1
List of Publications Where Cluster has Been the Primary Source of Observations, and the Main Focus has Been on Properties or Processes at the Magnetopause

Topic	Reference
Macroscopic features and topology	
Location, orientation, motion, thickness	Horbury et al. (2003); Sonnerup, Haaland, et al. (2004); Sonnerup, Haaland, et al. (2006); Zhang et al. (2007); Panov et al. (2008); Farrugia et al. (2008); R. L. Lin et al. (2010); Panov et al. (2011); Shen et al. (2011); Lavraud et al. (2011); Fuselier et al. (2012); Tátrallyay et al. (2012); Case and Wild (2013); Y. Wang et al. (2013); Haaland et al. (2014)
Thickness	Bosqued et al. (2001); Haaland and Gjerloev (2013)
Location and shape	Farrugia et al. (2008); Shen et al. (2011); Lavraud et al. (2013); Case and Wild (2013); T. Huang et al. (2015); Petrinec et al. (2017)
Waves	Rezeau et al. (2001); André et al. (2001); Cattell et al. (2003); Owen et al. (2004); Stasiewicz et al. (2004); Vaivads, André, et al. (2004); André et al. (2004); Stenberg et al. (2005); Chaston et al. (2005); Stenberg et al. (2007); Vaivads et al. (2007); Trines et al. (2007); Cornilleau-Wehrlin et al. (2008); Attié et al. (2008); Laitinen et al. (2010); Pickett et al. (2011); Turkakin et al. (2013); Gunell et al. (2014); Graham et al. (2016)
Kelvin-Helmholz waves	Mann et al. (2002); Owen et al. (2004); Hasegawa et al. (2006); Foullon et al. (2008); Hasegawa et al. (2009); Foullon et al. (2010); Farrugia and Gratton (2011); Nishino et al. (2011); Hwang et al. (2012); Gunell et al. (2014); D. Lin et al. (2014) Ma et al. (2016); Pathak et al. (2019); Nakamura et al. (2020)
Composition, heavy and cold ions	Sauvaud et al. (2001); Bouhram et al. (2005); Taktakishvili et al. (2007); André et al. (2010); Fuselier, Petrinec, and Trattner (2010); Fuselier, Funsten, et al. (2010); S. Wang et al. (2014); Lee et al. (2014, 2015, 2016); Toledo-Redondo et al. (2016)
Transient events, flux ropes and islands	Owen et al. (2001); Lockwood et al. (2001); Sauvaud et al. (2001); Z. Y. Huang et al. (2004); Louarn et al. (2004); Xiao, Pu, Huang, et al. (2004); Xiao, Pu, Ma, et al. (2004); Marchaudon et al. (2005); Y. L. Wang et al. (2005); Yao et al. (2005); Pu et al. (2005); Wild et al. (2007); J. Wang et al. (2007); Penz et al. (2007); Zhang, Liu, et al. (2008); Cai et al. (2018) Owen et al. (2008); Fear et al. (2012); Vines et al. (2017); Cai et al. (2018)
Magnetopause processes	
Reconnection	Bosqued et al. (2001); Phan et al. (2003); Frey et al. (2003); Phan et al. (2004); Phan et al. (2005); Eriksson et al. (2004); Retinò et al. (2005); Fuselier et al. (2005); Dunlop et al. (2005); Zheng et al. (2005); Lavraud et al. (2006); Pu et al. (2007); G. Yan et al. (2008); Daum et al. (2008); Dunlop et al. (2008); Cai et al. (2009); Lindstedt et al. (2009); Wendel and Reiff (2009); Hasegawa et al. (2009); G. Q. Yan et al. (2009); Eriksson et al. (2009); André et al. (2010) Fuselier, Funsten, et al. (2010); Fuselier et al. (2011); Dunlop et al. (2011); Fuselier et al. (2011); Lavraud et al. (2011); Fuselier et al. (2011); Dunlop et al. (2011); Fuselier et al. (2011); Lavraud et al. (2011); Maynard et al. (2012); Broll et al. (2017); Lee et al. (2014); S. Wang et al. (2014, 2015); Lee et al. (2015); Vines et al. (2015); Souza et al. (2017)
high latitude/lobe	Fuselier et al. (2018)
jetting	Broll et al. (2017)
diffusion regions	Rogers et al. (2003); Vaivads, André, et al. (2004); Zhang, Zong, et al. (2008); Zong and Zhang (2018)
reconnection rates	Fuselier et al. (2005); Penz et al. (2007); Fuselier, Petrinec, and Trattner (2010); S. Wang et al. (2015)
location of	Trattner et al. (2012); Zhu et al. (2015)
Diffusion, impulsive penetration	Lundin et al. (2003); Panov, Büchner, Fränz, Korth, Savin, et al. (2006); Panov, Büchner, Fränz, Korth, Khotyaintsev, et al. (2006); Gunell et al. (2012)
Energy conversion	Rosenqvist et al. (2008); Anekallu et al. (2011); Palmroth et al. (2011); Palmroth et al. (2012); Anekallu et al. (2013)
Specific Regions	

Table A1
Continued

Topic	Reference
High latitude, incl. poleward of cusp	Popielawska et al. (2002); Phan et al. (2003); Xiao, Pu, Huang, et al. (2004); Moretto et al. (2005); Zheng et al. (2005); Retinò et al. (2005); Y. L. Wang et al. (2005); G. Yan et al. (2008); Panov et al. (2008); Fuselier et al. (2012); Ma et al. (2016); Fuselier et al. (2018)
Flanks and dawn-dusk asymmetry	Owen et al. (2004); Paschmann, Haaland, et al. (2005); Lund et al. (2006); Maynard et al. (2012); Lavraud et al. (2013); Haaland and Gjerloev (2013); Haaland et al. (2014); Walsh (2017); Cerri (2018)
Methodology	
Multi-spacecraft triangulation	Dunlop, Balogh, Cargill, et al. (2001); Horbury et al. (2003); Haaland, Sonnerup, Dunlop, Balogh, et al. (2004); Zhou et al. (2006); Blagau et al. (2010); Dorville, Belmont, Rezeau, Grappin, and Retinò (2014); Cai et al. (2018)
Gradient methods incl. curlometer and current determination	Dunlop, Balogh, and Glassmeier (2001); Haaland, Sonnerup, Dunlop, Balogh, et al. (2004); Xiao, Pu, Huang, et al. (2004); Xiao, Pu, Ma, et al. (2004); Liebert et al. (2017)
Dimensional analysis	Shi et al. (2005)
Reconstruction	Hasegawa, Sonnerup, et al. (2004); Hasegawa et al. (2005); De Keyser et al. (2004); De Keyser (2005); Sonnerup and Hasegawa (2005); Teh and Sonnerup (2008)
Remote sensing	Oksavik et al. (2002); Zong et al. (2004); Walsh et al. (2012)
Constellations and comparisons	
with MMS,	Nakamura et al. (2020); Escoubet et al. (2020)
with Themis or Geotail	Šafránková et al. (2012); Souza et al. (2017); Zhang et al. (2019); Nakamura et al. (2020)
with Double Star	Dunlop et al. (2005); Marchaudon et al. (2005); Wild et al. (2005); Wild et al. (2007); Pu et al. (2007); J. Wang et al. (2007); Zhang, Liu, et al. (2008); Berchem et al. (2008); Cornilleau-Wehrlin et al. (2008); Pitout et al. (2008); Zhang et al. (2011); Souza et al. (2017)
with ground based observations	Lockwood et al. (2001); Wild et al. (2001); Mann et al. (2002); Wild et al. (2003); Wild et al. (2005); Pitout et al. (2004); Maynard et al. (2004); Maynard et al. (2006); Zhang et al. (2011); Dougal et al. (2013)
with MHD and kinetic models and theories	Berchem et al. (2008); Daum et al. (2008); Tátrallyay et al. (2012); Turkakin et al. (2013); T. Huang et al. (2015); Blagau et al. (2015); Ma et al. (2016); Cerri (2018)
with other planets	Echim et al. (2011)

This list is partly based on a list of all Cluster publications maintained by the Cluster Science Archives (https://sci.esa.int/web/cluster/-/39766-cluster-and-double-star-refereed-publications)

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Data Availability Statement

All Cluster data are available from the Cluster Science Archive via the URL https://www.cosmos.esa.int/web/csa. Cluster magnetopause publications used to generate Figure 3, are based on the ESA Cluster publication database (https://sci.esa.int/web/cluster/-/39766-cluster-and-double-star-refereed-publications).

References

André, M., Behlke, R., Wahlund, J. E., Vaivads, A., Eriksson, A. I., Tjulin, A., et al. (2001). Multi-spacecraft observations of broadband waves near the lower hybrid frequency at the Earthward edge of the magnetopause. *Annales de Geophysique*, *19*(10), 1471–1481. https://doi.org/10.5194/angeo-19-1471-2001

André, M., Vaivads, A., Buchert, S. C., Fazakerley, A. N., & Lahiff, A. (2004). Thin electron-scale layers at the magnetopause. *Geophysical Research Letters*, *31*(3). L03803. https://doi.org/10.1029/2003GL018137

André, M., Vaivads, A., Khotyaintsev, Y. V., Laitinen, T., Nilsson, H., Stenberg, G., et al. (2010). Magnetic reconnection and cold plasma at the magnetopause. *Geophysical Research Letters*, *37*(22), L22108. https://doi.org/10.1029/2010GL044611

Anekallu, C. R., Palmroth, M., Koskinen, H. E. J., Lucek, E., & Dandouras, I. (2013). Spatial variation of energy conversion at the Earth's magnetopause: Statistics from Cluster observations. *Journal of Geophysical Research (Space Physics)*, *118*(5), 1948–1959. https://doi.org/10.1002/jgra.50233

Anekallu, C. R., Palmroth, M., Pulkkinen, T. I., Haaland, S. E., Lucek, E., & Dandouras, I. (2011). Energy conversion at the Earth's magnetopause using single and multispacecraft methods. *Journal of Geophysical Research: Space Physics*, *116*(A11), A11204. https://doi.org/10.1029/2011JA016783

Attié, D., Rezeau, L., Belmont, G., Cornilleau-Wehrlin, N., & Lucek, E. (2008). Power of magnetopause low-frequency waves: A statistical study. *Journal of Geophysical Research: Space Physics*, *113*(A7), A07213. https://doi.org/10.1029/2007JA012606

Berchem, J., Marchaudon, A., Dunlop, M., Escoubet, C. P., Bosqued, J. M., Reme, H., et al. (2008). Reconnection at the dayside magnetopause: Comparisons of global MHD simulation results with Cluster and Double Star observations. *Journal of Geophysical Research: Space Physics*, *113*(A7), A07S12. https://doi.org/10.1029/2007JA012743

Berchem, J., & Russell, C. T. (1982a). Magnetic field rotation through the magnetopause: ISEE 1 and 2 observations. *Journal of Geophysical Research*, *87*(A10), 8139–8148. https://doi.org/10.1029/JA087iA10p08139

Berchem, J., & Russell, C. T. (1982b). The thickness of the magnetopause current layer: ISEE 1 and 2 observations. *Journal of Geophysical Research*, *87*(A4), 2108–2114. https://doi.org/10.1029/JA087iA04p02108

Blagau, A., Klecker, B., Paschmann, G., Haaland, S., Marghitu, O., & Scholer, M. (2010). A new technique for determining orientation and motion of a 2-d, non-planar magnetopause. *Annales Geophysicae*, *28*(3), 753–778. https://doi.org/10.5194/angeo-28-753-2010

Blagau, A., Paschmann, G., Klecker, B., & Marghitu, O. (2015). Experimental test of the ρ(1-α) evolution for rotational discontinuities: Cluster magnetopause observations. *Annales Geophysicae*, *33*(1), 79–91. https://doi.org/10.5194/angeo-33-79-2015

Bosqued, J. M., Phan, T. D., Dandouras, I., Escoubet, C. P., Rème, H., Balogh, A., et al. (2001). Cluster observations of the high-latitude magnetopause and cusp: Initial results from the CIS ion instruments. *Annales Geophysicae*, *19*(10), 1545–1566. https://doi.org/10.5194/angeo-19-1545-2001

Bouhram, M., Klecker, B., Paschmann, G., Haaland, S., Hasegawa, H., Blagau, A., et al. (2005). Survey of energetic o^+ ions near the dayside mid-latitude magnetopause with cluster. *Annales de Geophysique*, *23*(4), 1281–1294. https://doi.org/10.5194/angeo-23-1281-2005

Broll, J. M., Fuselier, S. A., & Trattner, K. J. (2017). Locating dayside magnetopause reconnection with exhaust ion distributions. *Journal of Geophysical Research*, *122*(5), 5105–5113. https://doi.org/10.1002/2016JA023590

Burch, J. L., Moore, T. E., Torbert, R. B., & Giles, B. L. (2016). Magnetospheric multiscale overview and science objectives. *Space Science Reviews*, *199*(1–4), 5–21. https://doi.org/10.1007/s11214-015-0164-9

Cahill, L. J., & Amazeen, P. G. (1963). The boundary of the geomagnetic field. *Journal of Geophysical Research*, *68*(7), 1835–1843. https://doi.org/10.1029/JZ068i007p01835

Cai, C. L., Dandouras, I., Rème, H., Cao, J. B., Zhou, G. C., Shen, C., et al. (2009). Magnetosheath excursion and the relevant transport process at the magnetopause. *Annales Geophysicae*, *27*(8), 2997–3005. https://doi.org/10.5194/angeo-27-2997-2009

Cai, D., Lembège, B., Hasegawa, H., & Nishikawa, K. I. (2018). Identifying 3-D vortex structures at/around the magnetopause using a tetrahedral satellite configuration. *Journal of Geophysical Research: Space Physics*, *123*(12), 10158–10176. https://doi.org/10.1029/2018JA025547

Cargill, P. J., Lavraud, B., Owen, C. J., Grison, B., Dunlop, M. W., Cornilleau-Wehrlin, N., et al. (2005). Cluster at the Magnetospheric Cusps. *Space Science Reviews*, *118*(1–4), 321–366. https://doi.org/10.1007/s11214-005-3835-0

Case, N. A., & Wild, J. A. (2013). The location of the Earth's magnetopause: A comparison of modeled position and in situ Cluster data. *Journal of Geophysical Research: Space Physics*, *118*(10), 6127–6135. https://doi.org/10.1002/jgra.50572

Cattell, C., Neiman, C., Dombeck, J., Crumley, J., Wygant, J., Kletzing, C. A., et al. (2003). Large amplitude solitary waves in and near the EarthÂ's magnetosphere, magnetopause and bow shock: Polar and Cluster observations. *Nonlinear Processes in Geophysics*, *10*, 13–26. https://doi.org/10.5194/npg-10-13-2003

Cerri, S. S. (2018). Finite-Larmor-radius equilibrium and currents of the Earth's flank magnetopause. *Journal of Plasma Physics*, *84*(5), 555840501. https://doi.org/10.1017/S0022377818000934

Chanteur, G. (2021). Accuracy of field gradients estimation. *Journal of Geophysical Research*, *126*(A7).

Chapman, S., & Ferraro, V. C. A. (1930). A new theory of magnetic storms. *Nature*, *126*, 129–130. https://doi.org/10.1038/126129a0

Chaston, C. C., Phan, T. D., Bonnell, J. W., Mozer, F. S., Acuńa, M., Goldstein, M. L., et al. (2005). Drift-Kinetic Alfvén Waves observed near a reconnection x line in the earth's magnetopause. *Physical Review Letters*, *95*(6), 65002. https://doi.org/10.1103/PhysRevLett.95.065002

Chaston, C. C., Wilber, M., Mozer, F. S., Fujimoto, M., Goldstein, M. L., Acuna, M., et al. (2007). Mode conversion and anomalous transport in kelvin-helmholtz vortices and kinetic alfvén waves at the earth's magnetopause. *Physical Review Letters*, *99*, 175004. https://doi.org/10.1103/PhysRevLett.99.175004

Cornilleau-Wehrlin, N., Grison, B., Attié, D., Belmont, G., Rezeau, L., Robert, P., et al. (2008). Latitude and local time dependence of ULF wave power at the magnetopause: A Cluster-Double Star study. *Journal of Geophysical Research (Space Physics)*, *113*(A7), A07S09. https://doi.org/10.1029/2007JA012780

Cowley, S. W. H. (1974). Convection-region solutions for the re-connexion of anti-parallel magnetic fields of unequal magnitude in an incompressible plasma. *Journal of Plasma Physics*, *12*(2), 341–352. https://doi.org/10.1017/S0022377800025149

Daum, P., Wild, J. A., Penz, T., Woodfield, E. E., RèMe, H., Fazakerley, A. N., et al. (2008). Global MHD simulation of flux transfer events at the high-latitude magnetopause observed by the Cluster spacecraft and the SuperDARN radar system. *Journal of Geophysical Research (Space Physics)*, *113*(A7), A07S22. https://doi.org/10.1029/2007JA012749

Davis, L. R., & Williamson, J. W. (1962). Summary of early results from Explorer 12. *IG Bulletin*(58), 223.

De Keyser, J. (2005). The Earth's Magnetopause: Reconstruction of motion and structure. *Space Science Reviews*, *121*(1–4), 225–235. https://doi.org/10.1007/s11214-006-6731-3

De Keyser, J., Gustafsson, G., Roth, M., Darrouzet, F., Dunlop, M., Rème, H., et al. (2004). Reconstruction of the magnetopause and low-latitude boundary layer topology using cluster multi-point measurements. *Annales Geophysicae*, *22*(7), 2381–2389. https://doi.org/10.5194/angeo-22-2381-2004

Dorville, N., Belmont, G., Rezeau, L., Aunai, N., & Retinò, A. (2014). BV technique for investigating 1-D interfaces. *Journal of Geophysical Research: Space Physics*, *119*(3), 1709–1720. https://doi.org/10.1002/2013JA018926

Dorville, N., Belmont, G., Rezeau, L., Grappin, R., & Retinò, A. (2014). Rotational/compressional nature of the magnetopause: Application of the BV technique on a magnetopause case study. *Journal of Geophysical Research: Space Physics*, *119*(3), 1898–1908. https://doi.org/10.1002/2013JA018927

Dorville, N., Haaland, S., Anekallu, C., Belmont, G., & Rezeau, L. (2015). Magnetopause orientation: Comparison between generic residue analysis and BV method. *Journal of Geophysical Research: Space Physics*, *120*(5), 3366–3379. https://doi.org/10.1002/2014JA020806

Dougal, E. R., Nykyri, K., & Moore, T. W. (2013). Mapping of the quasi-periodic oscillations at the flank magnetopause into the ionosphere. *Annales Geophysicae*, *31*(11), 1993–2011. https://doi.org/10.5194/angeo-31-1993-2013

Dungey, J. W. (1958). Cosmic electrodynamics. *Quarterly Journal of the Royal Meteorological Society*, *85*(366), 450. https://doi.org/10.1002/qj.49708536628

Dungey, J. W. (1961). Interplanetary magnetic field and the auroral zones. *Physical Review Letters*, *6*, 47–48. https://doi.org/10.1103/physrevlett.6.47

Dungey, J. W. (1963). Interactions of solar plasma with the geomagnetic field. *Planetary and Space Science*, *10*, 233–237. https://doi.org/10.1016/0032-0633(63)90020-5

Dunlop, M. W. (2021). Curlometer techniques and applications. *Journal of Geophysical Research*, *126*(A7).

Dunlop, M. W., Balogh, A., Cargill, P., Elphic, R. C., Fornaçon, K. H., Georgescu, E., & Sedgemore-Schulthess, F. (2001). Fgm TeamCluster observes the Earth's magnetopause: Coordinated four-point magnetic field measurements. *Annales de Geophysique*, *19*(10), 1449–1460. https://doi.org/10.5194/angeo-19-1449-2001

Dunlop, M. W., Balogh, A., & Glassmeier, K. H. (2001). First application of multi-point magnetic field analysis techniques: The Curlometer and the discontinuity analyser. In B. Warmbein (Ed.), Sheffield Space Plasma Meeting: Multipoint Measurements Versus Theory (Vol. 492).

Dunlop, M. W., Southwood, D. J., Glassmeier, K. H., & Neubauer, F. M. (1988). Analysis of multipoint magnetometer data. *Advances in Space Research*, *8*(9–10), 273–277. https://doi.org/10.1016/0273-1177(88)90141-X

Dunlop, M. W., Taylor, M. G. G. T., Bogdanova, Y. V., Shen, C., Pitout, F., Pu, Z., et al. (2008). Electron structure of the magnetopause boundary layer: Cluster/Double Star observations. *Journal of Geophysical Research (Space Physics)*, *113*(A7), A07S19. https://doi.org/10.1029/2007JA012788

Dunlop, M. W., Taylor, M. G. G. T., Davies, J. A., Owen, C. J., Pitout, F., Fazakerley, A. N., et al. (2005). Coordinated cluster/double star observations of dayside reconnection signatures. *Annales Geophysicae*, *23*(8), 2867–2875. https://doi.org/10.5194/angeo-23-2867-2005

Dunlop, M. W., & Woodward, T. I. (1998). Multi-spacecraft discontinuity analysis: orientation and motion. *ISSI Scientific Reports Series*, *1*, 271–306.

Dunlop, M. W., Zhang, Q.-H., Bogdanova, Y. V., Trattner, K. J., Pu, Z., Hasegawa, H., et al. (2011). Magnetopause reconnection across wide local time. *Annales Geophysicae*, *29*(9), 1683–1697. https://doi.org/10.5194/angeo-29-1683-2011

Echim, M., Maggiolo, R., De Keyser, J., Zhang, T. L., Voitcu, G., Barabash, S., & Lundin, R. (2011). Comparative investigation of the terrestrial and Venusian magnetopause: Kinetic modeling and experimental observations by Cluster and Venus Express. *Planetary and Space Science*, *59*(10), 1028–1038. https://doi.org/10.1016/j.pss.2010.04.019

Eriksson, S., Elkington, S. R., Phan, T. D., Petrinec, S. M., RèMe, H., Dunlop, M. W., & André, M. (2004). Global control of merging by the interplanetary magnetic field: Cluster observations of dawnside flank magnetopause reconnection. *Journal of Geophysical Research: Space Physics*, *109*(A12), A12203. https://doi.org/10.1029/2003JA010346

Eriksson, S., Hasegawa, H., Teh, W. L., Sonnerup, B. U. Ö., McFadden, J. P., Glassmeier, K. H., et al. (2009). Magnetic island formation between large-scale flow vortices at an undulating postnoon magnetopause for northward interplanetary magnetic field. *Journal of Geophysical Research: Space Physics*, *114*(A2), A00C17. https://doi.org/10.1029/2008JA013505

Eriksson, S., Lavraud, B., Wilder, F. D., Stawarz, J. E., Giles, B. L., Burch, J. L., et al. (2016). Magnetospheric Multiscale observations of magnetic reconnection associated with Kelvin-Helmholtz waves. *Geophysical Research Letters*, *43*(11), 5606–5615. https://doi.org/10.1002/2016GL068783

Escoubet, C. (2021). Cluster after 20 years of operations: Science highlights and technical challenges. *Journal of Geophysical Research*, *126*(A7). https://doi.org/10.1029/2021ja029474

Escoubet, C. P., Fehringer, M., & Goldstein, M. (2001). Introductionthe cluster mission. *Annales Geophysicae*, *19*(10/12), 1197–1200. https://doi.org/10.5194/angeo-19-1197-2001

Escoubet, C. P., Hwang, K. J., Toledo-Redondo, S., Turc, L., Haaland, S. E., Aunai, N., et al. (2020). Cluster and MMS simultaneous observations of magnetosheath high speed jets and their impact on the magnetopause. *Frontiers in Astronomy and Space Sciences*, *6*, 78. https://doi.org/10.3389/fspas.2019.00078

Escoubet, C. P., Schmidt, R., & Goldstein, M. L. (1997). Cluster-Science and mission overview. *Space Science Reviews*, *79*, 11–32. https://doi.org/10.1023/A:1004923124586

Fairfield, D. H., Otto, A., Mukai, T., Kokubun, S., Lepping, R. P., Steinberg, J. T., et al. (2000). Geotail observations of the kelvin-helmholtz instability at the equatorial magnetotail boundary for parallel northward fields. *Journal of Geophysical Research: Space Physics*, *105*(A9), 21159–21173. https://doi.org/10.1029/1999JA000316

Farrugia, C. J., & Gratton, F. T. (2011). Aspects of magnetopause/magnetosphere response to interplanetary discontinuities, and features of magnetopause Kelvin-Helmholtz waves. *Journal of Atmospheric and Solar-Terrestrial Physics*, *73*(1), 40–51. https://doi.org/10.1016/j.jastp.2009.10.008

Farrugia, C. J., Gratton, F. T., Lund, E. J., Sand holt, P. E., Cowley, S. W. H., Torbert, R. B., et al. (2008). Two-stage oscillatory response of the magnetopause to a tangential discontinuity/vortex sheet followed by northward IMF: Cluster observations. *Journal of Geophysical Research: Space Physics*, *113*(A3), A03208. https://doi.org/10.1029/2007JA012800

Fear, R. C., Palmroth, M., & Milan, S. E. (2012). Seasonal and clock angle control of the location of flux transfer event signatures at the magnetopause. *Journal of Geophysical Research: Space Physics*, *117*(A4), A04202. https://doi.org/10.1029/2011JA017235

Fear, R. C., Trenchi, L., Coxon, J. C., & Milan, S. E. (2017). How much flux does a flux transfer event transfer? *Journal of Geophysical Research*, *122*(12), 310–312. https://doi.org/10.1002/2017JA024730

Foullon, C., Farrugia, C. J., Fazakerley, A. N., Owen, C. J., Gratton, F. T., & Torbert, R. B. (2008). Evolution of Kelvin-Helmholtz activity on the dusk flank magnetopause. *Journal of Geophysical Research: Space Physics*, *113*(A11), A11203. https://doi.org/10.1029/2008JA013175

Foullon, C., Farrugia, C. J., Owen, C. J., Fazakerley, A. N., Gratton, F. T., Maksimovic, M., et al. (2010). Kelvin-Helmholtz multi-spacecraft studies at the earth's magnetopause boundaries. In M. Maksimovic, K. Issautier, N. Meyer-Vernet, M. Moncuquet, & F. Pantellini (Eds.), *Twelfth International Solar Wind Conference* (Vol. 1216, pp. 483–486). https://doi.org/10.1063/1.3395908

Freeman, J. W., van Allen, J. A., & Cahill, L. J. (1963). Explorer 12 Observations of the Magnetospheric Boundary and the Associated Solar Plasma on September 13, 1961. *Journal of Geophysical Research*, *68*(8), 2121–2130. https://doi.org/10.1029/JZ068i008p02121

Frey, H. U., Phan, T. D., Fuselier, S. A., & Mende, S. B. (2003). Continuous magnetic reconnection at Earth's magnetopause. *Nature*, *426*(6966), 533–537. https://doi.org/10.1038/nature02084

Fuselier, S. A., Funsten, H. O., Heirtzler, D., Janzen, P., Kucharek, H., McComas, D. J., et al. (2010). Energetic neutral atoms from the Earth's subsolar magnetopause. *Geophysical Research Letters*, *37*(13), L13101. https://doi.org/10.1029/2010GL044140

Fuselier, S. A., Petrinec, S. M., & Trattner, K. J. (2010). Antiparallel magnetic reconnection rates at the Earth's magnetopause. *Journal of Geophysical Research: Space Physics*, *115*(A10), A10207. https://doi.org/10.1029/2010JA015302

Fuselier, S. A., Trattner, K. J., & Petrinec, S. M. (2011). Antiparallel and component reconnection at the dayside magnetopause. *Journal of Geophysical Research: Space Physics*, *116*(A10), A10227. https://doi.org/10.1029/2011JA016888

Fuselier, S. A., Trattner, K. J., Petrinec, S. M., & Lavraud, B. (2012). Dayside magnetic topology at the Earth's magnetopause for northward IMF. *Journal of Geophysical Research: Space Physics*, *117*(A8), A08235. https://doi.org/10.1029/2012JA017852

Fuselier, S. A., Trattner, K. J., Petrinec, S. M., Lavraud, B., & Mukherjee, J. (2018). Nonlobe reconnection at the Earth's magnetopause for Northward IMF. *Journal of Geophysical Research: Space Physics*, *123*(10), 8275–8291. https://doi.org/10.1029/2018JA025435

Fuselier, S. A., Trattner, K. J., Petrinec, S. M., Owen, C. J., & RèMe, H. (2005). Computing the reconnection rate at the Earth's magnetopause using two spacecraft observations. *Journal of Geophysical Research: Space Physics*, *110*(A6), A06212. https://doi.org/10.1029/2004JA010805

Giovanelli, R. G. (1947). Magnetic and electric phenomena in the Sun's atmosphere associated with sunspots. *Monthly Notices of the Royal Astronomical Society*, *107*, 338–355. https://doi.org/10.1093/mnras/107.4.338

Graham, D. B., Khotyaintsev, Y. V., Vaivads, A., & André, M. (2016). Electrostatic solitary waves and electrostatic waves at the magnetopause. *Journal of Geophysical Research: Space Physics*, *121*(4), 3069–3092. https://doi.org/10.1002/2015JA021527

Gunell, H., Nilsson, H., Stenberg, G., Hamrin, M., Karlsson, T., Maggiolo, R., et al. (2012). Plasma penetration of the dayside magnetopause. *Physics of Plasmas*, *19*(7), 72906. https://doi.org/10.1063/1.4739446

Gunell, H., Stenberg Wieser, G., Mella, M., Maggiolo, R., Nilsson, H., Darrouzet, F., et al. (2014). Waves in high-speed plasmoids in the magnetosheath and at the magnetopause. *Annales Geophysicae*, *32*(8), 991–1009. https://doi.org/10.5194/angeo-32-991-2014

Haaland, S., & Gjerloev, J. (2013). On the relation between asymmetries in the ring current and magnetopause current. *Journal of Geophysical Research: Space Physics*, *118*(12), 7593–7604. https://doi.org/10.1002/2013JA019345

Haaland, S., Paschmann, G., Øieroset, M., Phan, T., Hasegawa, H., Fuselier, S. A., et al. (2020). Characteristics of the Flank Magnetopause: MMS Results. *Journal of Geophysical Research (Space Physics)*, *125*(3), e27623. https://doi.org/10.1029/2019JA027623

Haaland, S., Reistad, J., Tenfjord, P., Gjerloev, J., Maes, L., DeKeyser, J., et al. (2014). Characteristics of the flank magnetopause: Cluster observations. *Journal of Geophysical Research: Space Physics*, *119*(11), 9019–9037. https://doi.org/10.1002/2014JA020539

Haaland, S., Runov, A., Artemyev, A., & Angelopoulos, V. (2019). Characteristics of the Flank Magnetopause: THEMIS Observations. *Journal of Geophysical Research (Space Physics)*, *124*(5), 3421–3435. https://doi.org/10.1029/2019JA026459

Haaland, S., Runov, A., & Forsyth, C. (Eds.), (2017). *Dwan-dusk asymmetries in planetary plasma environments*. Wiley.

Haaland, S., Sonnerup, B. U. Ö., Dunlop, M. W., Georgescu, E., Paschmann, G., Klecker, B., & Vaivads, A. (2004). Orientation and motion of a discontinuity from Cluster curlometer capability: Minimum variance of current density. *Geophysical Research Letters*, *31*(10), L10804. https://doi.org/10.1029/2004GL020001

Haaland, S. E., Sonnerup, B. U. O., Dunlop, M. W., Balogh, A., Georgescu, E., Hasegawa, H., et al. (2004). Four-spacecraft determination of magnetopause orientation, motion and thickness: Comparison with results from single-spacecraft methods. *Annales de Geophysique*, *22*(4), 1347–1365. https://doi.org/10.5194/angeo-22-1347-2004

Harvey, C. C. (1998). Spatial gradients and the volumetric tensor. *ISSI Scientific Reports Series*, *1*, 307–310. https://doi.org/10.3354/meps164307

Hasegawa, H. (2012). Structure and dynamics of the magnetopause and its boundary layers. *Monographs on Environment, Earth and Planets*, *1*(2), 71–119. https://doi.org/10.5047/meep.2012.00102.0071

Hasegawa, H., Fujimoto, M., Phan, T. D., Rème, H., Balogh, A., Dunlop, M. W., et al. (2004). Transport of solar wind into Earth's magnetosphere through rolled-up Kelvin-Helmholtz vortices. *Nature*, *430*(7001), 755–758. https://doi.org/10.1038/nature02799

Hasegawa, H., Fujimoto, M., Takagi, K., Saito, Y., Mukai, T., & RèMe, H. (2006). Single-spacecraft detection of rolled-up Kelvin-Helmholtz vortices at the flank magnetopause. *Journal of Geophysical Research: Space Physics*, *111*(A9), A09203. https://doi.org/10.1029/2006JA011728

Hasegawa, H., Retinò, A., Vaivads, A., Khotyaintsev, Y., André, M., Nakamura, T. K. M., et al. (2009). Kelvin-Helmholtz waves at the Earth's magnetopause: Multiscale development and associated reconnection. *Journal of Geophysical Research (Space Physics)*, *114*(A12), A12207. https://doi.org/10.1029/2009JA014042

Hasegawa, H., Sonnerup, B., Dunlop, M., Balogh, A., Haaland, S., Klecker, B., et al. (2004). Reconstruction of two-dimensional magnetopause structures from Cluster observations: Verification of method. *Annales de Geophysique*, *22*(4), 1251–1266. https://doi.org/10.5194/angeo-22-1251-2004

Hasegawa, H., Sonnerup, B. U. Ö., Klecker, B., Paschmann, G., Dunlop, M. W., & Rème, H. (2005). Optimal reconstruction of magnetopause structures from Cluster data. *Annales de Geophysique*, *23*(3), 973–982. https://doi.org/10.5194/angeo-23-973-2005

Horbury, T. S., Balogh, A., Dunlop, M. W., Cargill, P. J., Lucek, E. A., Oddy, T., et al. (2003). Cluster magnetic field observations of magnetospheric boundaries. In *Cluster Magnetic Field Observations Of Magnetospheric Boundaries* (Vol. 133, pp. 63–69). Washington DC American Geophysical Union Geophysical Monograph Series. https://doi.org/10.1029/133GM06

Huang, T., Wang, H., Shue, J. H., Cai, L., & Pi, G. (2015). The dayside magnetopause location during radial interplanetary magnetic field periods: Cluster observation and model comparison. *Annales Geophysicae*, *33*(4), 437–448. https://doi.org/10.5194/angeo-33-437-2015

Huang, Z.-Y., Pu, Z.-Y., Xiao, C.-J., Xong, Q.-G., Fu, S.-Y., Xie, L., et al. (2004). Multiple flux rope events at the high-latitude magnetopause: Cluster/rapid observation on January 26, 2001. *Chinese Journal of Geophysics*, *47*, 197–206. https://doi.org/10.1002/cjg2.473

Hwang, K. J. (2021). Kelvin-Helmholtz waves in the magnetosphere. *Journal of Geophysical Research*.

Hwang, K. J., Goldstein, M. L., Kuznetsova, M. M., Wang, Y., ViñAs, A. F., & Sibeck, D. G. (2012). The first in situ observation of Kelvin-Helmholtz waves at high-latitude magnetopause during strongly dawnward interplanetary magnetic field conditions. *Journal of Geophysical Research: Space Physics*, *117*(A8), A08233. https://doi.org/10.1029/2011JA017256

Hwang, K. J., Kuznetsova, M. M., Sahraoui, F., Goldstein, M. L., Lee, E., & Parks, G. K. (2011). Kelvin-Helmholtz waves under southward interplanetary magnetic field. *Journal of Geophysical Research: Space Physics*, *116*(A8), A08210. https://doi.org/10.1029/2011JA016596

Johnson, J. R., Wing, S., & Delamere, P. A. (2014). Kelvin Helmholtz instability in planetary magnetospheres. *Space Science Reviews*, *184*(1–4), 1–31. https://doi.org/10.1007/s11214-014-0085-z

Kavosi, S., & Raeder, J. (2015). Ubiquity of kelvin–helmholtz waves at earth's magnetopause. *Nature Communications*, *6*. https://doi.org/10.1038/ncomms8019

Khrabrov, A. V., & Sonnerup, B. U. Ö. (1998a). DeHoffmann-Teller Analysis. *ISSI Scientific Reports Series*, *1*, 221–248.

Khrabrov, A. V., & Sonnerup, B. U. Ö. (1998b). Orientation and motion of current layers: Minimization of the Faraday residue. *Geophysical Research Letters*, *25*(13), 2373–2376. https://doi.org/10.1029/98GL51784

Laakso, H. e. a. (2021). From cluster science data system to active archive. *Journal of Geophysical Research*.

Laitinen, T. V., Khotyaintsev, Y. V., André, M., Vaivads, A., & Rème, H. (2010). Local influence of magnetosheath plasma beta fluctuations on magnetopause reconnection. *Annales Geophysicae*, *28*(5), 1053–1063. https://doi.org/10.5194/angeo-28-1053-2010

Lavraud, B., Foullon, C., Farrugia, C. J., & Eastwood, J. P. (2011). The Magnetopause its boundary layers and pathways to the magnetotail. In W. Liu, & M. Fujimoto (Eds.), *The Dynamic Magnetosphere* (Vol. 3, pp. 3–28). https://doi.org/10.1007/978-94-007-0501-2_1

Lavraud, B., Larroque, E., Budnik, E., Génot, V., Borovsky, J. E., Dunlop, M. W., et al. (2013). Asymmetry of magnetosheath flows and magnetopause shape during low Alfvén Mach number solar wind. *Journal of Geophysical Research: Space Physics*, *118*(3), 1089–1100. https://doi.org/10.1002/jgra.50145

Lavraud, B., Thomsen, M. F., Lefebvre, B., Schwartz, S. J., Seki, K., Phan, T. D., et al. (2006). Evidence for newly closed magnetosheath field lines at the dayside magnetopause under northward IMF. *Journal of Geophysical Research: Space Physics*, *111*(A5), A05211. https://doi.org/10.1029/2005JA011266

Lee, S. H., Zhang, H., Zong, Q. G., Otto, A., Rème, H., & Liebert, E. (2016). A statistical study of plasmaspheric plumes and ionospheric outflows observed at the dayside magnetopause. *Journal of Geophysical Research: Space Physics*, *121*(1), 492–506. https://doi.org/10.1002/2015JA021540

Lee, S. H., Zhang, H., Zong, Q. G., Otto, A., Sibeck, D. G., Wang, Y., et al. (2014). Plasma and energetic particle behaviors during asymmetric magnetic reconnection at the magnetopause. *Journal of Geophysical Research: Space Physics*, *119*(3), 1658–1672. https://doi.org/10.1002/2013JA019168

Lee, S. H., Zhang, H., Zong, Q. G., Wang, Y., Otto, A., Rème, H., & Glassmeier, K. H. (2015). Asymmetric ionospheric outflow observed at the dayside magnetopause. *Journal of Geophysical Research: Space Physics*, *120*(5), 3564–3573. https://doi.org/10.1002/2014JA020943

Levy, R., Petschek, H., & Siscoe, G. (1964). Aerodynamic aspects of the magnetospheric flow. *American Institute of Aeronautics and Astronautics Journal*, *2*, 2065–2076. https://doi.org/10.2514/3.2745

Liebert, E., Nabert, C., Perschke, C., Fornaçon, K.-H., & Glassmeier, K.-H. (2017). Statistical survey of day-side magnetospheric current flow using Cluster observations: Magnetopause. *Annales Geophysicae*, *35*(3), 645–657. https://doi.org/10.5194/angeo-35-645-2017

Lin, D., Wang, C., Li, W., Tang, B., Guo, X., & Peng, Z. (2014). Properties of Kelvin-Helmholtz waves at the magnetopause under northward interplanetary magnetic field: Statistical study. *Journal of Geophysical Research: Space Physics*, *119*(9), 7485–7494. https://doi.org/10.1002/2014JA020379

Lin, R. L., Zhang, X. X., Liu, S. Q., Wang, Y. L., & Gong, J. C. (2010). A three-dimensional asymmetric magnetopause model. *Journal of Geophysical Research (Space Physics)*, *115*(A4), A04207. https://doi.org/10.1029/2009JA014235

Lindstedt, T., Khotyaintsev, Y. V., Vaivads, A., André, M., Fear, R. C., Lavraud, B., et al. (2009). Separatrix regions of magnetic reconnection at the magnetopause. *Annales de Geophysique*, *27*(10), 4039–4056. https://doi.org/10.5194/angeo-27-4039-2009

Lockwood, M., Fazakerley, A., Opgenoorth, H., Moen, J., van Eyken, A. P., Dunlop, M., et al. (2001). Coordinated cluster and ground-based instrument observations of transient changes in the magnetopause boundary layer during an interval of predominantly northward IMF: Relation to reconnection pulses and FTE signatures. *Annales Geophysicae*, *19*(10/12), 1613–1640. https://doi.org/10.5194/angeo-19-1613-2001

Louarn, P., Fedorov, A., Budnik, E., Fruit, G., Sauvaud, J. A., Harvey, C. C., & Balogh, A. (2004). Cluster observations of complex 3D magnetic structures at the magnetopause. *Geophysical Research Letters*, *31*(19), L19805. https://doi.org/10.1029/2004GL020625

Lund, E. J., Farrugia, C. J., Sandholt, P. E., Kistler, L. M., Fairfield, D. H., Gratton, F. T., et al. (2006). The changing topology of the duskside magnetopause boundary layer in relation to IMF orientation. *Advances in Space Research*, *37*(3), 497–500. https://doi.org/10.1016/j.asr.2004.11.035

Lundin, R., Sauvaud, J. A., Rème, H., Balogh, A., Dandouras, I., Bosqued, J. M., et al. (2003). Evidence for impulsive solar wind plasma penetration through the dayside magnetopause. *Annales de Geophysique*, *21*(2), 457–472. https://doi.org/10.5194/angeo-21-457-2003

Ma, X., Otto, A., Delamere, P. A., & Zhang, H. (2016). Interaction between reconnection and Kelvin-Helmholtz at the high-latitude magnetopause. *Advances in Space Research*, *58*(2), 231–239. https://doi.org/10.1016/j.asr.2016.02.025

Mann, I. R., Voronkov, I., Dunlop, M., Donovan, E., Yeoman, T. K., Milling, D. K., et al. (2002). Coordinated ground-based and cluster observations of large amplitude global magnetospheric oscillations during a fast solar wind speed interval. *Annales Geophysicae*, *20*(4), 405–426. https://doi.org/10.5194/angeo-20-405-2002

Marchaudon, A., Owen, C. J., Bosqued, J.-M., Fear, R. C., Fazakerley, A. N., Dunlop, M. W., et al. (2005). Simultaneous double star and cluster ftes observations on the dawnside flank of the magnetosphere. *Annales Geophysicae*, *23*(8), 2877–2887. https://doi.org/10.5194/angeo-23-2877-2005

Masson, A., & Nykyri, K. (2018). Kelvin-Helmholtz Instability: Lessons learned and ways forward. *Space Science Reviews*, *214*(4), 71. https://doi.org/10.1007/s11214-018-0505-6

Maynard, N., Moen, J., Burke, W., Lester, M., Ober, D., Scudder, J., et al. (2004). Temporal-spatial structure of magnetic merging at the magnetopause inferred from 557.7-nm all-sky images. *Annales Geophysicae*, *22*(8), 2917–2942. https://doi.org/10.5194/angeo-22-2917-2004

Maynard, N. C., Burke, W. J., Ebihara, Y., Ober, D. M., Wilson, G. R., Siebert, K. D., et al. (2006). Characteristics of merging at the magnetopause inferred from dayside 557.7-nm all-sky images: Imf drivers of poleward moving auroral forms. *Annales Geophysicae*, *24*(11), 3071–3098. https://doi.org/10.5194/angeo-24-3071-2006

Maynard, N. C., Farrugia, C. J., Burke, W. J., Ober, D. M., Mozer, F. S., Rème, H., et al. (2012). Cluster observations of the dusk flank magnetopause near the sash: Ion dynamics and flow-through reconnection. *Journal of Geophysical Research: Space Physics*, *117*(A10), A10201. https://doi.org/10.1029/2012JA017703

Moore, T. W., Nykyri, K., & Dimmock, A. P. (2016). Cross-scale energy transport in space plasmas. *Nature Physics*, *12*(12), 1164–1169. https://doi.org/10.1038/nphys3869

Moore, T. W., Nykyri, K., & Dimmock, A. P. (2017). Ion-Scale wave properties and enhanced ion heating across the low-latitude boundary layer during Kelvin-Helmholtz instability. *Journal of Geophysical Research: Space Physics*, *122*(11), 11128–11153. https://doi.org/10.1002/2017JA024591

Moretto, T., Sibeck, D. G., Lavraud, B., Trattner, K. J., Rème, H., & Balogh, A. (2005). Flux pile-up and plasma depletion at the high latitude dayside magnetopause during southward interplanetary magnetic field: A cluster event study. *Annales Geophysicae*, *23*(6), 2259–2264. https://doi.org/10.5194/angeo-23-2259-2005

Mozer, F. S., Bale, S. D., & Phan, T. D. (2002). Evidence of diffusion regions at a subsolar magnetopause crossing. *Physical Review Letters*, *89*(1), 015002. https://doi.org/10.1103/PhysRevLett.89.015002

Nakamura, T. Â. K. Â. M., Stawarz, J. Â. E., Hasegawa, H., Narita, Y., Franci, L., Wilder, F. D., et al. (2020). Effects of fluctuating magnetic field on the growth of the Kelvin-Helmholtz instability at the earth's magnetopause. *Journal of Geophysical Research (Space Physics)*, *125*(3), e27515. https://doi.org/10.1029/2019JA027515

Nakamura, T. K. M., Hasegawa, H., Daughton, W., Eriksson, S., Li, Y. W., & Nakamura, R. (2017). Turbulent mass transfer caused by vortex induced reconnection in collisionless magnetospheric plasmas. *Nature Communications*, *8*. https://doi.org/10.1038/s41467-017-01579-0

Nishino, M. N., Hasegawa, H., Fujimoto, M., Saito, Y., Mukai, T., Dandouras, I., et al. (2011). A case study of Kelvin-Helmholtz vortices on both flanks of the Earth's magnetotail. *Planetary and Space Science*, *59*(7), 502–509. https://doi.org/10.1016/j.pss.2010.03.011

Nykyri, K., Otto, A., Lavraud, B., Mouikis, C., Kistler, L. M., Balogh, A., & Rème, H. (2006). Cluster observations of reconnection due to the kelvin-helmholtz instability at the dawnside magnetospheric flank. *Annales Geophysicae*, *24*(10), 2619–2643. https://doi.org/10.5194/angeo-24-2619-2006

Oksavik, K., Fritz, T. A., Zong, Q. G., Søraas, F., & Wilken, B. (2002). Three-dimensional energetic ion sounding of the magnetopause using Cluster/RAPID. *Geophysical Research Letters*, *29*(9), 61–1–61–4. https://doi.org/10.1029/2001GL014265

Owen, C. J., Fazakerley, A. N., Carter, P. J., Coates, A. J., Krauklis, I. C., Szita, S., et al. (2001). Cluster peace observations of electrons during magnetospheric flux transfer events. *Annales Geophysicae*, *19*(10/12), 1509–1522. https://doi.org/10.5194/angeo-19-1509-2001

Owen, C. J., Marchaudon, A., Dunlop, M. W., Fazakerley, A. N., Bosqued, J. M., Dewhurst, J. P., et al. (2008). Cluster observations of "crater" flux transfer events at the dayside high-latitude magnetopause. *Journal of Geophysical Research (Space Physics)*, *113*(A7), A07S04. https://doi.org/10.1029/2007JA012701

Owen, C. J., Taylor, M. G. G. T., Krauklis, I. C., Fazakerley, A. N., Dunlop, M. W., & Bosqued, J. M. (2004). Cluster observations of surface waves on the dawn flank magnetopause. *Annales Geophysicae*, *22*(3), 971–983. https://doi.org/10.5194/angeo-22-971-2004

Palmroth, M., Fear, R. C., & Honkonen, I. (2012). Magnetopause energy transfer dependence on the interplanetary magnetic field and the earth's magnetic dipole axis orientation. *Annales Geophysicae*, *30*(3), 515–526. https://doi.org/10.5194/angeo-30-515-2012

Palmroth, M., Laitinen, T. V., Anekallu, C. R., Pulkkinen, T. I., Dunlop, M., Lucek, E. A., & Dandouras, I. (2011). Spatial dependence of magnetopause energy transfer: Cluster measurements verifying global simulations. *Annales Geophysicae*, *29*(5), 823–838. https://doi.org/10.5194/angeo-29-823-2011

Panov, E. V., Artemyev, A. V., Nakamura, R., & Baumjohann, W. (2011). Two types of tangential magnetopause current sheets: Cluster observations and theory. *Journal of Geophysical Research (Space Physics)*, *116*(A12), A12204. https://doi.org/10.1029/2011JA016860

Panov, E. V., Büchner, J., Fränz, M., Korth, A., Khotyaintsev, Y., Nikutowski, B., et al. (2006). CLUSTER spacecraft observation of a thin current sheet at the Earth's magnetopause. *Advances in Space Research*, *37*(7), 1363–1372. https://doi.org/10.1016/j.asr.2005.08.024

Panov, E. V., Büchner, J., Fränz, M., Korth, A., Savin, S. P., Fornaçon, K. H., et al. (2006). CLUSTER observation of collisionless transport at the magnetopause. *Geophysical Research Letters*, *33*(15), L15109. https://doi.org/10.1029/2006GL026556

Panov, E. V., Büchner, J., FräNz, M., Korth, A., Savin, S. P., RèMe, H., & FornaçOn, K. H. (2008). High-latitude Earth's magnetopause outside the cusp: Cluster observations. *Journal of Geophysical Research (Space Physics)*, *113*(A1), A01220. https://doi.org/10.1029/2006JA012123

Parker, E. N. (1963). The Solar-Flare Phenomenon and the Theory of Reconnection and Annihiliation of Magnetic Fields. *Astrophysical Journal Supplement*, *8*, 177. https://doi.org/10.1086/190087

Paschmann, G., Haaland, S., Sonnerup, B. U. O., Hasegawa, H., Georgescu, E., Klecker, B., et al. (2005). Characteristics of the near-tail dawn magnetopause and boundary layer. *Annales de Geophysique*, *23*(4), 1481–1497. https://doi.org/10.5194/angeo-23-1481-2005

Paschmann, G., Haerendel, G., Sckopke, N., Rosenbauer, H., & Hedgecock, P. C. (1976). Plasma and magnetic field characteristics of the distant polar cusp near local noon: The entry layer. *Journal of Geophysical Research*, *81*(16), 2883–2899. https://doi.org/10.1029/JA081i016p02883

Paschmann, G., Papamastorakis, I., Sckopke, N., Haerendel, G., Sonnerup, B. U. O., Bame, S. J., et al. (1979). Plasma acceleration at the earth's magnetopause - Evidence for reconnection. *Nature*, *282*, 243–246. https://doi.org/10.1038/282243a0

Paschmann, G., & Daly, P. W. (Eds.), (1998). *Analysis Methods for Multi-Spacecraft Data. ISBN 1608-280X, 1998* (Vol. 1). ESA/ISSI.

Paschmann, G., & Daly, P. W. (Eds.), (2008). *Multi-Spacecraft Analysis Methods 1260 Revisited*. ESA/ISSI.

Paschmann, G., Schwartz, S., Haaland, S., & Escoubet, C. (Eds.), (2005). *Outer magnetosphere boundaries: Cluster results*. Springer.

Pathak, N., Uma, R., & Sharma, R. P. (2019). Localized Structures and Turbulent Spectra in the Magnetopause. *Journal of Geophysical Research*, *124*(4), 2515–2526. https://doi.org/10.1029/2018JA026147

Penz, T., Farrugia, C. J., Ivanova, V. V., Semenov, V. S., Ivanov, I. B., Cowley, S. W. H., et al. (2007). Modeled variations of the reconnection electric field at the dayside magnetopause during continued flux transfer event activity. *Journal of Geophysical Research: Space Physics*, *112*(A1), A01S90. https://doi.org/10.1029/2006JA011937

Petrinec, S. M., Redmon, R. J., & Rastaetter, L. (2017). Nowcasting and forecasting of the magnetopause and bow shock—A status update. *Space Weather*, *15*(1), 36–43. https://doi.org/10.1002/2016SW001565

Petschek, H. E. (1964). *Magnetic field annihilation* (Vol. 50, p. 425). Nasa special publication.

Phan, T., Frey, H. U., Frey, S., Peticolas, L., Fuselier, S., Carlson, C., et al. (2003). Simultaneous Cluster and IMAGE observations of cusp reconnection and auroral proton spot for northward IMF. *Geophysical Research Letters*, *30*(10), 1509. https://doi.org/10.1029/2003GL016885

Phan, T. D., Dunlop, M. W., Paschmann, G., Klecker, B., Bosqued, J. M., Rème, H., et al. (2004). Cluster observations of continuous reconnection at the magnetopause under steady interplanetary magnetic field conditions. *Annales Geophysicae*, *22*(7), 2355–2367. https://doi.org/10.5194/angeo-22-2355-2004

Phan, T. D., Escoubet, C. P., Rezeau, L., Treumann, R. A., Vaivads, A., Paschmann, G., et al. (2005). Magnetopause Processes. *Space Science Reviews*, *118*(1–4), 367–424. https://doi.org/10.1007/s11214-005-3836-z

Phan, T. D., Shay, M. A., Eastwood, J. P., Angelopoulos, V., Oieroset, M., Oka, M., & Fujimoto, M. (2016). Establishing the context for reconnection diffusion region encounters and strategies for the capture and transmission of diffusion region burst data by MMS. *Space Science Reviews*, *199*(1–4), 631–650. https://doi.org/10.1007/s11214-015-0150-2

Pickett, J. S., Christopher, I. W., Grison, B., Grimald, S., Santolík, O., Décréau, P. M. E., et al. (2011). On the propagation and modulation of electrostatic solitary waves observed near the magnetopause on cluster. In D. Vassiliadis, S. F. Fung, X. Shao, I. A. Daglis, & J. D. Huba (Eds.), *American Institute Of Physics Conference Series* (Vol. 1320, pp. 115–124). https://doi.org/10.1063/1.3544316

Pitout, F. (2021). The polar cusp seen by cluster. *Journal of Geophysical Research*, *126*(A7).

Pitout, F., Dunlop, M. W., Blagau, A., Bogdanova, Y., Escoubet, C. P., Carr, C., et al. (2008). Coordinated Cluster and Double Star observations of the dayside magnetosheath and magnetopause at different latitudes near noon. *Journal of Geophysical Research (Space Physics)*, *113*(A7), A07S06. https://doi.org/10.1029/2007JA012767

Pitout, F., Escoubet, C., & Lucek, E. (2004). Ionospheric plasma density structures associated with magnetopause motion: A case study using the Cluster spacecraft and the EISCAT Svalbard Radar. *Annales de Geophysique*, *22*(7), 2369–2379. https://doi.org/10.5194/angeo-22-2369-2004

Popielawska, B., Sandahl, I., Styazhkin, V. A., Stenuit, H., & Zakharov, A. V. (2002). Magnetopause poleward of the cusp: Comparison of plasma and magnetic signature of the boundary for southward and northward directed interplanetary magnetic field. *Advances in Space Research*, *30*(12), 2799–2808. https://doi.org/10.1016/S0273-1177(02)80416-1

Pu, Z. Y., Zhang, X. G., Wang, X. G., Wang, J., Zhou, X. Z., Dunlop, M. W., et al. (2007). Global view of dayside magnetic reconnection with the dusk-dawn IMF orientation: A statistical study for Double Star and Cluster data. *Geophysical Research Letters*, *34*(20), L20101. https://doi.org/10.1029/2007GL030336

Pu, Z. Y., Zong, Q. G., Fritz, T. A., Xiao, C. J., Huang, Z. Y., Fu, S. Y., et al. (2005). Multiple flux rope events at the high-latitude magnetopause: Cluster/rapid observation on 26 January, 2001. *Surveys in Geophysics*, *26*(1–3), 193–214. https://doi.org/10.1007/s10712-005-1878-0

Raab, W., Branduardi-Raymont, G., Wang, C., Dai, L., Donovan, E., Enno, G., et al. (2016). SMILE: A joint ESA/CAS mission to investigate the interaction between the solar wind and Earth's magnetosphere. In J.-W. A. den Herder, T. Takahashi, & M. Bautz (Eds.), *Space Telescopes And Instrumentation 2016: Ultraviolet To Gamma Ray* (Vol. 9905, pp. 1–9). https://doi.org/10.1117/12.2231984

Rae, I. J., Donovan, E. F., Mann, I. R., Fenrich, F. R., Watt, C. E. J., Milling, D. K., et al. (2005). Evolution and characteristics of global Pc5 ULF waves during a high solar wind speed interval. *Journal of Geophysical Research: Space Physics*, *110*(A12), A12211. https://doi.org/10.1029/2005JA011007

Retinò, A., Bavassano Cattaneo, M. B., Marcucci, M. F., Vaivads, A., André, M., Khotyaintsev, Y., et al. (2005). Cluster multispacecraft observations at the high-latitude duskside magnetopause: Implications for continuous and component magnetic reconnection. *Annales Geophysicae*, *23*(2), 461–473. https://doi.org/10.5194/angeo-23-461-2005

Rezeau, L., Sahraoui, F., D'Humières, E., Belmont, G., Chust, T., Cornilleau-Wehrlin, N., et al. (2001). A case study of low-frequency waves at the magnetopause. *Annales de Geophysique*, *19*(10), 1463–1470. https://doi.org/10.5194/angeo-19-1463-2001

Robert, P. (2021). Accuracy of current density determination. *Journal of Geophysical Research*, *126*(A7).

Robert, P., Roux, A., Harvey, C. C., Dunlop, M. W., Daly, P. W., & Glassmeier, K.-H. (1998). Tetrahedron Geometric Factors. *ISSI Scientific Reports Series*, *1*, 323–348.

Rogers, B. N., Denton, R. E., & Drake, J. F. (2003). Signatures of collisionless magnetic reconnection. *Journal of Geophysical Research (Space Physics)*, *108*(A3), 1111. https://doi.org/10.1029/2002JA009699

Rosenqvist, L., Vaivads, A., Retinò, A., Phan, T., Opgenoorth, H. J., Dandouras, I., & Buchert, S. (2008). Modulated reconnection rate and energy conversion at the magnetopause under steady IMF conditions. *Geophysical Research Letters*, *35*(8), L08104. https://doi.org/10.1029/2007GL032868

Russell, C. T., & Elphic, R. C. (1978). Initial ISEE Magnetometer Results: Magnetopause Observations (Article published in the special issues: Advances in Magnetospheric Physics with GEOS- 1 and ISEE - 1 and 2.). *Space Science Reviews*, *22*(6), 681–715. https://doi.org/10.1007/BF00212619

Russell, C. T., & Elphic, R. C. (1979). ISEE observations of flux transfer events at the dayside magnetopause. *Geophysical Research Letters*, *6*(1), 33–36. https://doi.org/10.1029/GL006i001p00033

Šafránková, J., Dušík, Š., & Němeček, Z. (2005). The shape and location of the high-latitude magnetopause. *Advances in Space Research*, *36*(10), 1934–1939. https://doi.org/10.1016/j.asr.2004.05.009

Šafránková, J., Goncharov, O., Němeček, Z., Přech, L., & Sibeck, D. G. (2012). Asymmetric magnetosphere deformation driven by hot flow anomaly(ies). *Geophysical Research Letters*, *39*(15), L15107. https://doi.org/10.1029/2012GL052636

Šafránková, J., Zastenker, G., Němeček, Z., Fedorov, A., Simersky, M., & Prech, L. (1997). Small scale observation of magnetopause motion: Preliminary results of the interball project. *Annales Geophysicae*, *15*(5), 562–569. https://doi.org/10.1007/s00585-997-0562-8

Sauvaud, J. A., Lundin, R., Rème, H., McFadden, J. P., Carlson, C., Parks, G. K., et al. (2001). Intermittent thermal plasma acceleration linked to sporadic motions of the magnetopause, first Cluster results. *Annales Geophysicae*, *19*, 1523–1532. https://doi.org/10.5194/angeo-19-1523-2001

Schwartz, S. J. (1998). Shock and discontinuity normals, mach numbers, and related parameters. *ISSI Scientific Reports Series*, *1*, 249–270. https://doi.org/10.2307/3052576

Shen, C., Dunlop, M., Ma, Y. H., Chen, Z. Q., Yan, G. Q., Liu, Z. X., et al. (2011). The magnetic configuration of the high-latitude cusp and dayside magnetopause under strong magnetic shears. *Journal of Geophysical Research (Space Physics)*, *116*(A9), A09228. https://doi.org/10.1029/2011JA016501

Shen, C., Li, X., Dunlop, M., Liu, Z. X., Balogh, A., Baker, D. N., et al. (2003). Analyses on the geometrical structure of magnetic field in the current sheet based on cluster measurements. *Journal of Geophysical Research: Space Physics*, *108*(A5), 1168. https://doi.org/10.1029/2002JA009612

Shi, Q. Q., Shen, C., Dunlop, M. W., Pu, Z. Y., Zong, Q. G., Liu, Z. X., et al. (2006). Motion of observed structures calculated from multi-point magnetic field measurements: Application to Cluster. *Geophysical Research Letters*, *33*(8), L08109. https://doi.org/10.1029/2005GL025073

Shi, Q. Q., Shen, C., Pu, Z. Y., Dunlop, M. W., Zong, Q. G., Zhang, H., et al. (2005). Dimensional analysis of observed structures using multipoint magnetic field measurements: Application to Cluster. *Geophysical Research Letters*, *32*(12), L12105. https://doi.org/10.1029/2005GL022454

Shi, Q. Q., Tian, A. M., Bai, S. C., Hasegawa, H., Degeling, A. W., Pu, Z. Y., et al. (2019). Dimensionality, coordinate system and reference frame for analysis of in-situ space plasma and field data. *Space Science Reviews*, *215*(4), 35. https://doi.org/10.1007/s11214-019-0601-2

Sibeck, D., & Kudela, K. (Eds.), (1999). Interball in the ISTP program. (Vol. 537).

Sonnerup, B., Hasegawa, H., Teh, W.-L., & Hau, L.-N. (2006). Grad-Shafranov reconstruction: An overview. *Journal of Geophysical Research: Space Physics*, *111*(A9), A09204. https://doi.org/10.1029/2006JA011717

Sonnerup, B., & Scheible, M. (1998). Minimum and maximum variance analysis. *ISSI Scientific Reports Series*, *1*, 185–220.

Sonnerup, B., Teh, W.-L., & Hasegawa, H. (2008). Grad-Shafranov and MHD Reconstructions. *ISSI Scientific Reports Series*, *8*, 81–90.

Sonnerup, B. U. Ö. (1974). Magnetopause reconnection rate. *Journal of Geophysical Research*, *79*(10), 1546–1549. https://doi.org/10.1029/JA079i010p01546

Sonnerup, B. U. O. (1979). Magnetic field reconnection, vol III. In *Solar system plasma physics*.

Sonnerup, B. U. Ö., & Cahill, J. (1967). Magnetopause structure and attitude from explorer 12 observations. *Journal of Geophysical Research*, *72*, 171. https://doi.org/10.1029/JZ072i001p00171

Sonnerup, B. U. Ö., Haaland, S., Paschmann, G., Dunlop, M. W., RèMe, H., & Balogh, A. (2006). Orientation and motion of a plasma discontinuity from single-spacecraft measurements: Generic residue analysis of Cluster data. *Journal of Geophysical Research: Space Physics*, *111*(A5), A05203. https://doi.org/10.1029/2005JA011538

Sonnerup, B. U. Ö., Haaland, S., Paschmann, G., Lavraud, B., Dunlop, M. W., Rème, H., & Balogh, A. (2004). Orientation and motion of a discontinuity from single-spacecraft measurements of plasma velocity and density: Minimum mass flux residue. *Journal of Geophysical Research: Space Physics*, *109*(A3), A03221. https://doi.org/10.1029/2003JA010230

Sonnerup, B. U. Ö., & Hasegawa, H. (2005). Orientation and motion of two-dimensional structures in a space plasma. *Journal of Geophysical Research: Space Physics*, *110*(A6), A06208. https://doi.org/10.1029/2004JA010853

Sonnerup, B. U. Ö., Hasegawa, H., & Paschmann, G. (2004). Anatomy of a flux transfer event seen by Cluster. *Geophysical Research Letters*, *31*(11), L11803. https://doi.org/10.1029/2004GL020134

Souza, V. M., Gonzalez, W. D., Sibeck, D. G., Koga, D., Walsh, B. M., & Mendes, O. (2017). Comparative study of three reconnection X line models at the Earth's dayside magnetopause using in situ observations. *Journal of Geophysical Research: Space Physics*, *122*(4), 4228–4250. https://doi.org/10.1002/2016JA023790

Stasiewicz, K., Khotyaintsev, Y., & Grzesiak, M. (2004). Dispersive Alfvén Waves Observed by Cluster at the Magnetopause. *Physica Scripta*, *107*, 171. https://doi.org/10.1238/Physica.Topical.107a00171

Stenberg, G., Oscarsson, T., André, M., Vaivads, A., Backrud-Ivgren, M., Khotyaintsev, Y., et al. (2007). Internal structure and spatial dimensions of whistler wave regions in the magnetopause boundary layer. *Annales Geophysicae*, *25*(11), 2439–2451. https://doi.org/10.5194/angeo-25-2439-2007

Stenberg, G., Oscarsson, T., André, M., Vaivads, A., Morooka, M., Cornilleau-Wehrlin, N., et al. (2005). Electron-scale sheets of whistlers close to the magnetopause. *Annales Geophysicae*, *23*(12), 3715–3725. https://doi.org/10.5194/angeo-23-3715-2005

Sweet, P. A. (1958). The Neutral Point Theory of Solar Flares. In B. Lehnert (Ed.), *Electromagnetic phenomena in cosmical physics* (Vol. 6, pp. 123. https://doi.org/10.1017/s0074180900237704

Taktakishvili, A., Zimbardo, G., Amata, E., Savin, S., Greco, A., Veltri, P., & Lopez, R. E. (2007). Ion escape from the high latitude magnetopause: Analysis of oxygen and proton dynamics in the presence of magnetic turbulence. *Annales Geophysicae*, *25*(8), 1877–1885. https://doi.org/10.5194/angeo-25-1877-2007

Tátrallyay, M., Erdös, G., Németh, Z., Verigin, M. I., & Vennerstrom, S. (2012). Multispacecraft observations of the terrestrial bow shock and magnetopause during extreme solar wind disturbances. *Annales Geophysicae*, *30*(12), 1675–1692. https://doi.org/10.5194/angeo-30-1675-2012

Taylor, M. G. G. T., Hasegawa, H., Lavraud, B., Phan, T., Escoubet, C. P., Dunlop, M. W., et al. (2012). Spatial distribution of rolled up kelvin-helmholtz vortices at earth's dayside and flank magnetopause. *Annales Geophysicae*, *30*(6), 1025–1035. https://doi.org/10.5194/angeo-30-1025-2012

Teh, W.-L., & Sonnerup, B. U. O. (2008). First results from ideal 2-d MHD reconstruction: Magnetopause reconnection event seen by cluster. *Annales Geophysicae*, *26*(9), 2673–2684. https://doi.org/10.5194/angeo-26-2673-2008

Teh, W. L., Sonnerup, B. U. Ö., & Hau, L. N. (2007). Grad-Shafranov reconstruction with field-aligned flow: First results. *Geophysical Research Letters*, *34*(5), L05109. https://doi.org/10.1029/2006GL028802

Toledo-Redondo, S., André, M., Vaivads, A., Khotyaintsev, Y. V., Lavraud, B., Graham, D. B., et al. (2016). Cold ion heating at the dayside magnetopause during magnetic reconnection. *Geophysical Research Letters*, *43*(1), 58–66. https://doi.org/10.1002/2015GL067187

Torbert, R. B., Burch, J. L., Phan, T. D., Hesse, M., Argall, M. R., Shuster, J., et al. (2018). Electron-scale dynamics of the diffusion region during symmetric magnetic reconnection in space. *Science*, *362*(6421), 1391–1395. https://doi.org/10.1126/science.aat2998

Trattner, K. J., Petrinec, S. M., Fuselier, S. A., & Phan, T. D. (2012). The location of reconnection at the magnetopause: Testing the maximum magnetic shear model with THEMIS observations. *Journal of Geophysical Research: Space Physics*, *117*(A1), A01201. https://doi.org/10.1029/2011JA016959

Trines, R., Bingham, R., Dunlop, M. W., Vaivads, A., Davies, J. A., Mendonça, J. T., et al. (2007). Spontaneous Generation of self-organized solitary wave structures at earth's magnetopause. *Physical Review Letters*, *99*(20), 205006. https://doi.org/10.1103/PhysRevLett.99.205006

Turkakin, H., Rankin, R., & Mann, I. R. (2013). Primary and secondary compressible Kelvin-Helmholtz surface wave instabilities on the Earth's magnetopause. *Journal of Geophysical Research (Space Physics)*, *118*(7), 4161–4175. https://doi.org/10.1002/jgra.50394

Vaivads, A., André, M., Buchert, S. C., Wahlund, J. E., Fazakerley, A. N., & Cornilleau-Wehrlin, N. (2004). Cluster observations of lower hybrid turbulence within thin layers at the magnetopause. *Geophysical Research Letters*, *31*(3), L03804. https://doi.org/10.1029/2003GL018142

Vaivads, A., Khotyaintsev, Y., André, M., Retinò, A., Buchert, S. C., Rogers, B. N., et al. (2004). Structure of the magnetic reconnection diffusion region from four-spacecraft observations. *Physical Review Letters*, *93*(10), 105001. https://doi.org/10.1103/PhysRevLett.93.105001

Vaivads, A., Santolík, O., Stenberg, G., André, M., Owen, C. J., Canu, P., & Dunlop, M. (2007). Source of whistler emissions at the dayside magnetopause. *Geophysical Research Letters*, *34*(9), L09106. https://doi.org/10.1029/2006GL029195

Vasyliunas, V. M. (1975). Theoretical models of magnetic field line merging, 1. *Reviews of Geophysics and Space Physics*, *13*, 303–336. https://doi.org/10.1029/RG013i001p00303

Verigin, M. I., Kotova, G. A., Bezrukikh, V. V., Zastenker, G. N., & Nikolaeva, N. (2009). Analytical model of the near-Earth magnetopause according to the data of the Prognoz and Interball satellite data. *Geomagnetism and Aeronomy*, *49*(8), 1176–1181. https://doi.org/10.1134/S0016793209080283

Vines, S. K., Fuselier, S. A., Petrinec, S. M., Trattner, K. J., & Allen, R. C. (2017). Occurrence frequency and location of magnetic islands at the dayside magnetopause. *Journal of Geophysical Research: Space Physics*, *122*(4), 4138–4155. https://doi.org/10.1002/2016JA023524

Vines, S. K., Fuselier, S. A., Trattner, K. J., Petrinec, S. M., & Drake, J. F. (2015). Ion acceleration dependence on magnetic shear angle in dayside magnetopause reconnection. *Journal of Geophysical Research: Space Physics*, *120*(9), 7255–7269. https://doi.org/10.1002/2015JA021464

Vogt, J., Haaland, S., & Paschmann, G. (2011). Accuracy of multi-point boundary crossing time analysis. *Annales Geophysicae*, *29*(12), 2239–2252. https://doi.org/10.5194/angeo-29-2239-2011

Vogt, J., Paschmann, G., & Chanteur, G. (2008). Reciprocal Vectors. *ISSI Scientific Reports Series*, *8*, 33–46.

Walsh, B. M. (2017). Magnetopause plasma parameters and asymmetries in solar wind magnetosphere coupling. In S. Haaland, A. Runov, & C. Forsyth (Eds.), *Dawn-dusk asymmetries in planetary plasma environments* (Vol. 230, pp. 29–39). https://doi.org/10.1002/9781119216346.ch3

Walsh, B. M., Haaland, S. E., Daly, P. W., Kronberg, E. A., & Fritz, T. A. (2012). Energetic electrons along the high-latitude magnetopause. *Annales de Geophysique*, *30*(6), 1003–1013. https://doi.org/10.5194/angeo-30-1003-2012

Wang, J., Dunlop, M. W., Pu, Z. Y., Zhou, X. Z., Zhang, X. G., Wei, Y., et al. (2007). TC1 and Cluster observation of an FTE on 4 January 2005: A close conjunction. *Geophysical Research Letters*, *34*(3), L03106. https://doi.org/10.1029/2006GL028241

Wang, S., Kistler, L. M., Mouikis, C. G., Liu, Y., & Genestreti, K. J. (2014). Hot magnetospheric $o^+$and cold ion behavior in magnetopause reconnection: Cluster observations. *Journal of Geophysical Research (Space Physics)*, *119*(12), 9601–9623. https://doi.org/10.1002/2014JA020402

Wang, S., Kistler, L. M., Mouikis, C. G., & Petrinec, S. M. (2015). Dependence of the dayside magnetopause reconnection rate on local conditions. *Journal of Geophysical Research*, *120*(8), 6386–6408. https://doi.org/10.1002/2015JA021524

Wang, Y., Sibeck, D. G., Merka, J., Boardsen, S. A., Karimabadi, H., Sipes, T. B., et al. (2013). A new three-dimensional magnetopause model with a support vector regression machine and a large database of multiple spacecraft observations. *Journal of Geophysical Research: Space Physics*, *118*(5), 2173–2184. https://doi.org/10.1002/jgra.50226

Wang, Y. L., Elphic, R. C., Lavraud, B., Taylor, M. G. G. T., Birn, J., Raeder, J., et al. (2005). Initial results of high-latitude magnetopause and low-latitude flank flux transfer events from 3 years of Cluster observations. *Journal of Geophysical Research (Space Physics)*, *110*(A11), A11221. https://doi.org/10.1029/2005JA011150

Webster, J. M., Burch, J. L., Reiff, P. H., Daou, A. G., Genestreti, K. J., Graham, D. B., et al. (2018). Magnetospheric multiscale dayside reconnection electron diffusion region events. *Journal of Geophysical Research: Space Physics*, *123*(6), 4858–4878. https://doi.org/10.1029/2018JA025245

Wendel, D. E., & Reiff, P. H. (2009). Magnetopause reconnection impact parameters from multiple spacecraft magnetic field measurements. *Geophysical Research Letters*, *36*(20), L20108. https://doi.org/10.1029/2009GL040228

Wild, J. A., Cowley, S. W. H., Davies, J. A., Khan, H., Lester, M., Milan, S. E., et al. (2001). First simultaneous observations of flux transfer events at the high-latitude magnetopause by the cluster spacecraft and pulsed radar signatures in the conjugate ionosphere by the cutlass and eiscat radars. *Annales Geophysicae*, *19*(10/12), 1491–1508. https://doi.org/10.5194/angeo-19-1491-2001

Wild, J. A., Milan, S. E., Cowley, S. W. H., Bosqued, J. M., Rème, H., Nagai, T., et al. (2005). Simultaneous in-situ observations of the signatures of dayside reconnection at the high- and low-latitude magnetopause. *Annales de Geophysique*, *23*(2), 445–460. https://doi.org/10.5194/angeo-23-445-2005

Wild, J. A., Milan, S. E., Cowley, S. W. H., Dunlop, M. W., Owen, C. J., Bosqued, J. M., et al. (2003). Coordinated interhemispheric superdarn radar observations of the ionospheric response to flux transfer events observed by the cluster spacecraft at the high-latitude magnetopause. *Annales Geophysicae*, *21*(8), 1807–1826. https://doi.org/10.5194/angeo-21-1807-2003

Wild, J. A., Milan, S. E., Davies, J. A., Dunlop, M. W., Wright, D. M., Carr, C. M., et al. (2007). On the location of dayside magnetic reconnection during an interval of duskward oriented IMF. *Annales Geophysicae*, *25*(1), 219–238. https://doi.org/10.5194/angeo-25-219-2007

Xiao, C.-J., Pu, Z.-Y., Huang, Z.-Y., Fu, S.-Y., Xie, L., Zhong, Q.-G., et al. (2004). Multiple flux rope events at the high-latitude magnetopause on January 26, 2001: Current density calculation. *Chinese Journal of Geophysics*, *47*, 635–643. https://doi.org/10.1002/cjg2.3531

Xiao, C. J., Pu, Z. Y., Ma, Z. W., Fu, S. Y., Huang, Z. Y., & Zong, Q. G. (2004). Inferring of flux rope orientation with the minimum variance analysis technique. *Journal of Geophysical Research: Space Physics*, *109*(A11). https://doi.org/10.1029/2004JA010594

Yan, G., Shen, C., Liu, Z., Dunlop, M., Lucek, E., Reme, H., et al. (2008). Solar wind transport into magnetosphere caused by magnetic reconnection at high latitude magnetopause during northward IMF: Cluster-DSP conjunction observations. *Science in China E: Technological Sciences*, *51*, 1677–1684. https://doi.org/10.1007/s11431-008-0260-0

Yan, G. Q., Liu, Z. X., Shen, C., Dunlop, M. W., Balogh, A., Rème, H., et al. (2009). Solar wind entry via flux tube into magnetosphere observed by Cluster measurements at dayside magnetopause during southward IMF. *Science in China E: Technological Sciences*, *52*, 2104–2111. https://doi.org/10.1007/s11431-009-0088-2

Yao, L., Lui, S.-L., Jin, S.-P., Shi, J.-K., Balogh, A., Reme, H., et al. (2005). A study of orientation and motion of flux transfer events observed at high-latitude dayside magnetopause. *Chinese Journal of Geophysics*, *48*, 1307–1315. https://doi.org/10.1002/cjg2.778

Zhang, H., Dunlop, M. W., Zong, Q. G., Fritz, T. A., Balogh, A., & Wang, Y. (2007). Geometry of the high-latitude magnetopause as observed by Cluster. *Journal of Geophysical Research (Space Physics)*, *112*(A2), A02204. https://doi.org/10.1029/2006JA011774

Zhang, H., Fu, S., Pu, Z., Lu, J., Zhong, J., Zhu, C., et al. (2019). Statistics on the magnetosheath properties related to magnetopause magnetic reconnection. *Acta Pathologica Japonica*, *880*(2), 122. https://doi.org/10.3847/1538-4357/ab290e

Zhang, H., Zong, Q. G., Fritz, T. A., Fu, S. Y., Schaefer, S., Glassmeier, K. H., et al. (2008). Cluster observations of collisionless Hall reconnection at high-latitude magnetopause. *Journal of Geophysical Research: Space Physics*, *113*(A3), A03204. https://doi.org/10.1029/2007JA012769

Zhang, Q.-H., Liu, R. Y., Dunlop, M. W., Huang, J. Y., Hu, H. Q., Lester, M., et al. (2008). Simultaneous tracking of reconnected flux tubes: Cluster and conjugate superdarn observations on 1 April 2004. *Annales Geophysicae*, *26*(6), 1545–1557. https://doi.org/10.5194/angeo-26-1545-2008

Zhang, Y. C., Shen, C., Liu, Z. X., Pu, Z. Y., Dand ouras, I., Marchaudon, A., et al. (2011). Magnetopause response to variations in the solar wind: Conjunction observations between Cluster, TC-1, and SuperDARN. *Journal of Geophysical Research (Space Physics)*, *116*(A8), A08209. https://doi.org/10.1029/2011JA016462

Zheng, Y., Le, G., Slavin, J. A., Goldstein, M. L., Cattell, C., Balogh, A., et al. (2005). Cluster observation of continuous reconnection at dayside magnetopause in the vicinity of cusp. *Annales Geophysicae*, *23*(6), 2199–2215. https://doi.org/10.5194/angeo-23-2199-2005

Zhou, X.-Z., Zong, Q.-G., Pu, Z. Y., Fritz, T. A., Dunlop, M. W., Shi, Q. Q., et al. (2006). Multiple triangulation analysis: Another approach to determine the orientation of magnetic flux ropes. *Annales Geophysicae*, *24*(6), 1759–1765. https://doi.org/10.5194/angeo-24-1759-2006

Zhu, C. B., Zhang, H., Ge, Y. S., Pu, Z. Y., Liu, W. L., Wan, W. X., et al. (2015). Dipole tilt angle effect on magnetic reconnection locations on the magnetopause. *Journal of Geophysical Research: Space Physics*, *120*(7), 5344–5354. https://doi.org/10.1002/2015JA020989

Zong, Q. G., Fritz, T. A., Spence, H., Oksavik, K., Pu, Z. Y., Korth, A., & Daly, P. W. (2004). Energetic particle sounding of the magnetopause: A contribution by Cluster/RAPID. *Journal of Geophysical Research: Space Physics*, *109*(A4), A04207. https://doi.org/10.1029/2003JA009929

Zong, Q.-G., Zhang, H., & Zhang, H. (2018). In situ detection of the electron diffusion region of collisionless magnetic reconnection at the high-latitude magnetopause. *Earth and Planetary Physics*, *2*(3), 231–237. https://doi.org/10.26464/epp2018022