Key Points:
- We review 20 years of cusp research with one of ESA's milestones: the Cluster mission
- A multipoint capability, appropriate orbits, and a comprehensive instrumentation made Cluster the ideal space mission to study the cusp
- Cluster enabled to address key questions including cusp dynamics, ion dispersions and their consequences on merging, and waves and turbulence

Correspondence to:
F. Pitout,
frederic.pitout@irap.omp.eu

The Polar Cusp Seen by Cluster

F. Pitout[1] and **Y. V. Bogdanova[2]**

[1]IRAP, Université de Toulouse 3/CNES/CNRS, Toulouse cedex 4, France, [2]RAL Space, Rutherford Appleton Laboratory, Science and Technology Facilities Council, UK Research and Innovation, Harwell Oxford, Didcot, UK

Abstract The investigation of the magnetospheric polar cusps was one of the main objectives of the Cluster mission. The four satellites have crossed those regions numerous times over the years and, with their suitable instrumentation, favorable orbits, and unique multipoint measurements, many aspects of the cusp have been unveiled. The first of those is its highly dynamic nature. With four satellites, whatever their altitude and thus their configuration, the spatial/temporal ambiguity has been lifted and a completely new insight into the motion of the cusp and evolution of the transient small-scale structures within it was given. Second, the high altitude or exterior cusp, its properties and dynamics, magnetic configuration, the energetic particles observed within, and its boundary with the magnetosheath were characterized in a number of case studies and on a statistical basis. Third, the Cluster cusp observations brought a fresh eye on the reconnection process at the magnetopause, including its location and spatio-temporal variability. Finally, the complete payload with particle, field and wave detectors have made it possible to treat cusp as a plasma physics laboratory to progress our understanding of wave-particle interaction and turbulence within the cusp. We have no choice but to note that Cluster has been extremely successful for all these matters.

1. Introduction

1.1. The Polar Cusp Before the Space Era

The polar cusps are small and yet essential regions of Earth's magnetosphere. They can be defined as the region where the dayside and nightside geomagnetic field lines converge toward the geomagnetic dipoles. This definition or property was envisioned well before the cusp were actually observed. In the pioneer works by Chapman and Ferraro (1931), it was already understood that the interaction between the interplanetary magnetic field and the geomagnetic field could lead to a comet tail-like shape of the magnetosphere with two regions separating the compressed dayside geomagnetic field lines and the nightside elongated field lines. Initially, Chapman and Ferraro imagined a flat interface between the solar wind and the Earth's magnetic environment (Figure 1). Kawashema and Fukushima (1964) proposed a model experiment to explain the interaction between the solar wind plasma stream and the geomagnetic field, and Mead (1964, 1967) realized that this geometry would necessary lead to two magnetic null points. Dungey (1965) anticipated that magnetic reconnection would occur at those null points.

The polar cusps were alternatively called "horns" (Chapman & Ferraro, 1931), "valleys of the magnetic field" (Mead, 1964), "geomagnetic traps" (Pletnev et al., 1965) and eventually "cusps" (Willis, 1969). Spreiter and Summers (1967) proposed that they would fill up with solar wind plasma–actually the shocked solar wind of the magnetosheath–to form two denser regions in the magnetosphere. Thus, the solar wind plasma would have a direct access to the inner magnetosphere and upper atmosphere through the cusps (Willis, 1969). This is the second definition, based on plasma entry. We should note that in the past a region of the nightside magnetosphere was also named cusp (Anderson & Ness, 1966; Ness, 1969).

1.2. Early In-Situ Measurements

When the first scientific satellites were launched in the late 1950s (for the International Geophysical Year), the main scientific questions were to find out whether a stream of charged particles coming from the Sun–the solar wind–existed, and to probe Earth's magnetic environment (with an emphasis on the radiation belts discovered then).
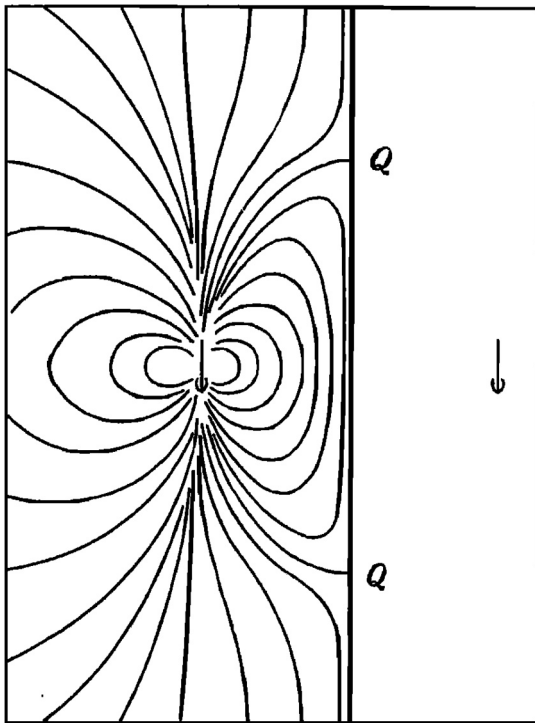
FIG. 4—Meridian section

Figure 1. Schematic showing the compressed Earth magnetic field as imagined by Chapman & Ferraro, 1931.

The first clear in situ measurements of the polar cusps occurred in 1971. That year, the satellites ISIS 1 (Heikkila & Winningham, 1971), IMP 5 (Frank, 1971), and OGO 5 (Russell et al., 1971) flew through the high-latitude dayside magnetosphere or ionosphere around magnetic noon and recorded large densities and fluxes of low-energy charged particles. From then on, a variety of observations paved the way to modern cusp research: plasma waves were observed (Scarf et al., 1972) and, more importantly for solar wind-magnetospheric coupling, the role of the orientation of the interplanetary magnetic field (IMF) was evidenced (Burch, 1972; Kivelson et al., 1973).

In the late 1970s and early 1980s, several spacecraft were launched with favorable (polar) orbits to fly through the cusps. With AE-C data, Reiff et al. (1977) showed that the injected magnetosheath ions undergo a velocity filter effect as they flow down along the cusp magnetic field lines. Crooker (1979) modeled the location of the reconnection between the interplanetary magnetic field and the Earth's magnetic field using a simple anti-parallel model giving a good agreement with observations.

In the mid 1980s, Dynamics Explorer 1 and 2 allowed the first dual point measurements with similar instruments in the polar cusp. This was a great breakthrough. For the first time, researchers could work on data taken simultaneously at two different altitudes in the cusp. That allowed them to confirm the magnetosheath particle precipitation in the cusp and to quantify the effect of the varying magnetic intensity on those particles as they flow downward (Burch et al., 1986; Lin et al., 1986; Maynard et al., 1991). Escoubet and Bosqued (1989), using the Franco-Soviet Aureol-3 spacecraft, showed that the boundaries of the cusp where strongly correlated with IMF-B_z when an ion dispersion was observed.

At low altitude, the Defense Meteorological Space Program (DMSP) satellites have also contributed extensively to the understanding of the cusp region. Several satellites and fast orbits lead to frequent cusp crossings and a statistical approach of precipitating particles in the cusp as well as the location and dynamics of the cusp could be performed. Thus, the cusp particle precipitation as well as that of the neighboring layers were characterized (e.g., Newell & Meng, 1988b, 1994). The dependency of the location of the cusp on the IMF orientation was also studied (Newell et al., 1989).

At higher altitude, the Polar satellite (Harten & Clark, 1995), with a comprehensive set of instruments (including an auroral imager) helped scientists to make considerable progresses as the cusp exploration and understanding are concerned. High-energy particles were recorded and became a puzzle to explain (e.g., Chen et al., 1998); Polar's long lifetime allowed also statistical studies of the cusp location (Zhou et al., 1999, 2000). Let us note that Polar was launched in 1996, that is, a few years earlier than Cluster, and has a few similarities with the latter: a polar orbit and a very similar instrumentation. Therefore, Polar proved to be very complementary to Cluster.

Many pre-Cluster studies already indicated that the cusp could be an extremely dynamic region. This was seen in the cusp flow channels (e.g., Lockwood et al., 1993) or in the intermittent soft particle precipitation (e.g., Sandholt et al., 1989) for instance. Nevertheless, it was still a mystery whether this behavior was common or if, at least at times, the cusp could be a more static region in response to a steady reconnection process (Levy et al., 1964; Petschek, 1964).

For more details on the state of the art on cusp at the time Cluster was launched, the reader may want to read review papers by Smith and Lockwood (1996) and Russell (2000a, 2000b).
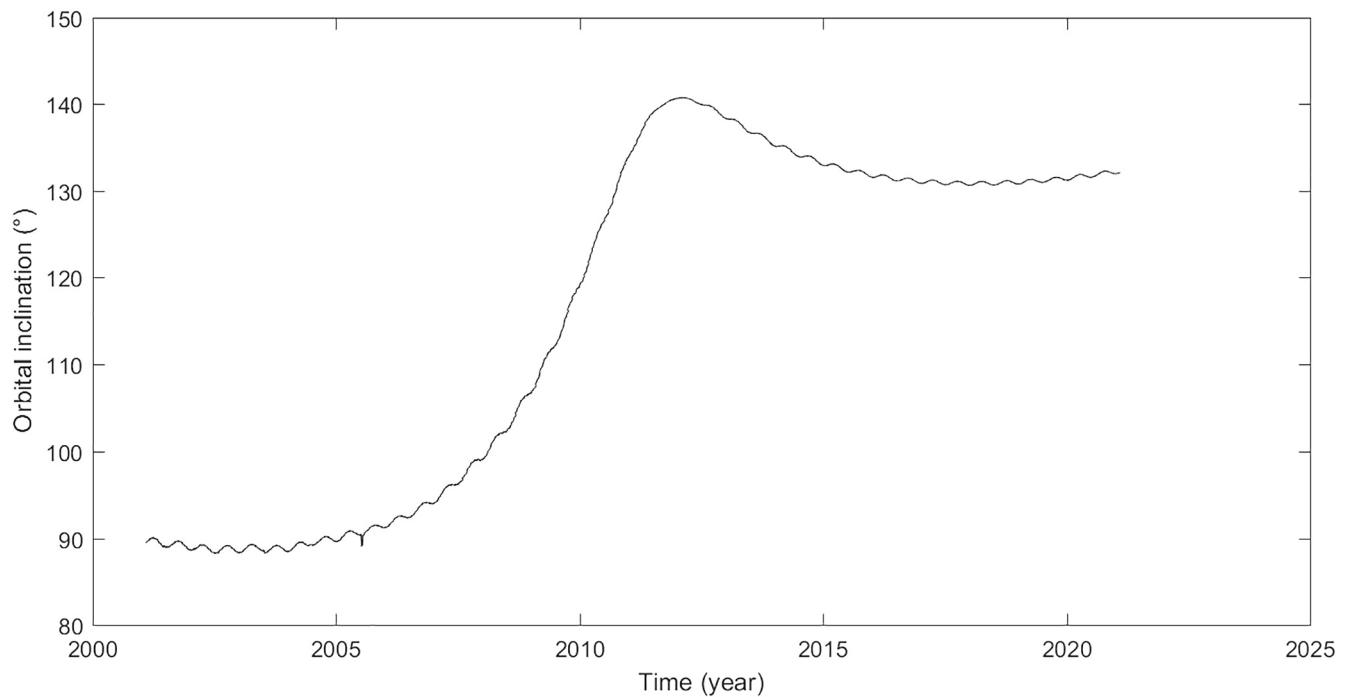
Figure 2. Orbital inclination of Cluster 3 as a function of time.

1.3. The Polar Cusp as a Main Science Objective of the Cluster Mission

Investigations of the solar wind-magnetosphere coupling and particularly the shocked solar wind penetration through the polar cusps were one of the main science objectives of the Cluster mission (Escoubet et al., 2001). To achieve those investigations, Cluster has three advantages compared to previous magnetospheric missions.

1. Four identical satellites flying in formation. Single point measurements showed their limitations and Cluster allows to lift temporal/spatial ambiguities and to perform 3D analysis techniques, allowing to study the thickness, orientation and motion of the boundaries and structures inside and around cusp region.
2. A comprehensive instrumentation for a complete diagnostic of the particles, fields, and waves with much better energy and time resolutions than that previous missions.
3. The cusp was one of the prime scientific goals of the Cluster mission. Therefore, its orbit was designed to maximize the crossings of the cusp regions (Rodriguez-Canabal et al., 1993). Its suitable polar and elliptical orbit goes through the cusp alternatively at middle altitude and at high altitude depending of the time of the year (at least in the early years of the mission). With this type of orbit, the cusps were crossed almost every orbit near perigee at middle altitude between July and September and at high altitude from January to March when the apogee was in the solar wind. Therefore, each year two periods were favorable for cusp studies with, apart from the altitude, an important difference: the configuration. In fact, at high altitude the four satellites are in tetrahedral configuration, which is suitable for 3D analysis techniques, such as the curlometer (Dunlop et al., 2002) or k-filtering (Grison et al., 2005). On the other hand, at middle altitude, closer to perigee, the four spacecraft no longer form a tetrahedron and the 3D analysis techniques are not applicable in this case. Nevertheless, interesting information on temporal evolution of the crossed structures may still be inferred. As the orbital inclination of Cluster increased with time (Figure 2) and its apogee moved down to lower Z_{GSE}, the cusps were very rarely crossed for several years between early 2008 and late 2014 (Figure 3). From 2015, the cusps were crossed again occasionally at almost constant latitude.

Cluster constellation 2001-2020
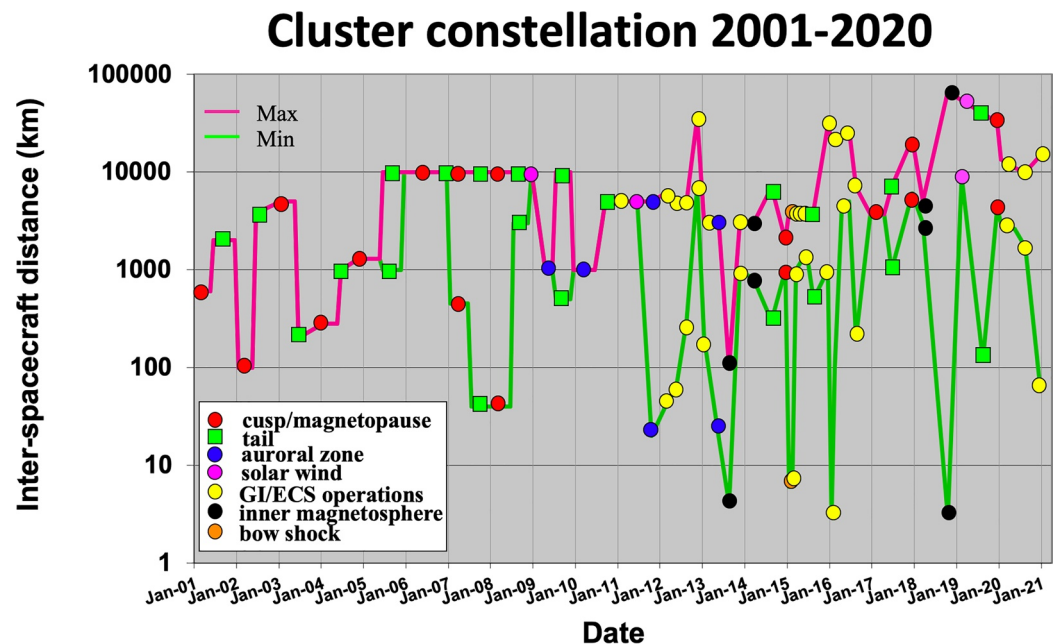
Figure 3. Cluster separation versus time. Favorable periods for cusp crossings are marked by red dots.

1.4. Scope and Organization of This Review

The readers will find other reviews on the Cluster contribution to cusp studies, which were written relatively early in the mission's lifetime (e.g., Cargill et al., 2005; Dunlop et al., 2005; Lavraud & Cargill, 2005; Lavraud, Dunlop, et al., 2005; Lavraud, Fedorov, et al., 2005). A topical book also set the state of the art five years into Cluster's lifetime, which is also retrospectively very early (Fritz & Fung, 2005). The present paper summarizes a much larger time period and it is obviously impossible to cite all the works carried out. Hence our choice to put emphasis on results that have made the most of the 3D capability of the Cluster mission.

We have organized the paper in six thematic sections. Section 2 is devoted to the observation and modeling of the cusps' magnetic field. In Section 3, we report on the exterior cusp and its boundary with the magnetosheath. Section 4 summarizes the works on the location and dynamics of the cusp with, among other things, the cusp response during IMF changes. Section 5 highlights numerous studies on particle precipitation, mainly at middle altitude. We shall demonstrate that the study of the particle spectra (ions in particular) allow to investigate various topics such as the merging at the magnetopause, the double (or multiple) cusp, or the interhemispheric asymmetries. Section 6 deals with the surprising presence of energetic particles in the cusp and the possible ways those particles are energized. Section 7 focusses on waves and ion energization and outflow, to which Cluster as greatly contributed. Section 8 tackles turbulence in the cusp. Of course, some overlaps between those sections–and with other articles of this special issue–are unavoidable and, although they may be beneficial, we have tried to minimize them.

2. Magnetic Configuration of the Cusp

As mentioned in Section 1.1, the cusp is, from its magnetic field point of view, a funnel-shaped region where the high-latitude dayside (compressed) and night side (elongated) magnetic field lines converge toward the geomagnetic poles. Previous space missions saw it as a diamagnetic cavity in which the magnetic field intensity is weaker due to the precipitation of magnetosheath plasma. Thanks to its multipoint capabilities, Cluster was able for the very first time to unveil the 3D nature of the cusps' magnetic field.

Early observations by Cargill et al. (2001, 2004) using the Flux Gate Magnetometers (FGM; Balogh et al., 1997, 2001) on board the four spacecraft confirmed the diamagnetic nature of the cusp region, which manifests itself as a magnetic depression. Furthermore, measurements showed small-scale field-aligned currents within the well-known large-scale field aligned current system in the mid-altitude cusp and

revealed structures whose sizes are smaller than the spacecraft separation (300 km in the case reported). The same authors reported an exterior cusp crossing (at higher altitude) where the magnetic field exhibits its highly disturbed nature, quite different from the turbulence found in the magnetosheath. The magnetic field is thus a good way to differentiate the exterior cusp and the adjacent magnetosheath. It was found that many of the low frequency magnetic fluctuations in the exterior cusp are due to back and forth motion of the whole diamagnetic cavity and to magnetic reconnection (Nykyri, Otto, Adamson, & Tjulin, 2011).

Taking full advantage of the four spacecraft in tetrahedral configuration, the curlometer technique (Dunlop et al., 2002) was applied to magnetic field measurements in the cusp. This technique consists of calculating the curl of B in each of the four sides of the tetrahedron formed by the spacecraft, and to eventually infer the electric current density with the Ampère law. The authors could thus work out the three components on the field-aligned currents in the cusp and found, at high altitude, values of the order of a few nA/m², which is 10 times larger than the values given by the Tsyganenko 96 model (Tsyganenko, 1995).

The magnetic structure of the cusp and the geometry of the interface with the surrounding boundaries have been considered further in several studies. Dunlop et al. (2005) showed that the exterior cusp is associated with a significant decrease in the magnetic field magnitude and ULF wave activity. This study also confirmed that the exterior cusp has magnetically defined boundaries at both the outer cusp or magnetosheath interface and the inner cusp/lobe or cusp/dayside magnetosphere interface, in agreement with a funnel geometry. It was shown that the cusp position and its extent is directly controlled by the IMF and that the magnetic field geometry is sometimes complex, although it was possible to estimate the thickness of the boundaries' current layers, ranging from a few hundred (for the inner cusp boundaries) to 1,000 km. The magnetopause indentation also have been studied, with the authors suggesting that there is an uncertainty in the magnetopause definition within the cusp region regarding whether the magnetopause corresponds to the external boundary between exterior cusp and magnetosheath or follows internal boundaries.

Tsyganenko (2009) performed a statistical analysis of Cluster and Polar data and compared the results to the TS05 model of geomagnetic field (Tsyganenko & Sitnov, 2005). He modeled the cusp magnetic field between 2 and 12 Earth radii (R_E). The author found that (a) the magnetic field depression due to incoming charged particles is visible round 4–5 R_E and above; (b) a significant offset in the location of the cusp is found: the model underestimates the latitude of center of the field depression by 2°; (c) the Y- component of the cusp magnetic field correlates well with the Y component of the IMF. Cluster data also contributed to the development of TS07 model (Tsyganenko & Sitnov, 2007) by improving the description of the magnetic field and electric currents in and around the cusp region.

The 3D structure of the geomagnetic field in and near the cusp was investigated further. For instance, Shen et al. (2011) verified the existence of the cusp funnel via a direct estimate of the local field curvature for the first time and showed a possible indentation of the high-altitude magnetopause (Figure 4), concentrating on the cases of strong magnetic shear across the magnetopause which allows to clearly identify the magnetopause. It has been confirmed that pre-cusp magnetic field lines bend sunward while in the post-cusp region the field lines bend tailward and that the minimum curvature radius of the near-magnetopause field lines is about 2.2 R_E in both pre- and post-cusp regions. The analysis also verified the existence of the magnetic bottles in these regions, which can trap the magnetospheric particles.

Later, Xiao et al. (2018) investigated the gradient and curvature of the cusps' magnetic field by analyzing two events in detail and also doing a statistical study on 19 cusp crossings. The authors showed that the curvature radius of the cusp magnetic field lines is for southward IMF conditions smaller than for northward IMF. The radius is on average 5.13 R_E compared to 19.75 R_E, respectively. Thus the cusp magnetic field is clearly more curved for southward IMF. They also reported that the cusp magnetic properties, such as the directional angle of curvature and the gradient of the magnetic field are much more disturbed under southward IMF.

Magnetic holes were also reported in the high-altitude cusp (Shi, Pu, et al., 2009). Those are small-scale magnetic depression region of typical size of a few hundred km across. They probably are produced by a mirror instability and very likely originate in the upstream solar wind or magnetosheath. It is not clear whether magnetic holes alternatively could emerge also locally in the cusp.
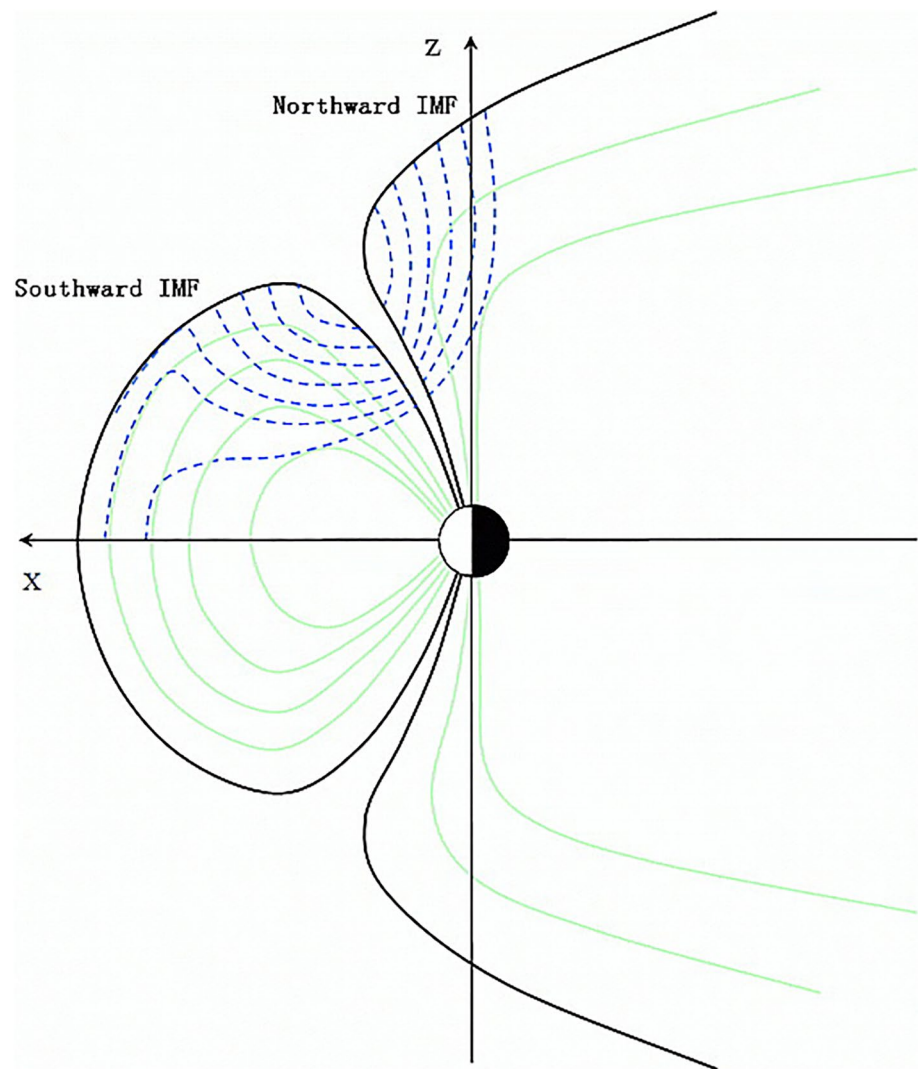
Figure 4. Cross-section of the magnetosphere in the noon-midnight meridian plane. In green are the magnetic field lines, in black the more external magnetic field lines (defining the magnetopause), and in blue the isocontours of the magnetic field strength (Shen et al., 2011).

It is also interesting to note that Cluster have offered opportunities to perform coordinated studies with ground-based instruments (see paper by Fear, this issue) or other space missions. Efforts were made to better determine the magnetic conjugacy between two points of the geospace (Keith & Stubbs, 2008) and Cluster greatly contributed to those efforts, directly or indirectly through modeling. This led to initiatives (or to the improvement of existing tools) aiming at facilitating the forecast and the visualization of conjunctions, like the Conjunction Event Finder (Miyashita et al., 2011) or the European Cluster Assimilation Technology (e.g., Boakes et al., 2014). Lately, a Conjunction Search Tool was also added to the 3DView Orbit Visualization Tool (Génot et al., 2018). This concerns all regions of the magnetosphere-ionosphere system but has been of particular interest for cusp studies.

3. The Exterior Cusp and Its Boundary With the Magnetopause

The high-altitude cusp region, its upper-most part, called the exterior cusp, and the interface between the magnetosphere and magnetosheath inside the cusp and the surrounding boundary regions were one of the main targets of the Cluster mission in order to clarify the plasma entry characteristics in the high-altitude cusp.

Based on the HEOS-2 data, Paschmann et al. (1976), Haerendel (1978), Haerendel et al. (1978) suggested that the high-altitude cusp consists of a few region. A plasma 'entry layer' lays at the cusp equatorward edge, this layer is adjacent to the magnetopause and is the main region for the solar wind plasma to enter the magnetosphere. The entry layer is characterized by the diffusive and turbulent plasma transport, plasma bursts and large-scale plasma eddies. Poleward of the entry layer the cusp region was defined by the perturbed magnetic field and intermittent flows, with a large part of this region being stagnant (Haerendel et al., 1978), with the stagnation region being separated from the magnetosheath by a boundary (Hansen et al., 1976). In addition (Rosenbauer et al., 1975), defined the plasma mantle region near the cusp poleward boundary which is characterized by the upward and tailward moving plasma population of the magnetosheath origin.

The interface between magnetosheath and magnetosphere inside the cusp was investigated in terms of the exterior cusp, defined as the region adjusted to the magnetosheath plasma in the cusp magnetic geometry, characterized by a significant depletion in the magnetic field strength and changes in the magnetic field direction (Russell, 2000a, 2009b). Two distinct regions inside the polar cusp, the interior and exterior cusps, have also been identified in some studies (Chen et al., 1997). To add to the cusp's region complexity some studies reported a diamagnetic nature of the high-altitude cusp region (e.g., Tsyganenko & Russell 1999), and observations of turbulence inside the exterior part of the cusp also have been reported (e.g., Pickett, et al., 2001; Savin, Buchner, et al., 2002; Savin et al., 2004).

While studies pre-dating Cluster (e.g., Smith & Lockwood, 1996, and references therein) provided evidence of the cusp structured by the reconnection process at the magnetopause (Dungey, 1961), the properties of the high-altitude cusp and its interface with the magnetosheath were still poorly understood before the Cluster's launch. The magnetic geometry of the cusp funnel and definition and geometry of the magnetopause also needed further investigation as there were conflicting observations of the high-latitude magnetopause with and without indentation around the cusp (Eastman et al., 2000; Dunlop et al., 2000; Merka et al., 2002; Zhou & Russell, 1997). The questions also remained how plasma dynamics inside the exterior cusp is governed by the solar wind and IMF parameters.

The first Cluster multi-spacecraft measurements characterized the high-altitude cusp region as a highly dynamic region populated by magnetosheath-like plasma and governed by reconnection, and showed that parts of the cusp, on newly reconnected field lines, are highly convective, in disagreement with the suggested previously cusp stagnation.

Thus, Cargill et al. (2001) presented the first observations of the magnetic structure of the mid- and high-altitude cusp regions based on the FGM measurements. The high-altitude cusp was marked by the depression in the total magnetic field in comparison with the magnetosheath values. The cusp magnetic field structure was found to be highly dynamic, changing on a time scale of a few seconds, and it was suggested that large amplitude waves were most likely present.

Bosqued et al. (2001) presented the first four-spacecraft observations of the plasma structure and characteristics inside the high-altitude cusp under northward IMF conditions based on the Cluster Ion Spectrometer (CIS) measurements (Reme, et al., 2001). The observations displayed a reverse energy-latitude "saw tooth" dispersions, corresponding to the sporadic injections of the magnetosheath ions, presumably from the lobe reconnection site. Analysis of the ion distribution functions inside injected structures showed a clear evolution with time from the D-shaped distributions toward distributions of both downgoing and mirroring ion populations. Relatively isotropic distributions were also observed, with a population of locally trapped magnetosheath ions. The first four-point measurements of electron population inside the high-altitude cusp region from the Plasma Electron And Current Experiment (PEACE) instrument (Johnstone et al., 1997) were discussed by Taylor et al. (2001) demonstrating advantages of multi-point measurements in the inferring dynamic nature of this region and separating spatial and temporal plasma behavioral characteristics.

Lavraud et al. (2002) presented the first multi-spacecraft observations of the exterior cusp and its boundaries under the northward IMF. The exterior cusp was characterized by a very low magnetic field strength and hot and isotropic ions (with ion temperature being 4 times higher than in the magnetosheath). Due to low plasma convection, the authors defined the observed region as the Stagnant Exterior Cusp (SEC). This region had clear boundaries with the surrounding regions, confirming a funnel-like magnetic topology. The

equatorward boundary was compatible with the indented magnetopause-like boundary, while the pole-ward edge was characterized by higher magnetic field fluctuations and plasma jets consistent with the lobe reconnection site. There were abrupt changes of the magnetic field and plasma parameters at the SEC/magnetosheath boundary which satisfied the Walén test, although a simple rotational discontinuity was ruled out as isotropic ion distributions did not agree with a local plasma entry. It was noted that the SEC population could be pre-existing and not being an immediate result of the heating and slowing down of the magnetosheath plasma across the boundary.

Vontrat-Reberac et al. (2003) performed a detailed analysis of the plasma properties inside the high-altitude cusp region (7–9 R_E) during northward IMF. It was shown that the cusp consisted of plasma injections with a repetition rate between 1 and 5 min. The reverse ion dispersion signatures inside injections and plasma convection typical for the lobe convection pattern suggested the existence of the pulsed reconnection in the high-latitude magnetopause, poleward of the Cluster. Using four-point boundary analysis, the diameter of the individual flux tubes, corresponding to separate injections, has been estimated to be 2,000–4,000 km, and the drift directions and velocities (6–15 km/s) were in close agreement with those expected from the lobe reconnection convective patterns. It was also shown that the overall convection pattern responds in ∼3–5 min to abrupt changes in the IMF B_z orientation and that motion of the cusp boundary (with a velocity ∼ 20 km/s) is induced nearly immediately by the IMF changes.

Cargill et al. (2004) presented the high-altitude/exterior cusp observations during steady southward IMF conditions, showing that the cusp is highly dynamic and is largely convective, in agreement with the expectations from the sub-solar reconnection process. The magnetic field inside the cusp was characterized by the field depression and high fluctuations. The magnetopause boundary was clearly identifiable via a rotation of the magnetic field, a normal field component and a plasma flow across the boundary, however, it was not identified positively as a rotational discontinuity. It was also shown that the magnetopause boundary underwent significant distortion from its nominal shape, moving rapidly and exhibiting structure on scales of the order of the spacecraft separation or less.

Lavraud, Phan, et al. (2004) showed that the SEC region, defined by the presence of the stagnant and iso-tropic plasma and depression in the magnetic field, is observed under northward IMF even with a strong B_Y component. Based on a smooth evolution of the plasma parameters inside the cusp region when spacecraft was moving from the field lines with plasma injections from the lobe side to the central cusp with stagnant and isotropic plasma, Lavraud, Phan, et al. (2004) suggested that the SEC region is not a separate region, but is a continuation of the high-altitude cusp which is formed by a high-latitude reconnection with plasma gradually becoming stagnant due to mirroring from the low altitudes and scattering. In addition, a potential role of the ULF waves in plasma isotropisation has been suggested. In this study, the SEC-magnetosheath boundary was clearly identifiable in the plasma data by the abrupt changes in the density and velocity and by the changes in the magnetic field. It was shown that the boundary always has a rotational-like nature and is compatible with a discontinuity propagating from the lobe reconnection. In some cases, the boundary was considered as a rotational discontinuity based on Walén tests. A Plasma Depletion Layer (PDL) of sub-Alfvénic nature was often observed outside the boundary described above. The observations were explained in terms of a steady reconnection site tailward of the cusp that stability was maintained by the presence of the sub-Alfvénic PDL.

Lavraud, Fedorov, et al. (2004) presented the results of the statistical study of the high-altitude cusp magnetic field and plasma parameters based on the first three years of the Cluster observations. It was shown that the exterior cusp is a well-defined region existing between the magnetosheath and the rest of the magnetosphere. This region is diamagnetic in nature and is characterized by the lower plasma density and velocity, and higher temperature than inside the magnetosheath. Figure 5 shows an example of the statistics performed, presenting magnetic field distribution, magnetic pressure, density and temperature distributions inside the exterior cusp and surrounding regions. The exterior cusp has distinctive boundaries with the lobes, the dayside plasma sheet and the magnetosheath, the later boundary was characterized by an abrupt gradient in the plasma parameters. The plasma and magnetic pressure distributions suggested that the exterior cusp is in equilibrium with its surroundings in the statistical sense. The internal boundaries form a funnel, while the external boundary does not show a clear indentation, seen in some previous studies. These observations led the authors to suggest that the question of the magnetopause indentation is related
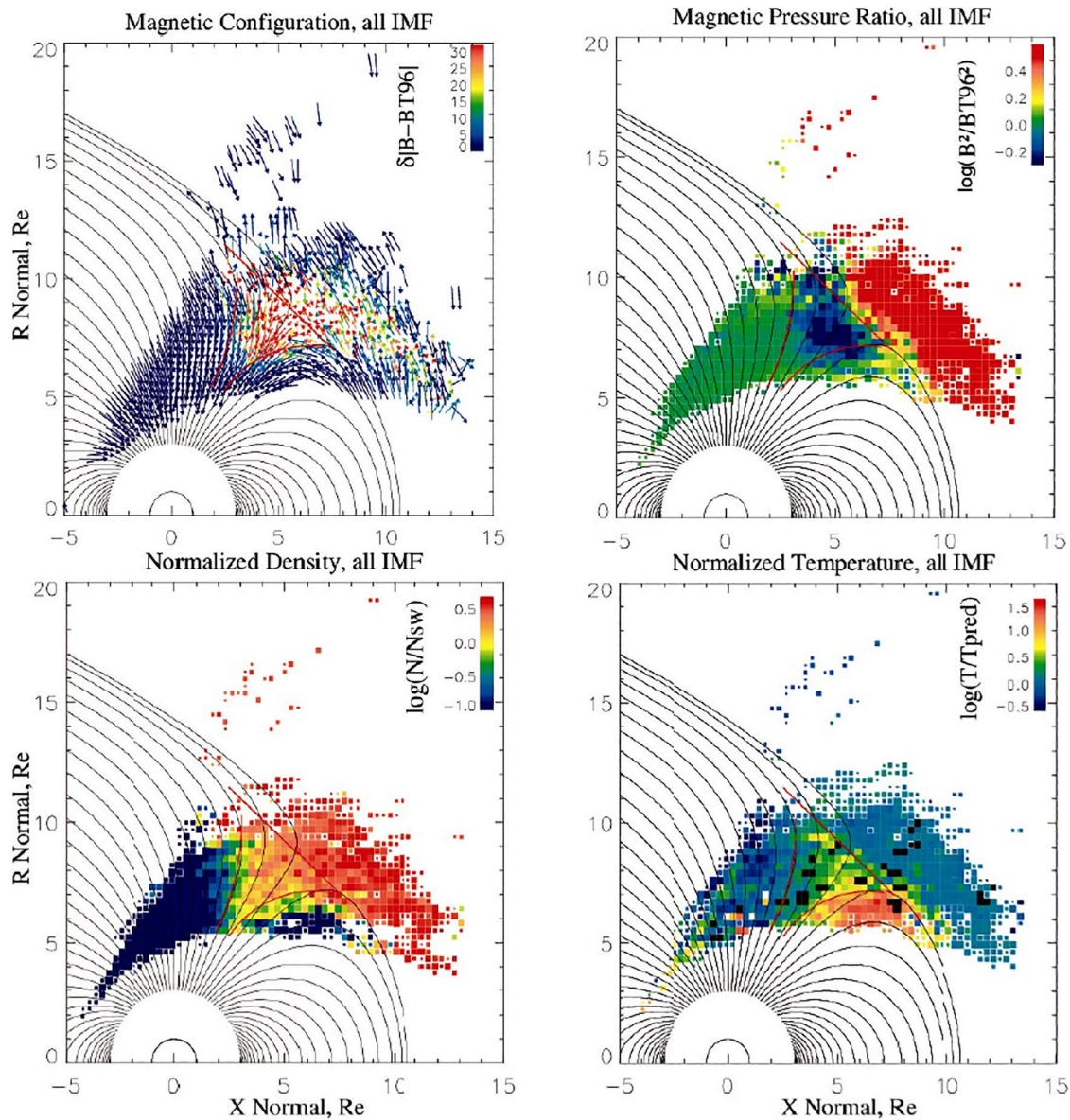
Figure 5. The statistical spatial distribution of the magnetic field and plasma population inside the exterior cusp and surrounding regions. (a) The distribution of the magnetic field vectors. The size of each vector is magnetic field magnitude in logarithmic scale. The color corresponds to the deviation of the measured magnitude to the model T96 magnitude. (b) The scalar spatial distribution of the ratio between the square of the measured magnetic field (i.e., the pressure) and that from the T96 model in logarithmic scale; (c) the density distribution normalized to the solar wind density; (d) the temperature distribution normalized to the predicted temperature in the magnetosheath. See Lavraud, Fedorov, et al. (2004) for more details.

to the definition of magnetopause in different studies and whether the external or internal boundary of the exterior cusp is defined as the magnetopause.

The plasma flows inside the high-altitude cusp measured during the different IMF orientation were investigated in the follow-on statistical study (Lavraud, Dunlop, et al., 2005; Lavraud, Fedorov, et al., 2005). During southward IMF, large parallel downward flows were observed at the equatorward edge of the cusp alongside the anti-sunward convection inside the cusp. During the northward IMF, the plasma penetration was observed near the poleward boundary of the cusp accompanied by some sunward flows, although the cusp region appeared more stagnant during the northward IMF in comparison with the southward IMF case. The dusk-dawn convection inside the cusp region appeared to be controlled by the IMF B_Y component. These observations led the authors to conclude that the large-scale structure of the cusp is determined by
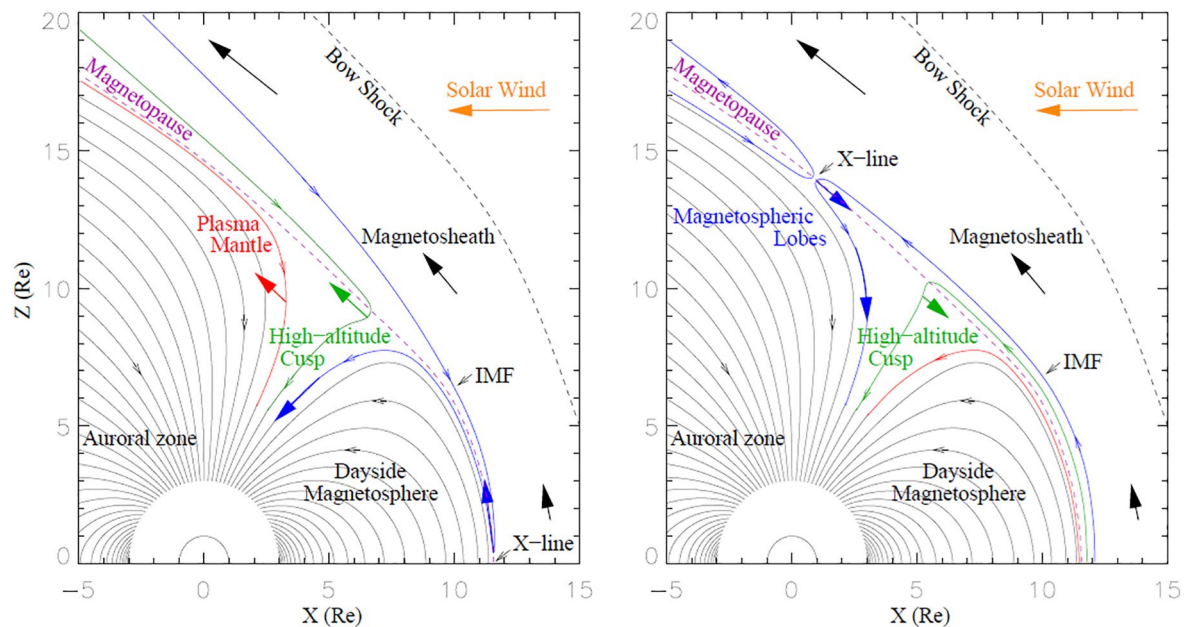
Figure 6. A schematic of the large-scale cusp topology during southward (left) and northward (right) interplanetary magnetic field (IMF) and location of the reconnection at the magnetopause, based on the statistical results of the Cluster high-altitude cusp crossing. Adapted from Lavraud & Cargill, 2005 (Figure 3).

the occurrence of magnetic reconnection at the high-latitude magnetopause for northward IMF and at the low-latitude magnetopause for southward IMF, represented in Figure 6. It was also shown that the magnetosheath adjacent to the exterior cusp is more sub-Alfvénic for the northward IMF than for the southward IMF, which is consistent with the development of the PDL.

Bogdanova et al. (2005) combined the Cluster observations inside the high-altitude cusp region with the SuperDARN observations of the ionospheric convection in order to investigate the origin of the SEC region. The analysis of the pulsed ionospheric flows distributed over a large MLT sector suggested the existence of the two anti-parallel reconnection sites in two hemispheres. The authors argued that the SEC region may be located on newly re-closed field lines, which have been reconnected first in the northern hemisphere dusk lobe sector, evolved inside the cusp and then reconnected again poleward of the southern hemisphere cusp, at the dawn lobe sector. This reconnection scenario, shown in Figure 7 is in agreement with the "dual lobe reconnection" model (e.g., Song and Russell (1992)). It was pointed out that the Cluster observations of plasma distribution inside different regions of the high-altitude cusp agree with this scenario, and that dual lobe reconnection would decouple the SEC field lines from the solar wind flow, which explained the lack of significant convection, the lack of particle injections and nearly isotropic nature of the plasma population.

Bogdanova et al. (2008) investigated further the sub-structure of the cusp region and surrounding boundary layers during northward IMF based on unique nearly simultaneous observations of the cusp by Cluster and Low Latitude Boundary Layer (LLBL) near the subsolar magnetopause by Double Star TC-1 satellite. These observations were complemented by observations of the sunward ionospheric convection in both high-latitude hemispheres by SuperDARN, suggesting the existence of lobe reconnection in both hemispheres. Detailed analysis of the plasma signatures inside the cusp indicated that one part of the cusp was located on open field lines reconnected once in the lobe sector of one hemisphere and the another part was located on the field lines reconnected the second time in the lobe sector of the opposite hemisphere. A boundary layer near the equatorward edge of the cusp has also been identified. This additional boundary layer had a mixed magnetosheath and plasma sheet electron populations with smooth changes in density and temperature, which were attributed to the diffusion process. The study showed a good agreement of the plasma parameters inside the different LLBL sub-layers observed near the dayside magnetopause and sub-layers of the cusp region.
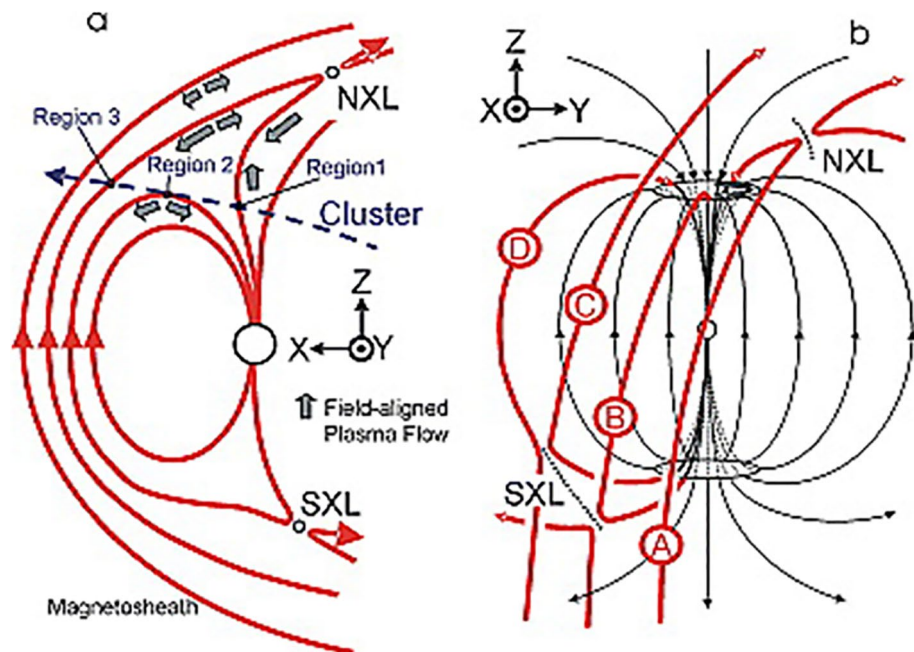
Figure 7. Magnetic field configuration with two (North and South) X-lines (NXL and SXL) and Cluster trajectory. See Bogdanova et al. (2005) for more details.

Yordanova et al. (2007) used the conjugated ionospheric (EISCAT and MIRACLE facilities) and high-altitude cusp observations by Cluster to highlight the role of the high-altitude cusp region in the energy deposition from the solar wind to the ionospheric cusp. It was shown that the earthward energy flux of the magnetosheath-like particles observed at Cluster altitude closely matched the energy required for the plasma heating in the F-region and it was suggested that direct precipitation of the magnetosheath plasma into the ionosphere was responsible for the F-region heating. In addition, the estimated earthward Poynting flux mapped to the ionosphere was more than enough to explain the Joule heating of the E-region.

Zhang et al. (2006) performed a statistical study of the boundary separating the high-latitude cusp and magnetosheath based on the 4 years of Cluster measurements. It was shown that for the northward IMF, over the clock-angle (−65° and 81°) this boundary is very clear in the plasma and magnetic field data. However for other clock-angles, there were cases with not a clear boundary between magnetosheath and the cusp. For these cases, a smooth transition from the magnetosheath to the cusp without abrupt changes in any parameter, except changes in the energetic particle flux, was observed. The superposed epoch analysis showed that for the northward IMF the boundary is characterized by the plasma flow and density decrease and the proton temperature increase across the magnetopause from the magnetosheath to the cusp. It was also shown that for the extreme storm times the cusp is more turbulent than during quiet times and that no clear density changes were observed across the magnetopause.

The cusp boundaries with the surrounding regions have been revisited by Zhang et al. (2007), investigating magnetic field distribution and boundaries normal vectors. The case studies showed clear boundaries between the cusp and the mantle, cusp and the dayside plasma sheet (or high-latitude trapping region), with these boundaries forming a funnel shape, defining equatorial and poleward boundaries of the cusp. The boundaries and their orientation between the cusp and magnetosheath and the dayside plasma sheet and magnetosheath were investigated on a statistical basis using data from 2001 to 2002 for the events with clear abrupt changes between the cusp and the magnetosheath across the interface boundary. It was shown that the boundary between the magnetosheath and cusp shows a clear indentation on the dawn and dusk side of the cusp in the X-Y plane, while near noon the normal vectors pointing duskward and duskward are mixed. The boundary is less clearly indented in the X-Z plane.

The properties of the boundary separating magnetosheath and magnetospheric plasma at high latitudes also have been estimated statistically by Panov et al. (2008), including investigation of the pressure balance and magnetopause properties, e.g., the orientation, distributions of velocity, thickness and current density. In this study, the authors separated the magnetospheric regions adjacent to the magnetopause as Low-Latitude Boundary Layer, entry layer, cusp and plasma mantle, and two regions with mixed plasma properties of the entry layer and cusp and cusp and plasma mantle. There was a clear difference in the plasma parameters inside the entry layer and the cusp. The entry layer was located equatorward of the cusp and was characterized by high-velocity flow bursts, while the cusp was identified by stagnant and intermittent plasma flows and decreased magnetic field magnitude. This study also confirmed the result by Lavraud, Phan, et al. (2004) that magnetosheath flows are sub-Alfénic above the plasma mantle.

Shi, Zong, et al. (2009) presented observations of the transition layer existing equatorward of the cusp during the northward IMF and containing both magnetosheath and magnetospheric populations which has been interpreted in terms of an entry layer. This layer had clear differences, sometimes step-like, with the adjacent regions and it was proposed that this layer is possibly formed by high-latitude reconnection in both hemispheres.

Walsh et al. (2012) presented unique observations of the exterior cusp region based on the simultaneous observations by Cluster and Polar satellites. The cusp was characterized by the low and turbulent magnetic field. These observations revealed that the exterior cusp is an extended region in latitude spanning 4.5 R_{E} (and possibly up to $9R_{\text{E}}$) along the magnetopause. It was estimated that the diamagnetic exterior cusp has a dimension of 1.3 R_{E} perpendicular to the magnetopause. This estimation was limited by the spacecraft orbits and should be considered as a minimum value, as the diamagnetic properties of the cusp may extend deeper down the cusp "throat." These observations were in agreement with the first results of the 3-D mesoscale MHD simulations of the cusp geometry performed by Adamson and Nykyri (2011). The results of the simulations under northward IMF conditions showed that the cusp diamagnetic cavity has a depth of 1–2 R_{E} normal to the magnetospheric boundary and an extent of ~5–9 R_{E} tangential to the boundary with the magnetosheath and that the cusp has a gradual inner boundary with the magnetospheric lobes.

The surrounding cusp high-altitude boundary layers often exhibit a high level of complexity. Thus, Zong, Fritz, Spence, Zhang, et al. (2005) presented observations of the plasmoid-like structure in the vicinity of the cusp region with a denser and hotter plasma inside in comparison with ambient plasma. While the observed structure did not show traditional Flux Transfer Event (FTE) characteristics, the Walén test indicated that the structure was formed by reconnection, and multiple X-line reconnection in the dusk side of the stagnant cusp region was suggested. Fear et al. (2005) discussed the advantages of the multipoint observations of the FTE structure both in the magnetosheath and magnetospheric sides near the cusp region, pointing out that the magnetospheric part of the FTE does not exhibit a traditional bipolar signature in the normal direction at high latitudes. The addition of the open flux to the region of the high-altitude cusp was investigated by Le et al. (2008) using conjugated observations of the FTE by Polar near the subsolar region and by Cluster near the high-altitude cusp. It was shown that the high-latitude FTE does not exhibit the characteristic bipolar perturbation in the magnetic field while plasma observations inside the FTE showed open magnetic field geometry. The observations indicated that the magnetic field lines inside the FTE have straightened and became closer aligned to the neighboring flux tubes as the FTE moves to the cusp.

4. Location, Dynamics, and Convection

Among the first topics one can find in the very first published papers containing Cluster data, the location and dynamics of the polar cusps were reported and discussed. It became evident that this region was highly dynamic depending of the external conditions.

Many studies dealt with the cusp location and motion with DMSP and Polar among other space missions. They revealed the cusps as highly dynamic regions whose location is ruled by the IMF orientation and amplitude on one hand, and by the solar wind pressure of the other hand. What has Cluster brought in the understanding of the cusp behavior? That is what we are reviewing in this section.
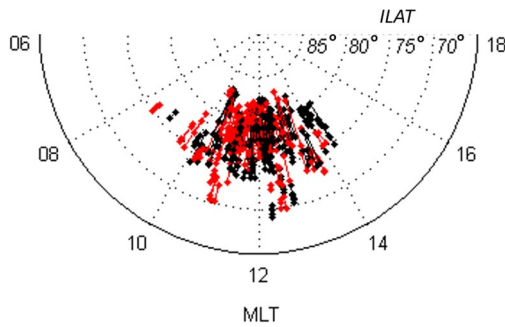
Figure 8. Cusp crossings on a MLT/ILAT polar projection. Black and red traces are for crossings having occurred in the northern and southern hemisphere, respectively (Adapted from Pitout, Escoubet, Klecker, & Reme, 2006.).

4.1. Location and Dynamics, Statistical Approaches

A few early papers granted importance to the cusp location and response to IMF and solar wind conditions, although this kind of studies had already been performed before with other satellites.

As for its location, the cusp is known to sit most of the time between 75° and 80° magnetic latitudes and between 10 and 14h MLT (Figure 8) under typical external conditions and depending on the IMF orientation (Bogdanova et al., 2006; Newell et al., 1989; Palmroth et al., 2001; Pitout, Escoubet, Klecker, & Reme, 2006; Zhou et al., 1999). However, several parameters come into play in determining its actual location.

The first of these parameters is the dipole tilt that influences the cusp latitudinal position. This was revealed by earlier studies (Newell & Meng, 1989; Zhou et al., 1999). In their statistical study of the location and dynamics of the cusp, Pitout, Escoubet, Klecker, and Reme (2006) had to remove this effect to isolate the effect of the IMF orientation (see below). Also, Xiao et al. (2020) investigated the dependence of the cusp location to the dipole tilt. We summarize the results of the above-mentioned studies below, which give the latitudinal displacement of the cusp obtained for +1° of tilt (1° toward the Sun).

1. Newell et al. (1989) using DMSP: +0.06° MLAT
2. Zhou et al. (1999) using Polar: +0.07° MLAT
3. Pitout, Escoubet, Klecker, and Reme (2006) using Cluster: +0.09° MLAT

Shi et al. (2012) pointed out that the tilt dependency varies with altitude. They also showed that this dependency is not the same in the two hemispheres (see Section 5.6).

Statistical studies also confirmed that the cusp region moves to lower latitude when the Z component of the IMF becomes more negative. Here are results found by various authors giving the magnetic latitude of the cusp equatorward boundary Λ as a function of IMF B_z for negative B_z:

1. Newell et al. (1989) using DMSP: $\Lambda = 0.76B_z + 77.0$
2. Escoubet and Bosqued (1989 using Aureol-3: $\Lambda = 0.64B_z + 75.0$
3. Zhou et al. (1999) using Polar: $\Lambda = 0.86B_z + 79.5$
4. Palmroth et al. (2001) using Polar: $\Lambda = 1.03B_z + 79.8$
5. Pitout, Escoubet, Klecker, and Reme (2006) using Cluster: $\Lambda = 0.64B_z + 77.5$

If one ignores the actual values in each expression, which vary from one author to the other by almost 0.4 for the slope of the straight line and 3° for the location at $B_z = 0$ (these variations may be due slight methodological differences), the main result is that the cusp does move down in latitude with increasing negative B_z. On the other hand, all studies agree with the fact that under northward IMF, the location of the cusp barely changes with the intensity of B_z.

With the four Cluster spacecraft, Pitout, Escoubet, Klecker, and Reme (2006) managed to determine that the latitudinal speed of displacement (V) of the cusp is proportional to the variation of IMF B_z:

$$V = 0.024 \left| \Delta B_z \right| \tag{1}$$

With V in °/min and ΔB_z in nT.

The other parameter that moves the cusp in latitude is the solar wind dynamic pressure. The problem is that a variation in pressure often comes with a change in IMF and therefore, the two causes are not easy to untangle. That is probably one reason why, again, not all authors find the same B_z dependency (on top of possible methodological differences). Since the latitude of the cusp does not change very much under northward IMF, it is easier to assess the role of the solar wind pressure when the IMF points northward (Pitout, Escoubet, Klecker, & Reme, 2006) and indeed, the latitude of the cusp equatorward boundary moves too lower latitude with an increasing solar wind dynamic pressure.

In the end, dipole tilt aside, whatever the main cause, a southward IMF causing magnetic erosion at the magnetopause or a high solar wind pressure compressing the magnetosphere, the latitudinal location of the cusp reflects the standoff distance of the magnetopause under southward IMF.

4.2. Convection in the Cusp

The convection is the transverse plasma motion ($E \times B$ drift). Its direction in the cusp depends directly on the orientation of the IMF. When the IMF points southward, the convection is antisunward and the convection pattern in the polar cap consists of two cells. On the other hand, when the IMF is northward, the convection in the cusp is sunward and the convection exhibits a more complex display with three or four cells, one or two of these being driven by lobe reconnection. All this is consistent with an open magnetosphere model with the convection driven by magnetic reconnection at the magnetopause and in the tail (e.g., Cowley & Lockwood, 1992; Smith & Lockwood, 1996).

The Cluster Electron Drift Instrument (EDI; Paschmann et al., 1997, 2001) has made measurements of the convection even in region of very low plasma density like in the lobes. Vaith et al. (2004) studied with the EDI the convection to investigate the convection in the whole polar cap. They showed that not only is the plasma flow antisunward under southward IMF, but large amplitude fluctuations are superimposed to the mean flow. The authors remarked that those fluctuations get more intense near the cusp/magnetopause boundary and they do not seem to be temporal features and are likely related to the motion of the magnetopause. By using the multipoint capability of Cluster, it was shown in this study that, globally over the polar cap, good inter-spacecraft correlations are found–under southward IMF–from at least a km-size separation (once mapped down in the ionosphere) and sometimes up to a few hundreds of km. Under northward IMF, the correlation gets very poor with typical length scale of a few tens of km. Lavraud, Dunlop, et al. (2005); Lavraud, Fedorov, et al. (2005) showed that convection inside the high-latitude cusp region is governed by the IMF orientation (see Section 3 for more details).

More locally inside the cusp, the convection exhibits almost periodic variations as a consequence of pulsed reconnection (Farrugia et al., 2004) and/or of solar wind pressure pulses (Cerisier et al., 2005)

4.3. Response to Sudden Changes in IMF

Beyond the statistical views that were brought by the DMSP satellites or Polar, and that Cluster confirmed, the multipoint capability of Cluster made it possible for the first time to study the transition between two states of the magnetosphere in response to an abrupt change of the IMF orientation.

The effect of "clean" IMF rotations have been reported. For instance, the detailed study of a cusp crossing at middle altitude on 23 September 2004 was carried out by Escoubet et al. (2008). On that day, the IMF rotated from southward to northward while the Cluster were flying through the cusp. The ion sensor on board two first spacecraft recorded a dispersion typical for southward IMF. The last spacecraft crossed the cusp as the IMF was rotating or very shortly thereafter; a southward-like dispersion was measured in the LLBL and a reverse dispersion, due to lobe reconnection, was found at high latitude. During the transition from southward to northward, the cusp was apparently characterized by both IMF orientations.

In addition, cases of multiple and rapid changes or rotations of the IMF direction were investigated (Cai et al., 2009; Escoubet et al., 2013; Pitout, Escoubet, Bogdanova, et al., 2006). Pitout, Escoubet, Bogdanova, et al. (2006) reported such a case. They showed that the cusp reacts very rapidly to changes in the IMF orientation, within a couple of minutes, with plasma convection reaching a speed of the order of 30 km/s in the south-north direction. Interestingly, that event also revealed that, during the transition phase from a southward to a northward IMF, two regions of injected magnetosheath particles coexist. Escoubet et al. (2013) have found speeds up to 90 km/s in the east-west direction in response to an change in the Y component of the IMF.

4.4. Response to Extreme Events

The dynamics of the cusp in response to extreme solar events were investigated on several occasions when the conditions were suitable, that is when the Cluster spacecraft were flying through the cusp when a solar

wind discontinuity hit the magnetosphere, or when the disturbed magnetosphere moved the cusp over the Cluster satellites. As Balan et al. (2007) showed, an extreme compression of the magnetosphere (during the Halloween storms in 2003 in their case) may also lead to an exterior cusp crossing while in Fall a mid-altitude cusp crossing was expected (see Section 1.3). The authors reported high plasma density in the cusp as well as powerful magnetic waves.

Bogdanova et al. (2007a) presented an interesting case where the cusp moved down in latitude as low as 68° ILAT due to an extreme magnetic erosion at the magnetopause. The cusp was also seen to be very thin in latitude, smaller than 1°, whereas its average in normal situation is about 2° according to Pitout, Escoubet, Klecker, and Reme (2006). The authors ascribed this low width to the strong negative IMF B_z. They also noted an unusual energy cut-off in the ion dispersion. This is very likely due to a high deHoffmann-Teller velocity, as a result of high Alfvén and magnetosheath speeds. The cusp response of event discussed by Bogdanova et al. (2007a) was modeled by Siscoe et al. (2007) and the simulations were in good agreement with the results and conclusions of the former authors.

While presenting another event, Bogdanova et al. (2007b) performed a statistical analysis of several cusp crossings under extreme conditions. They confirmed previous results on the dependency of the cusp equatorward boundary on the IMF B_z and on the solar wind pressure (e.g., Escoubet & Bosqued., 1989; Newell & Meng, 1989; Palmroth et al., 2001; Pitout, Escoubet, Klecker, & Reme, 2006). This study also showed some saturation in the cusp latitudinal position with an increasing IMF magnitude and solar wind dynamic pressure, which the authors explained by a potential saturation in the solar wind-magnetosphere coupling during the extreme conditions.

Korth et al. (2011) reported another interesting result obtained in the cusp by Cluster during a corotating interaction region high-speed stream event: using a wavelet analysis technique, the authors show that the proton density and temperature inside the cusp are affected by the Alfvén wave activity in the solar wind, as they exhibit the same characteristic frequencies. The authors conclude that the fluctuations in the IMF seem to be more important than variations of the solar wind velocity in transferring energy into the cusps.

Let us mention that during extreme solar events, the ion outflow from the cusp region greatly intensifies (see Dandouras, 2021, and references therein).

5. Cusp Precipitation, Ion Dispersions and Consequences on Merging

Among the great achievements of cusp studies with the Cluster fleet, we can cite the studies of the cusp ion dispersions. They have revealed many aspects of the way the IMF reconnects with the geomagnetic field and how the shocked solar wind penetrates the dayside magnetopause.

5.1. Ion and Electron Precipitation in the Cusp

The magnetosheath particles flowing down the cusp consist of relatively low energy ions in the range of 500 eV–5 keV typically, and of soft electrons around 50 eV. While the electrons are fast to reach lower altitudes (some reach the atmosphere where they form dayside auroras), the ions are much slower and have the time to undergo the $E \times B$ drift, which causes the so-called velocity filter effect: the high-energy ions reach a given altitude before the slower ones, the latter reaching the same given altitude at a different location. This time-of-flight effect combined with the transverse convection yields the well-known ion dispersions. These ion dispersions are not only used as a feature to identify the cusp in CIS data, they provide a wealth of information about the reconnection process.

The properties of the particles have long been used to differentiate the cusp itself from the other boundary layers (Newell & Meng, 1988b). In particular, the low latitude boundary layer (LLBL) which is adjusted to the magnetopause at the magnetospheric side maps to the cleft region equatorward of the cusp. Under southward IMF the LLBL is usually open and is populated by the magnetosheath particles whose properties are slightly different from those of the cusp. Bogdanova et al., 2006 identified an electron edge of the LLBL region consisting of low fluxes of magnetosheath electrons with electron beams without magnetosheath ions as the most equatorward part of the cleft, in agreement with expectations of different times of flight

of electrons and protons from magnetopause reconnection (Gosling et al., 1990). The latitudinal width of this layer was estimated to be between 0 and 2° (Bogdanova et al., 2006). Under northward IMF, the LLBL could have few different sub-layers with different, open or closed, magnetic topologies. These sub-layers are formed by single and dual lobe reconnection processes, and sometimes additional sub-layer(s), formed due to diffusion, could also be observed (e.g., Bogdanova et al., 2008).

Electrons may in the cusp form beams of higher fluxes in one or both directions along the magnetic field lines (e.g., Bogdanova et al., 2005; Hu et al., 2008; Shi et al., 2017). It was noted that analysis of the electron fluxes at 0° and 180° pitch-angles could be used to identify open or closed magnetic field lines geometry inside the cusp region (e.g., Bogdanova et al., 2005, 2008). Electrons are the main particle carrier of field-aligned currents in the cusp, up to 80% of the total current density according to Marchaudon et al. (2006). Marchaudon et al. (2009) showed a one-to-one correlation between field-aligned currents and dayside magnetosheath plasma injections. Shi et al. (2014) studied such electrons beams in the cusp and they reported electron fluxes up to 5×10^9 cm^{-2}s^{-1}, which is an order of magnitude larger than what commonly measured. They also estimated the latitudinal extend of the field-aligned electron beams (540 km) and the lower limit of the zonal extension (1,800 km).

### 5.2. Spatial Versus Temporal Nature of the Cusp: Steady or Pulsed Reconnection?

A long lasting puzzle has been the spatial or temporal nature of the cusp region. Very early in the history of cusp observations it was realized that several ion structures could be crossed by the satellites. Were the satellites repeatedly crossing the same structure which moves back and forth (as it can happen for the magnetopause), or is the cusp structured into several separate regions? Were they different ion populations coming from different reconnection sites at the magnetopause? Were they the manifestation of pulsed reconnection? Several authors tried to answer these questions with, at a first glance, very different conclusions.

Before Cluster was launched, some observations of the cusp over long time period suggested indeed that the cusp may be a very stable region with time (e.g., Trattner et al., 1999, Trattner, Fuselier, Peterson, & Carlson, 2002), without necessarily ruling out the pulsed reconnection hypothesis (Trattner, Fuselier, Peterson, Boehm, et al., 2002). For instance, Trattner et al. (2003, 2005) reported cases where two ion dispersions observed in the cusp do not originate from pulsed reconnection but from two separate regions of the magnetopause (Figure 9). The authors concluded that on large scale, the cusp structures crossed by Cluster are consistent with a stable spatial phenomenon. Escoubet et al. (2006) managed to study in details the development of an ion dispersion coming from different reconnection site to the main dispersion (Figure 10). These results were confirmed by modeling effort (Connor et al., 2012). Besides, long duration observations near the magnetopause also suggested that the reconnection process may yield continuous plasma jets without a moving X-line, which is a priori inconsistent with patchy or pulsed reconnection (Frey et al., 2003; Phan et al., 2004).

On the other hand, countless papers evidenced the sporadic nature of reconnection, yielding to flux transfer events or the so-called cusp ion steps (e.g., Bosqued et al., 2005; Escoubet al., 2006; Farrugia et al., 2004; Le et al., 2008; Lockwood et al., 2001; Marchaudon et al., 2004). This is even clearer in data collected by ground-based instruments, which are much less affected by the spatial/temporal ambiguity and where transient poleward moving features are clearly seen (Farrugia et al., 2004; Frey et al., 2019; Lockwood et al., 2001; Marchaudon et al., 2004; Moen et al., 2001).

5.3. Anti-parallel and/or Component Merging?

Another fundamental issue of solar wind–magnetosphere coupling is the necessary conditions under which the IMF and the Earth's magnetic field reconnect. It was initially believed that the two fields needed to be antiparallel for reconnection to occur as suggested by Figure 1 of the original paper by Dungey (1961). Then, it was realized that reconnection could happen even where the angle between the two field vectors was not strictly, or not even close to, 180°. For magnetic reconnection to occur it is sufficient that only one component of the vectors are opposite to each other. It is the so-called component reconnection.
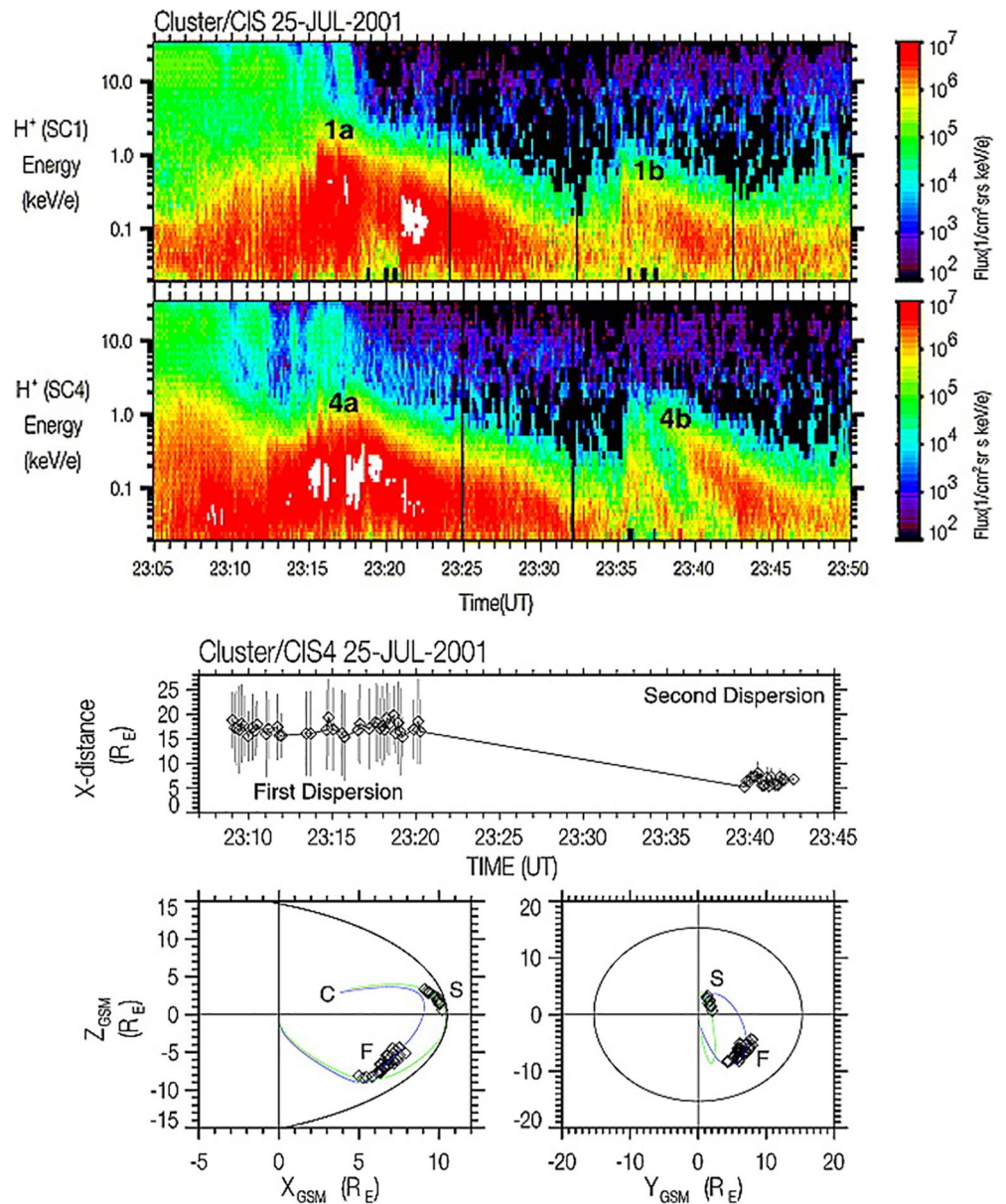
Figure 9. The top panel displays the ion energy-time spectrogram showing two ion dispersions on July 25, 2001. These two dispersions were used to infer the distance to the corresponding reconnection sites and the location of the latter on the magnetopause. From Trattner et al. (2005).

Studying the cusp contributed to answering this question, in particular by inferring the distance to the reconnection site, estimating where on the magnetopause reconnection takes place and under which magnetic shear (e.g., Trattner et al., 2005, 2006; 2008). It was concluded that not only could both types of reconnection exist, but that they could be at play simultaneously (Escoubet et al., 2007; Fuselier et al., 2011). It was also shown that reconnection could occur at low latitude under northward IMF (Fuselier et al., 2018).

5.4. Lobe and Dual Lobe Reconnection Under Northward IMF

When the IMF is southward, merging between the IMF and the geomagnetic field occur mainly at low latitude, between the two cusps (e.g., Twitty et al., 2004). This is an observational fact, irrespective of the reconnection model one considers. When the IMF point northward, lobe reconnection is more likely to
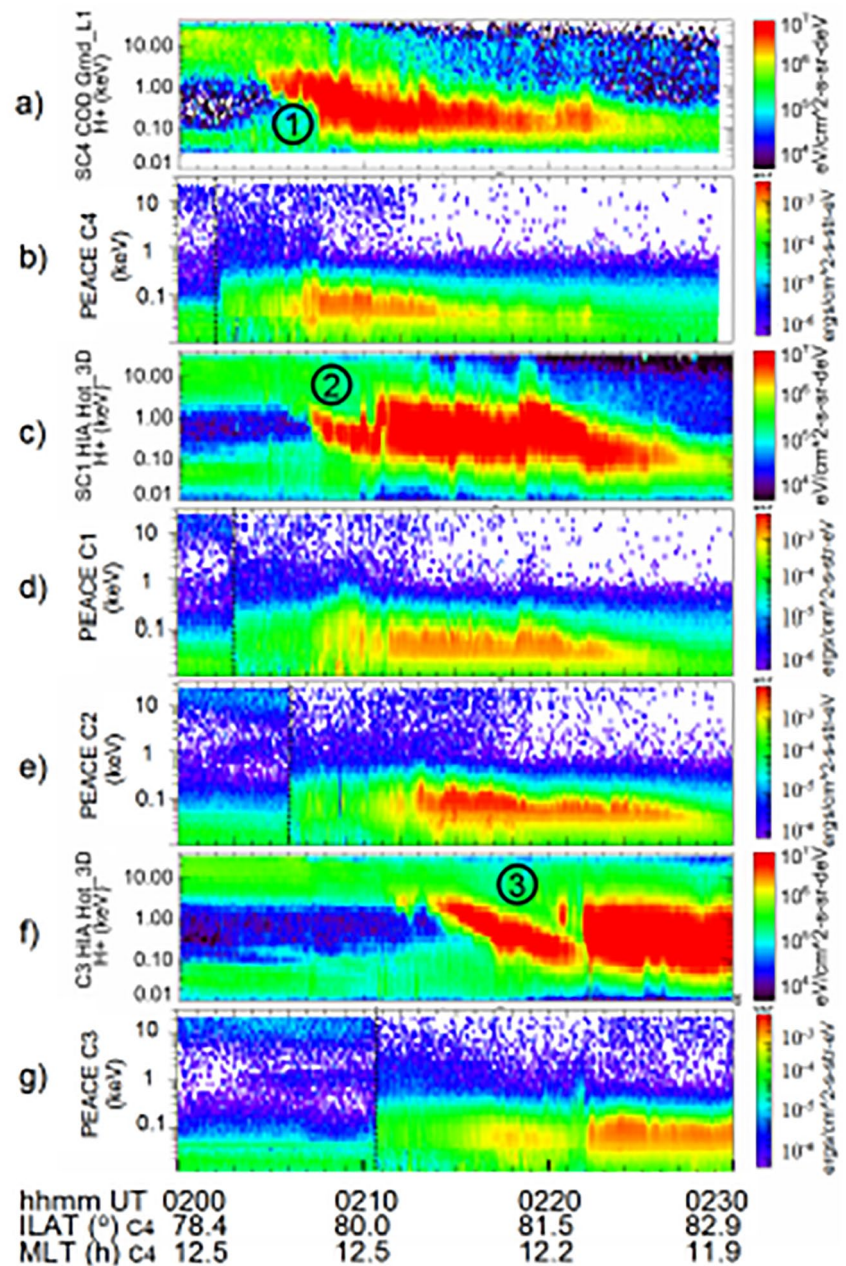
Figure 10. Ion and electron energy-time spectrograms from Cluster Ion Spectrometer (CIS) and Plasma Electron And Current Experiment (PEACE) on board the four spacecraft (CIS not operating on board SC2) showing the development of a cusp ion step, numbered 1, 2, and 3. From Escoubet et al. (2006).

occur at high latitude, poleward of the cusp (e.g., Bogdanova et al., 2005, 2008; Hasegawa et al., 2008; Phan et al., 2003; Pitout et al., 2001; Vontrat-Reberac et al., 2003). It was shown that the pulsed reconnection also can occur under these conditions (Pitout et al., 2001; Hasegawa et al., 2008; Hu et al., 2008).

A remarkable feature when the IMF points northward is the weak sunward convection in the cusp, yielding magnetosheath precipitation confined in a relative narrow region. This gives rise to the so-called proton auroral spot in the cusp ionosphere (Frey et al., 2002; Phan et al., 2003; Zong, Fritz, Spence, Frey, et al., 2005). Recent works suggest that electromagnetic ion cyclotron (EMIC) waves may scatter trapped energetic protons to precipitate into the atmosphere (Xiao et al., 2013).

Under northward IMF, when the X- and Y- components of the IMF are not too large relatively to the Z-component, reconnection may happen at both lobes at the same time. This dual lobe reconnection may yield reconnection between two open field lines, leading to the formation of newly closed field lines populated by trapped magnetosheath plasma. In PEACE data on board Cluster, this is seen as bidirectional electron beams with nearly equal fluxes at all energies (Bogdanova et al., 2005, 2008; Hu et al., 2008; Lavraud et al., 2006). In ion data, the reclosure of open field lines in the dayside is claimed to be responsible for the overlap of magnetosheath ion populations in the cusp (Pitout et al., 2012). This was backed up by hybrid-Vlasov simulations carried out by Grandin et al. (2020).

5.5. Multiple Cusps

Another recurrent question with single spacecraft observations of the cusp has been the explanation of multiple cusp regions crossed by mid- and low-altitude spacecraft (which is different from the ion steps we discussed in Section 5.2). Are those multiple crossings a consequence of the displacement of the whole region that is then encountered twice or more by a satellite (see Section 4.3)? Are they rather stable regions of magnetosheath particle precipitation due to several reconnection sites at the dayside magnetopause?

Some studies clearly showed than the former explanation is plausible: a moving cusp may yield multiple crossing by Cluster, especially at high altitude when the spacecraft are slow and the crossing duration longer. Zong et al. (2004, 2008) thus reported events when the Cluster fleet moves in and out of the cusp several times. In one of those events, Custer was skimming the boundary between the cusp and the closed field line magnetosphere and made several incursions in both regions within a couple of hours (Figure 11). This multiple cusp crossing was explained by the oscillating behavior of the magnetosphere (Zong et al., 2008). Likewise, Escoubet et al. (2013) pointed out that the "nested crossing" of two spacecraft through the gap between two cusp populations can hardly be explained in terms of two separate structures but rather as a unique and moving structure.

However, a few authors also showed that, on occasions, a southward IMF may lead to high-latitude lobe reconnection and reverse (sunward) convection in the cusp as long as the IMF has its Y- component greater that its Z-component (e.g., Escoubet et al., 2007; Maynard et al., 2003; Zong, Fritz, Korth, et al., 2005; Zong, Fritz, Spence, Frey, et al., 2005). Furthermore, the statistical study by Pitout et al. (2009) showed that most cases of double cusp occurring under stable IMF are found when IMF B_y dominates. This suggested that double cusp encounters are–or may sometimes be–actual stable spatial structures that the satellites cross one after the other. This implies two sources of magnetosheath plasma as proposed by earlier studies (e.g., Pitout et al., 2002; Wing et al., 2001): one at low latitude between the two cusps, and another one at high-latitude poleward of the cusp.

5.6. Hemispheric and Dawn-Dusk Asymmetries

Another topic Cluster has contributed to are the asymmetries between the two cusps. One often talks about the cusp in its singular form but there are two cusps in the magnetosphere and differences in properties and behaviors of the two cusps could well betray fundamental physical features. Most authors that have tacked this topic noticed that the Cluster orbits introduce a bias when comparing the cusps because the latter are not crossed at the same altitudes in the two hemispheres (e.g., Pitout, Escoubet, Klecker, & Reme, 2006; Shi et al., 2019). Consequently, any potential effect of this altitude difference must be taken into account.

Interhemispheric asymmetries of the dayside/cusp ionosphere and magnetosphere have long been observed. These were seen in the ground magnetic field: its variations are larger in the sunlit hemisphere (Wescott, 1962). The cusp location may also be affected: the cusp finds itself at lower/higher latitude when the dipole tilts antisunward/sunward (Burch, 1972). The effect of the dipole tilt is also seen in the convection pattern (e.g., Pettigrew et al., 2010). When it comes to particle precipitation, Newell and Meng (1988a) showed that it could be substantially different in the two cusps near solstice, assumable due to the faster magnetosheath flow above the winter hemisphere cusp.
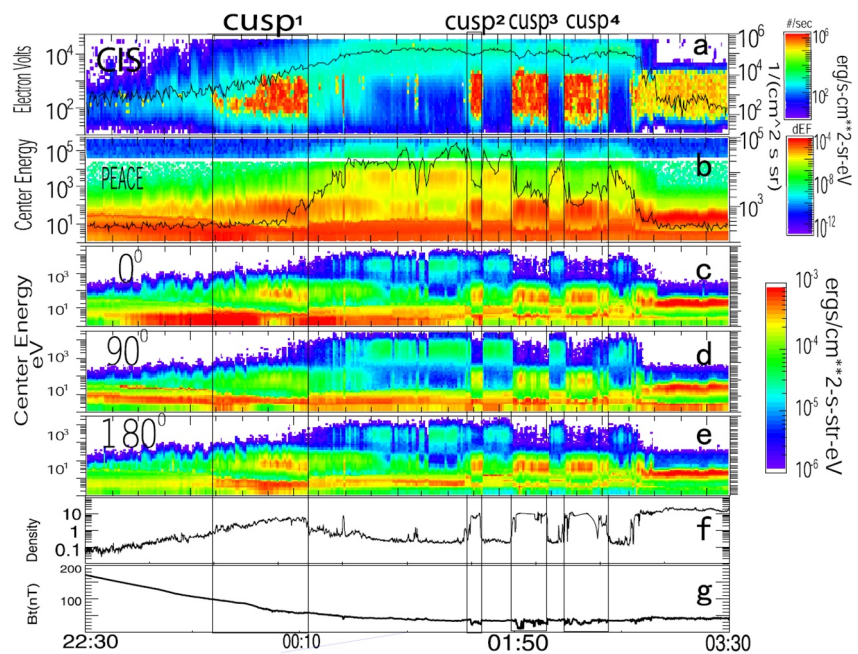
Figure 11. Composite plot displaying the multiple cusp entries with, from top to bottom, ion (a) and electron (b) energy-time spectrograms with, superimposed, the mean energy flux; three electron spectrogram (c–e) for three different pitch angles (0°, 90°, and 180°); the ion density (f), and the magnitude of the magnetic field (g). From Zong et al. (2008).
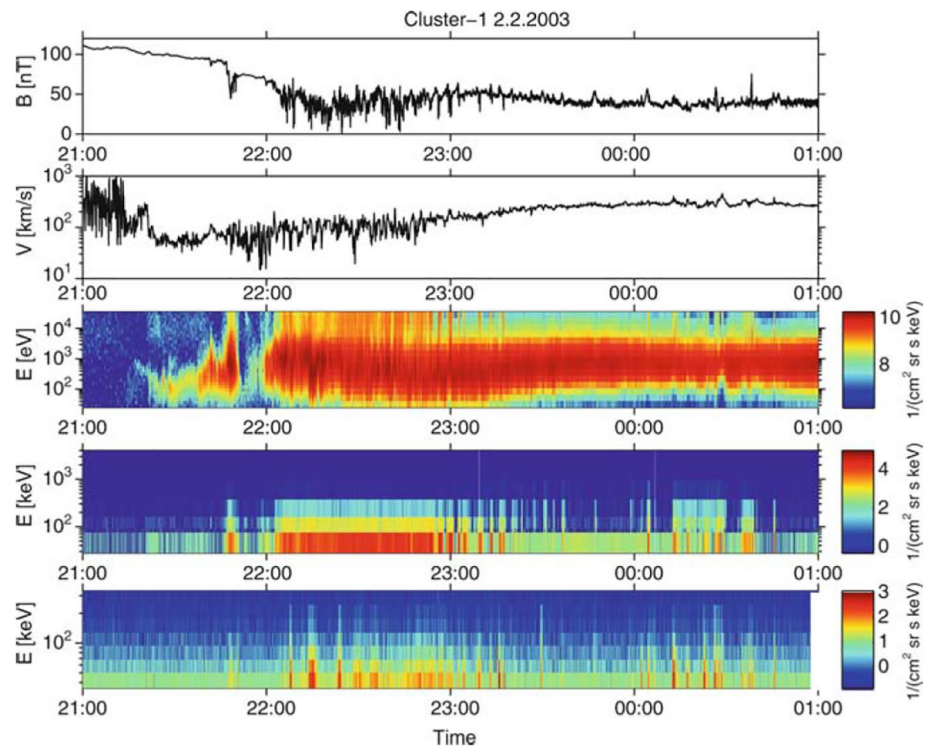
Figure 12. An example of the energetic particles observations by Cluster inside the cusp region. Panels from top to the bottom are magnetic field intensity, plasma flow velocity, low energy ion spectrum, energetic proton spectrum, and energetic electron spectrum. From Asikainen (2010).
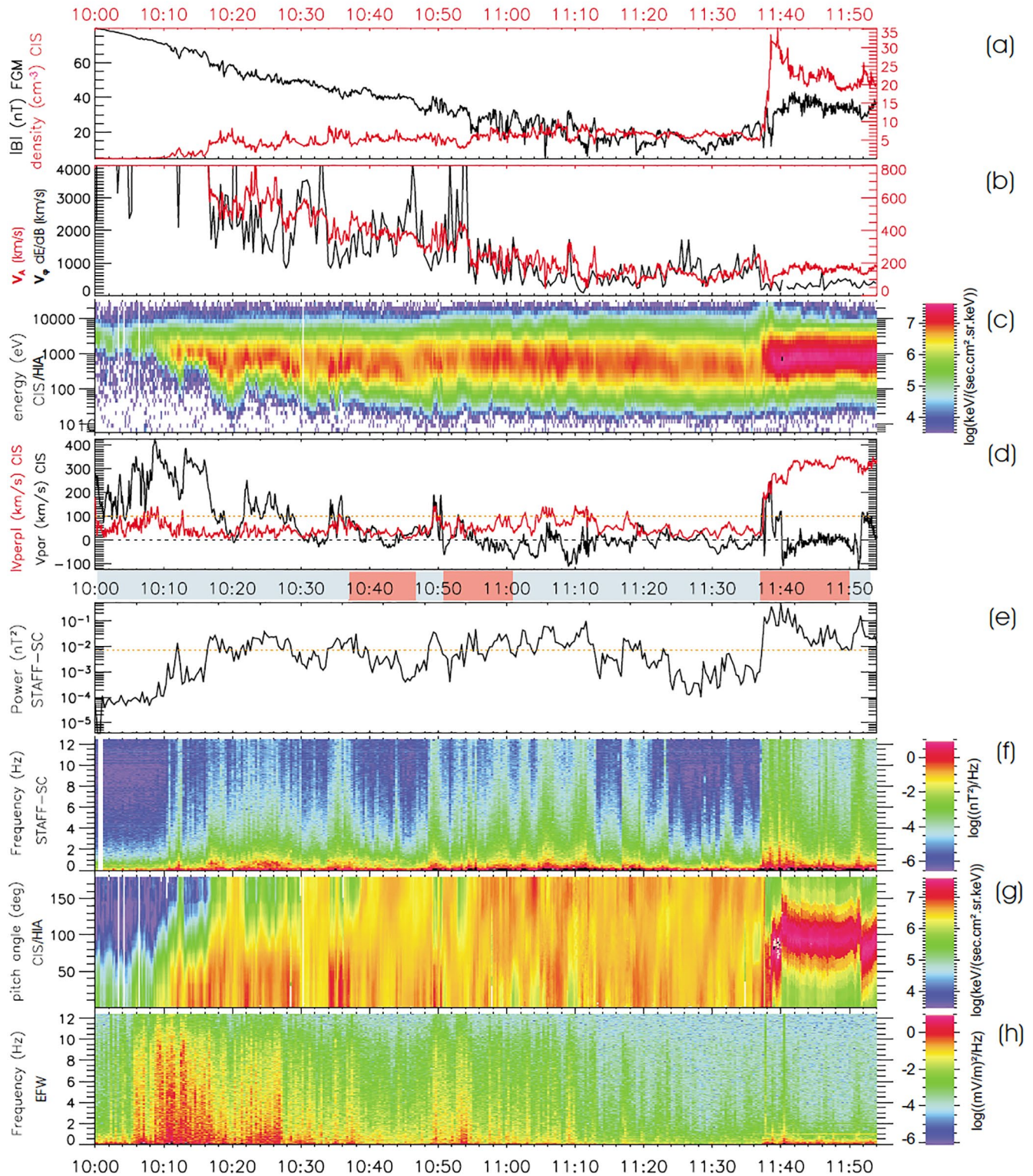
Figure 13.

The effect of the dipole tilt has been studied with Cluster by several authors. In their statistical study of the cusp location, Pitout, Escoubet, Klecker, and Reme (2006) had to remove the effect of the tilt to isolate the effect of the IMF orientation. This was later tackled again by Shi et al. (2012) and they showed that the dipole tilt dependency of the cusp location was not the same in the northern and southern hemispheres.

Förster and Haaland (2015), using the EDI instruments, investigated the convection at high-latitude in the two hemispheres and found substantial differences that they ascribed to the different feedbacks from the two polar ionospheres.

Pitout et al. (2020) compared data from Cluster in the northern cusp and Polar in the southern cusp around equinox and found that the electromagnetic energy (Poynting flux) injected in the two cusps was similar, as well as the energy transported by the particles. The slight differences found in the plasma convection velocity was interpreted as an effect of the dipole tilt.

During a rotation of the IMF, Cluster data showed that a strong north-south asymmetry in the cusp response may develop and this was confirmed by magnetohydrodynamics (MHD) and large-scale kinetic (LSK) simulations (Berchem et al., 2016). In the event they investigated, while the IMF turned northward, lobe reconnection did not take place at the same locations in both hemispheres due to the X-component of the IMF. This configuration resulted in different topologies of the two cusps, especially their orientation in the $(X, Z)_{GSE}$ plane.

Although Cluster was not designed to cover large longitudinal or MLT distances, it helped constraining models to evidence a dawn-dusk asymmetry in dayside precipitations (Berchem et al., 2014). This asymmetry is ascribed to the asymmetry in parallel electric field: positive in the pre-noon sector and negative in the post-noon sector, in the northern hemisphere. Walsh et al. (2014) have addressed this topic in a wider review.

Last, field-aligned electron beams that we have discussed in Section 5.1 were seen to display a north-south asymmetry with more downward/upward electron beams in the southern/northern hemisphere (Shi et al., 2019). They also noticed that the peak of the distribution is found 1.3 R_E higher in the southern hemisphere (which may be an observational bias) and 5° latitude lower than in the north.

6. Energetic Particles in the Cusp

While the Polar observations have shown that the energetic particles are often observed in the high-altitude cusp (e.g., Chen & Fritz, 2005; Chen et al., 1998; Fritz, 2001), a number of the open questions remained, with the main questions being about the source or "seed" population of the energetic particles observed in the cusp and the acceleration processes allowing particles to reach high energies, with three different models suggested.

According to the first model, as the energetic particles are often observed inside the cusp diamagnetic cavities (CDC) with a low and turbulent magnetic field, the particles are accelerated locally by the electromagnetic waves (Chen et al., 1998; Fritz, 2001), including cyclotron resonant acceleration (Chen, 2008). According to the second model, the source population for the observed energetic ions lays inside the high-latitude boundary region which acts as a stable trapping region for the energetic particles due to magnetic minimum (Shabansky, 1968). It was suggested that particles on dayside closed field lines originating from plasma sheet, radiation belt and ring current may be transported under the action of mirror force toward higher latitudes where they can gain access to the outer cusp (Sheldon et al., 1998; Delcourt & Sauvaud, 1998, 1999). According to the third model (Chang et al., 1998; Trattner et al., 2001), the lower energy particles can be accelerated at the quasi-parallel bow shock, and enter the exterior cusp along the magnetic field lines

Figure 13. Overview of the cusp crossing on March 23, 2002. From the top to the bottom: (a) the DC magnetic field (black curve) and the ion density (red curve); (b) the δE/δB ratio (black curve) and the derived Alfvén velocity (red curve); (c) the ion energy spectrogram; (d) the parallel component of the bulk flow velocity (black curve) and the norm of perpendicular component (red curve); (e) the power of the magnetic field fluctuations integrated between 1 and 10 Hz, (f) the time frequency spectrogram of these fluctuations, (g) the ion pitch angle spectrogram (pitch angles are calculated in the spacecraft frame over the [100, 1,000] eV energy range); and (h) the time frequency spectrogram of electric field fluctuations. Time interval between those panels is colored in blue (red) for a northward (southward) IMF. From Grison et al. (2005).

magnetically connecting two regions, while higher energy population is due to diffusion from the inner magnetosphere.

It was also not clear why the energetic particles were observed for a prolonged time in the cusp as in the open magnetic field geometry such particles should escape in a matter of a few seconds, and whether the energetic particles are trapped in the cusp or there is a continuing supply of such energetic particles.

The differences in the energetic ion and electron fluxes and their temporal variabilities have also been noted, with energetic ions being present more often and showing more stable behavior while electron fluxes showing higher time variability. On Cluster, the energetic particles were observed by the Research with Adaptive Particle Imaging Detectors (RAPID) instrument (Wilken et al., 1997), the energetic particle spectrometer measuring electrons with energies 39–400 keV, protons with energies 28–4000 keV and some high-energy ions.

The energetic particles inside the high-altitude cusp region have been often observed by Cluster. Figure 12 from Asikainen (2010) presents a characteristic example of the energetic particles observations inside the exterior cusp, showing typical for this region turbulent and decreased magnetic field, dense plasma population, small and turbulent plasma velocity, alongside with stable high-energy proton fluxes and pulsed fluxes of the high-energy electrons. Many Cluster studies attempted to resolve the questions about the seed population and acceleration process of the cusp energetic particles, and all three models had some experimental evidence.

The majority of the published observations have been interpreted in a view that the high-latitude boundary layer with trapped energetic particles, also called High Latitude Plasma Sheet (HLPS) or High Latitude Trapping Region (HLTR), is the source population for the cusp energetic particles and that the reconnection process provides the access root for those particles into the cusp. Thus, Zong, Fritz, Daly, et al. (2003) and Asikainen and Mursula (2006) presented the case studies of the intense bursts of the energetic electrons and energetic particles coinciding with the magnetic flux rope or FTE magnetic geometry respectively with a strong pitch-angle filed-aligned anisotropy. These observations were interpreted in terms of the transient reconnection process releasing the energetic particles from the HLPS region into the exterior cusp. It was argued that while reconnection provides access for the energetic particles from closed field lines to the cusp, it is not able to accelerate low-energy plasma to the observed high energies. Zong, Fritz, Wilken, and Daly (2003), based on the analysis of the strong anisotropy of the energetic particles' azimuthal angular distributions inside and near the high-altitude cusp region for different IMF orientation, showed that the reconnection can provide access of the energetic particles to the cusp region for both southward and northward IMF orientations.

Asikainen and Mursula (2005) and Asikainen (2010) conducted statistical studies of the fluxes of energetic protons and electrons inside the exterior cusp and the adjacent HLPS observed by Cluster. The authors cross-compared observations in the exterior cusp and the HLPS and investigated how the energetic particle fluxes depend on the solar wind conditions and geomagnetic activity. It was shown that the total electron fluxes and fluxes of high-energy protons (>100 keV) in these two regions correlate with each other and that the spectral indices of electron and proton fluxes are the same in these two regions, suggesting a close connection between these regions and similar acceleration mechanisms for the plasma populations. These studies suggested that the high-latitude dayside plasma sheet is the main source of energetic particles in the exterior cusp, and both direct diffusion (for high-energy protons and electrons) and magnetic reconnection in the high-latitude magnetopause are responsible for the particle release from the HLPS into the exterior cusp.

Some studies were evidencing the local acceleration mechanisms, based on the observations of particles with 90° pitch-angles and wave activity. Vogiatzis et al. (2008) in a statistical study showed that the high-energy O^+ and H^+ ion fluxes anti-correlate with the magnetic field strength and correlate with the magnetic field ULF (0–12 Hz) wave power spectra, indicating the ongoing particles' acceleration inside the cusp by resonant interactions with the broadband low-frequency electromagnetic waves. Based on the analysis of the observations, including electron fluxes and pitch-angles, and on the modeled drift paths of energetic electrons with a fully relativistic three-dimensional particle trace, Walsh et al. (2010) argued that the observed energetic electron characteristics inside the cusp are only consistent with the local acceleration and

cannot be explained by the other mechanisms. Fritz (2010) pointed out that energetic particles are a consistent and common feature of the high-altitude cusp and that their presence is often associated with the cusp diamagnetic cavities. It was suggested that observations are indicative of both ionospheric and solar wind sources and that a local acceleration of plasma within the cusp is the primary source for the energetic particles observed. It was proposed that these results also show that the cusp can be considered as a major source of magnetospheric energetic particles and the ring currents ions, which was studied further in Fritz et al. (2012).

Walsh and Fritz (2011) performed a 7-year statistical study in order to determine the average properties of energetic electrons (37–400 keV) inside the high-altitude cusp and its adjacent regions and the origin of this population. This study confirmed the existence of the high latitudinal trapping region with significant fluxes of energetic electrons just equatorward of the cusp, similar to the trapping region observed by Asikainen and Mursula (2006). The energetic elections were observed inside the exterior cusp for both southward and northward IMF with fluxes around one order of magnitude smaller than in the trapping region. Analysis of the observations suggested that both sources, electrons from the trapping region and local acceleration, contributed to the observed energetic particles inside the cusp. Thus, similar spectral power laws of electrons inside the trapping region and the exterior cusp suggested that the trapping region provides some electron population to the cusp. The local acceleration was supported by the average pitch-angle distribution peaking at 90°, no apparent flux correlation with IMF B_z and flux enhancement over a wide range of cusp latitudes. The observations also showed that the energetic electron flux in the magnetosheath decreases with the distance from the magnetopause and electrons mainly propagating along open field lines from the cusp, ruling out the bow shock source.

The plausible source for the energetic particles inside the cusp diamagnetic cavity was studied by Nykyri, Otto, Adamson, Dougal, and Mumme (2011), Nykyri, Otto, Adamson, and Tjulin (2011), Nykyri et al. (2012) based on the analysis of one event with a large separation between Cluster spacecraft which enabled for the first time to observe the cusp diamagnetic cavity and its surrounding boundaries simultaneously. Nykyri, Otto, Adamson, Dougal, and Mumme (2011) showed that significant fluxes of energetic electrons, protons and heavy ions were observed inside the cavity, alongside with depressed and turbulent magnetic field. Based on the protons and O^+ ions moving anti-parallel to the magnetic field escaping the cavity, the local source for the energetic particles has been suggested. Nykyri, Otto, Adamson, and Tjulin (2011) analyzed the magnetic field fluctuations (0.01–10 Hz) inside the cusp diamagnetic cavity, arguing that the large-amplitude turbulence observed can be a result of the spacecraft crossing of the separate filamentary reconnected flux tubes as well as back and forth motion of the boundaries over the spacecraft. The analysis of the wave power indicated the lack of strong power at the vicinity of local ion cyclotron frequency, supporting the suggestion that wave-particle interaction was not a dominant source of the observed energetic ions. Nykyri et al. (2012) argued that the local acceleration process, different from the wave-particle interaction, is required for the electron acceleration. The authors performed the test particle simulations using a 3-D high-resolution MHD cusp model showing that low energy particles with initial isotropic velocity can gain energy up to 40 keV in the direction perpendicular to the magnetic field resulting in nearly 90° pitch-angles, observed in this case. The authors proposed that such acceleration is due to gradients in reconnection "quasi-potential" and that it may be possible that particles are recycled through this potential making the energy gain up to hundreds of keV.

While the majority of the published Cluster observations ruled out the bow shock as a source for the cusp energetic particles, there were also observations in favor of this model, presented by Trattner et al. (2011). The authors mapped newly reconnected field lines near the cusp region back to the solar wind, showing the magnetic connection with a quasi-parallel bow shock in the southern hemisphere, which would allow shock accelerated ions to stream into the northern cusp region. Such energetic particles streaming parallel to the magnetic field into the cusp region were observed in the magnetosheath, alongside the energetic ions just inside the magnetopause streaming Earthward. The authors argued that the presented observations are undoubtedly showed that shock accelerated ions are able to enter the cusp region along newly reconnected field lines and that a bow shock source can be a dominant contributor to the cusp energetic ion population.

The differences in the temporal behavior of energetic electrons and ions have been investigated in several studies to understand how the energetic particles can be trapped inside the cusp region. Zhang et al. (2005)

presented a statistical study of the high-altitude cusp crossings concentrating on the observations of the Stagnant Exterior Cusp (SEC). It was shown that that the energetic ions are observed in 80% of the SEC crossings while energetic electrons are observed in 22.5%, and the depressed magnetic field was observed in 72.5% of the crossings.

Zong, Fritz, Korth, et al. (2005) presented a study of the energetic particles inside the high latitude boundary layer and cusp regions during the southward and northward IMF. It was shown that both spike-like and stably trapped electrons were observed during different conditions. For the northward IMF case during a quiet geomagnetic interval, energetic electrons were observed inside the high latitude boundary/cusp region for more than 2 h, indicating either a closed field line geometry or a special open field line configuration that could trap electrons efficiently, or a long-lived source of these electrons. Contrary, during the southward IMF, while the energetic ions were still present inside the high latitude boundary/cusp region, there was an observed lack of the energetic electrons, suggesting a probable open field line geometry or a lack of a source of these electrons. The open field geometry responsible for the lack of energetic electrons was also suggested by Asikainen (2010).

Fu et al. (2005) presented observations of the energetic particles during a recovery phase of the major magnetic storm, showing a significant increase of the energetic particle fluxes in comparison with less active time. The observations showed that the energetic electrons have been observed for a short time, in the region with diminishing magnetic field including the null point, while fluxes of the energetic protons and heavy ions reached a maximum in that region. The authors suggested that a current sheet (existing at the null point of the observed magnetic field) inside the stagnant cusp region can play the role in the trapping of the energetic particles, especially electrons, in its vicinity by modifying their orbits. Finally, Walsh and Fritz (2011) suggested that as the exterior cusp frequently has a magnetic field strength lower than the magnetosheath's magnetic field strength, the exterior cusp can act as a magnetic trap that confines energetic particles within, even on open field lines.

7. Wave Activity in the Cusp

The observations from previous missions showed that the magnetic and electric field fluctuations over a wide range of frequencies, from sub-Hz frequencies (Savin et al., 2004) to the kHz range (Pickett et al., 2001), are often detected inside the cusp. It was suggested that the cusp is a region where a constant exchange of energy between plasma and fields take place as the collisionless plasma can be heated by wave-particle interactions.

The most typical identified modes were broadband emissions, lower-hybrid waves, Alfvén waves, and electron and ion cyclotron waves, observed alongside the accelerated and dynamic plasma populating the cusp region (André, 1997; Blecki et al., 2005, and references therein; D'Angelo, 1977; Le et al., 2001; Pickett et al., 2001). Different free wave energy sources have been suggested over the years, depending on the waves' mode and frequency, including ion and electron beams (e.g., Cattell et al., 2002; Norqvist et al., 1998), specific forms of the ion and electron distribution functions (Bingham et al., 1999), field aligned currents (e.g., André et al., 1998), plasma instabilities, velocity shears (Lakhina, 1990) and temperature anisotropy (André et al., 1986).

It was shown (e.g., André et al., 1998) that inside low-altitude cusp the ion perpendicular heating and outflow correlate with Broad Band Extremely Low Frequency (BBELF) wave power in the frequency range from below 1 Hz up to 1 kHz. It was suggested that the left-hand polarized fraction of these waves could heat the ions via resonant interaction near ion gyro frequency. The energy cascades from lower frequency waves to higher frequency were previously proposed (e.g., Savin et al., 2004) and observed by previous missions (Blecki et al., 2005) with a suggestion of complex wave-particle interactions, with lower hybrid waves heating electrons which can then generate higher frequencies waves.

Despite the previous progress in the cusp wave studies, the open questions remained about the identification of the waves modes, their properties (polarization, ellipticity, localization, coherence, propagation angle with respect to the background magnetic field), about waves generation mechanisms and locality of the sources (local vs. distant sources), and about the wave-particle interaction processes.
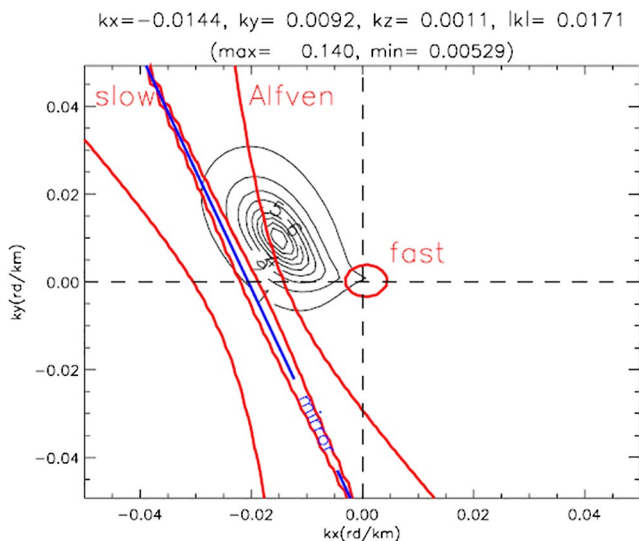
Figure 14. Energy distribution in the k-space of the most intense identified peak for the frequency $f = 0.26$ Hz. It is presented in the $k_z = 0.0011$ rd/km plane which contains the maximum of magnetic energy for this frequency. The black thin lines are the isocontours of energy in the (k_x, k_y) plane, whereas the colored lines are the theoretical dispersion relations of the LF modes Doppler shifted in the satellite frame. From Grison et al. (2005).

The magnetic and electric fields and their fluctuations are measured by five Cluster instruments: FGM, EFW, STAFF, WHISPER and WBD. The Spatio Temporal Analysis of Field Fluctuations (STAFF) experiment consists of a three-axis search coil magnetometer to measure magnetic field fluctuations at frequencies up to 4 kHz, a waveform unit (up to 10 Hz or 180 Hz) and a Spectrum Analyzer (up to 4 kHz) (Cornilleau-Wehrlin et al., 2003). Two electric field components are measured in the spin plane by the Electric Filed Wave (EFW) experiment (Gustafsson et al., 2001). The sampling rate of 25 Hz is achievable with these two instruments. The FGM instrument is able to provide the measurements at a different sampling rate, including 22 vectors/sec in normal mode and up to 67 vectors/sec in burst mode, which is useful for the low-frequency wave observations. The Waves of High frequency and Sounder for Probing of Electron density by Relaxation (WHISPER) instruments is measuring electric field emissions at high frequency (Decreau et al., 1997). The Wide Band Data (WBD) instrument (Gurnett et al., 1997) is designed to provide high-resolution measurements of both electric and magnetic fields in selected frequency bands from 25 Hz to 577 kHz.

7.1. Low Frequency Waves

The majority of the Cluster studies concentrated on the low-frequency range, from sub-Hz to around 10 Hz frequency. The typical observations of the ULF electromagnetic wave activity in high-altitude cusp are presented in Figure 13, from Grison et al. (2005), highlighting a good correlation between δE/δB ratio and calculated local Alfvén velocity, structured plasma injections, increased wave power and broadband form of the electric and magnetic field fluctuations inside the cusp region. The strong low-frequency electromagnetic wave activity was observed during the intervals with intense field-aligned proton fluxes, with particles most likely coming from the reconnection site and the waves generated locally. Figure 14 presents an example of the application of the k-filtering technique (Pincon & Motschmann, 1998) which took advantage of a close ∼100 km inter-spacecraft separation allowing simultaneous measurements of a given wavefield in several points in space. Figure 14 shows the wave energy distribution in the k-space with super-imposed theoretical dispersion relations of the low-frequency Doppler-shifted linear plasma modes (MHD and mirror mode) and kinetic modes computed from the WHAMP program (Ronnmark, 1982), showing a clear Alfvén mode identification. The analysis showed that during this cusp crossing kinetic Alfvén waves dominated in the frequency range up to 1 Hz, and that above 0.8 Hz intense Bernstein waves were present.

The characterizations of the BBELF emissions have been conducted in several studies. Bogdanova, Fazakerley, et al. (2004) showed that both electric and magnetic field fluctuations in the BBELF band of 1–10 Hz start just after the crossing the Open Closed Boundary, in the region populated by low-flux of the magnetosheath electrons with occasional electron beams and before the arrival of the accelerated ion population from the reconnection site. Jacobsen and Moen (2010) presented a statistical study of the BBELF electric field fluctuations in the frequency range 0.75–11 Hz. The authors showed that the BBELF region is contained within the cusp ion dispersion region and the equatorward boundaries of the BBELF and ion cusp collocate. Waara et al. (2011) showed that the BBELF (<1 Hz) fluctuations were observed over an extended range of altitudes sampled by Cluster. Both magnetic and electric field spectral densities vary with altitude, with magnetic field density increasing by 2.5 orders of magnitude over the altitude interval (5–15 R_E) while electric field spectral density varied by a factor of 3–4. High time variability of the BBELF fluctuations has also been noted, as the strong wave activity is typically observed only for a few minutes on each occasion (Waara et al., 2011).

The differences in the temporal behavior of the magnetic and electric field fluctuations inside the cusp have been noticed in several Cluster studies, with magnetic fluctuations being more localized than the electric fluctuations (e.g., Blecki et al., 2005; Bogdanova, Fazakerley, et al., 2004; Slapak et al., 2017). The differences

in the frequency range of the magnetic and electric field fluctuations also have been discussed, with a broader spectrum of the electric field fluctuations (Blecki et al., 2005). Lin et al. (2006) showed that the broad band magnetic field fluctuations, "magnetic noise," is observed at frequencies from several Hz to ~100 Hz, below the local electron cyclotron frequency, while strong broadband electrostatic emissions are observed at frequencies from several Hz to 20–30 kHz, with maximum intensity at frequencies below 100 Hz.

Numerous Cluster studies have shown that the low-frequency wave power correlates with the fluxes of the magnetosheath-like ions and electrons seen in the cusp (e.g., Duan et al., 2006; Grison et al., 2005; Jacobsen & Moen, 2010; Keith et al., 2005). Jacobsen and Moen (2010) pointed out that there is a greater degree of correlation between BBELF wave power and total fluxes in comparison with only field-aligned ion fluxes, suggesting that BBELF wave generation is independent of ion beam direction and therefore must be local. Despite this statistical result, some studies indicated that strong wave activity occurred in regions of strong field-aligned plasma velocity and strong field-aligned proton flux (Grison et al., 2005; Nykyri et al., 2003, 2004), indicating that plasma injections from the reconnection at the magnetopause are closely related to the strong wave activity observed in the cusp. In addition, it was noted that waves were also observed in the stagnant cusp without associated plasma injections (Nykyri et al., 2004) suggesting different wave excitation mechanism.

Analysis of the low frequency fluctuations on many occasions showed the presence of Alfvénic waves inside the cusp region. Nykyri et al. (2003, 2004) discussed the observations in terms of the Alfvén/ion cyclotron modes. In these studies, analysis of power spectra of magnetic field fluctuations showed that fluctuations have often peak near the ion cyclotron frequency both inside the region with plasma injections and inside the stagnant cusp. Duan et al. (2006) characterized electromagnetic fluctuations in the range of 0.3–10 Hz as being possibly kinetic Alfvén waves and solitary kinetic Alfvén waves. Chaston et al. (2005) using conjugated observations between Cluster and FAST identified the broadband waves as dispersive Alfvén waves with the frequencies in the plasma frame from 1 mHz up to 50 mHz. It was estimated that the waves have a variety of wavelengths perpendicular to the geomagnetic ambient field, from a fraction of L-shell down to the ion gyroradii and electron inertial length, and wavelengths along the geomagnetic field were of the order of the field line length between the ionosphere and equatorial plane. Grison et al. (2005) and Sundkvist, Krasoselskikh, et al. (2005), Sundkvist, Vaivads, et al. (2005) showed that kinetic Alfvén waves dominated in the frequency range up to 1 Hz, with Bernstein mode being identified above ~0.8 Hz (~ion cyclotron frequency). Lin et al. (2006) interpreted the VLF/ELF activity over extended frequency range in terms of Alfvénic turbulence or superposition of whistler and kinetic Alfvén waves. Waara et al. (2011) comparing the wave phase velocities to the local Alfvén velocity, showed that Alfvén waves were observed over extended altitude, 5–15 R_E, with a large range of velocity values, from a few hundred km/s up to few thousands.

The wave form characteristics have been investigated in several studies. Nykyri et al. (2004) showed that the identified waves have a wide range of propagation angles in respect to the ambient magnetic field, from parallel to perpendicular. The wave polarization was inferred to be both right- and left-handed in some studies (e.g., Nykyri et al., 2003, 2004), with polarization changing from one wave cycle to another, while other studies did not find a clear polarization of the wave perpendicular components (Sundkvist, Krasoselskikh, et al., 2005, Sundkvist, Vaivads, et al., 2005). Coherence length was estimated to be around ~100 km and below (Grison et al., 2005; Nykyri et al., 2003), with Sundkvist, Krasoselskikh, et al. (2005), Sundkvist, Vaivads, et al. (2005) citing smaller lengths, of the order of one ion gyroradius in the perpendicular direction and a few times larger in the parallel direction (with $\rho_p \sim 23$ km in the presented case).

The different free energy sources have been suggested for the low-frequency wave generation inside the cusp region. Based on the correlation between electron fluxes and wave power in the region with no magnetosheath ion injections, Bogdanova, Fazakerley, et al. (2004) suggested that the suprathermal electron beams are most likely the free energy source for the BBELF wave excitation and growth. Chaston et al. (2005) proposed that the dispersive Alfvén waves observed at Cluster and FAST altitudes are generated through the mode conversion of surface Alfvén waves driven by the tailward flows in the low-latitude boundary layer. Comparison of the wave Poynting flux with particles' energy and flux showed that energy is transferred from the waves to the plasma, via field-aligned electron acceleration, transverse ion heating and Joule heating.

Based on the observations of the strong wave activity with the enhanced power at ion cyclotron frequency in the region with the strong field-aligned sheared plasma flows coming from the magnetopause reconnection, Nykyri et al. (2003, 2004) argued that plasma shears can be the origin of the observed waves or waves can be generated near the reconnection site. Following these observations, Slapak et al. (2017) showed that the inverse ion cyclotron damping was responsible for the excitation of the waves at the ion cyclotron frequency and its harmonics in the northern cusp. The authors suggested that some other mechanism was responsible for the ion cyclotron waves observed in the southern cusp's shear region.

Taking into account close relations between the wave power and field-aligned ion fluxes, Grison et al. (2005) suggested that the identified Alfvén and Bernstein wave modes were generated locally, with the current instability and the specific distributions of the injected ions being plausible mechanisms for Alfvén and Bernstein modes, respectively (e.g., Bingham et al., 1999; Forslund et al., 1979; Janhunen et al., 2003). Sundkvist, Krasoselskikh, et al. (2005), Sundkvist, Vaivads, et al. (2005), based on the analysis of the wave Poynting flux, argued that the waves were generated near the local proton gyrofrequency along the flux tube. Based on the correspondence between waves and proton flux and analysis of the ion distribution functions, the authors suggested that a likely source for free energy to drive waves are injected ions with shell-like (horseshoe) type of distribution.

Lin et al. (2006) suggested that the magnetic broadband emissions can be related to the whistler and kinetic Alfvén waves modes generated in the reconnection outflow region while the electrostatic broadband emissions can be caused by current driven electrostatic instability or electron holes.

Cluster observation of the kinetic and dispersive Alfvén waves in the cusp region and detailed studies of their characteristics, from four spacecraft measurements, stimulated a number of theoretical studies of these waves which then confirmed the interpretation of the observed by Custer wave modes (Agarwal et al., 2011a, 2011b; Onishchenko et al., 2009).

Low-frequency waves have been also observed in the mantle region, poleward of the cusp. Matsui et al. (2007) presented a study of two cases of broadband ultralow frequency (ULF) waves observed near the dayside polar cap boundary, possibly mantle region, concentrating on the frequency range of 1–100 mHz, which is part of the Pc 1–5 frequency range. The authors showed that similar broadband spectra can correspond to the different wave modes with different properties. Thus it was shown that shear Alfvén waves with the phase velocity perpendicular to the magnetic field were observed in one case, with the suggested source being most likely transient reconnection. In the second case, the magnetic field variations included compressional components, indicating that waves can be fast mode waves possibly launched by the solar wind pressure variations impacting magnetopause.

Left-hand polarized band-limited Alfvén mode Pc 1–2 waves (0.2–1.0 Hz) with frequency $\sim 0.5\, f_{H^+}$ (with f_{H^+} being a proton gyrofrequency) have been also regularly observed in the high-altitude lobe/mantle regions, near the magnetopause by Engebretson et al. (2012). These waves were generally observed during southward IMF periods with significant B_Y component, favorable for the cusp reconnection, and often during the geomagnetically active times. These waves were associated with the periods of outflowing H^+ and O^+ ions and greatly enhanced H^+ fluxes. Further analysis showed that waves propagated Earthward, in opposite to the streaming ions direction and were associated with strong H^+ temperature anisotropy. The study showed that these waves can be generated by ion cyclotron instability, and the authors concluded that these waves can be identified as electromagnetic ion-cyclotron (EMIC) waves.

Grison et al. (2014) presented a detailed investigation of the similar narrowband (0.6–0.7 f_{H^+}) electromagnetic waves in the Pc 1–2 range using multi-spacecraft observations. This study reported the first direct wave vector measurements of these waves from the multi-spacecraft analysis and also showed that estimations via single spacecraft analysis agree well with the multi-spacecraft analysis in this frequency range. In agreement with Engebretson et al. (2012), the authors showed that the proton temperature anisotropy was the main source for the wave amplification process as the ion distributions were unstable to ion cyclotron instability. These waves, counter-streaming with respect to the plasma flow and coming from higher altitudes, were identified as the EMIC waves.

7.2. High Frequency Waves

High-frequency waves have been also detected inside the cusp region. Thus Khotyaintsev et al. (2004) presented a study of wave emissions in the frequency range 2–80 kHz for the electric field and 8–4,000 Hz for the magnetic field. The busty emissions with spectral peaks at frequencies below the electron-cyclotron frequency were seen through the whole cusp and were identified as whistlers. The different types of emissions were observed within few seconds next to each over or even at the same time, both broad-band and with enhanced power at the plasma frequency or spectral peaks at frequencies below the plasma frequency. The observations showed that wave emission intensity and spectral character are changing on a very short time scale of the order of 1 s. The strongest emissions with a strong spectral peak near the plasma frequency were observed usually on the edges of the narrow current sheets and it was suggested that such waves are generated by electron beams propagating along the separatrices of the reconnection region via bump-on-tail or electron two-stream instability.

Sundkvist et al. (2006) concentrated on the frequency range of 1–80 kHz, with wave emissions at electron cyclotron harmonics at the frequencies above the local plasma frequency being clearly observed. This study showed that electron cyclotron harmonics are generally observed when the electron distribution functions deviate from Maxwellian at low energies and has a positive slope in velocity space. Numerical calculations of waves' growth rate showed that such shell-like electron instability can provide free energy for the whistler waves, electron cyclotron harmonics, upper-hybrid as well as the RX mode. Based on the combination of these observations with previous case studies of the Alfvénic fluctuations typical for the cusp region, Sundkvist et al. (2006) suggested a mechanism of coupling between low and high frequency waves via electron population. It was proposed that the low frequency waves such as dispersive Alfvén waves or ion cyclotron waves accelerate electrons in the parallel direction (e.g., Chaston et al., 2005), creating electron beams which change into the shell-type distributions in the converging cusp magnetic field and these unstable distributions generate the high-frequency waves.

Rothkaehl et al. (2009) investigated high-frequency, 2–80 kHz, waves in the mid-altitude cusp showing that both broad-band emissions and emissions with the enhanced wave power at the particular frequencies (associated with electron cyclotron frequency) are typical for the cusp region, comparing Cluster data with data from low-orbiting FREJA satellite. The whistler waves, electron-cyclotron waves, electron acoustic waves and Langmuir waves have been detected in the cusp crossings, and the authors suggested that the majority of these wave modes were generated by electron beams, which were observed to accompany wave power enhancements.

7.3. Wave Activity and Ion Heating and Outflow

Investigation of waves in the cusp region is closely related to the studies of the energization of the ionospheric ions and ion outflow with the clef and cusp being one of the main sources of the oxygen ions in the magnetosphere. Three acceleration mechanisms were suggested to be important for ion escape, centrifugal acceleration, field-aligned potential gradients and wave-particle interaction (e.g., Slapak et al., 2011). In later mechanism, the ions are energized transverse to the magnetic field due to resonance interaction with the waves at the ion cyclotron frequency (e.g., André et al., 1998; Chang et al., 1986). In Cluster observations, the ion heating was often associated with the broadband waves (e.g., Bogdanova, Klecker, et al., 2004; Bogdanova, Fazakerley, et al., 2004; Bouhram et al., 2003, 2004).

The statistical study (Waara et al., 2011) showed that BBELF activity of Alfvénic nature exists over the extended altitude interval inside the cusp region and it was suggested that the waves at the O^+ gyrofrequency had enough power for the resonant heating of O^+ ions up to observed energies of 20–1,400 eV. In the accompanying paper, Slapak et al. (2011) considered case studies of the heating events in the cusp with the intense wave activity, developing a heating model which allows to estimate for how long the ions must have experience of the enhanced wave activity in order to explain the observed perpendicular temperatures and parallel velocities. The study showed that heating by waves can explain observed perpendicular O^+ energy by gyro resonance and that 25%–45% of the observed wave activity can explain gained perpendicular energy. It was noted that the enhanced wave activity is limited in space and time and that observed high-altitude high energy (1,000 eV) O^+ ions mainly have been heated within a few R_E from the point of observation.

The relation between the low frequency electric field fluctuations and oxygen energization was followed by Waara et al. (2012). It was shown that generally the wave intensity at the O^+ ions gyrofrequencies correlates with the oxygen ions temperature, although sometimes the perpendicular temperature is much higher than predicted from the model. Such events were explained by a sporadic nature of wave activity, with intense waves rarely continually observed longer than for minutes (usually less than 5 min). Thus, it was suggested that it is more likely to detect post-heating ion conics that can be observed over many R_E after heating stops rather than in-situ heating.

In this paper, we mention a limited number of studies regarding ion heating and outflow, in relation to the wave-particle interactions. A review on the oxygen energization inside the cleft and cusp regions and outflow is presented in Dandouras (2021) in this issue.

8. Turbulence

The previous Interball and Polar investigations have shown the existence of the magnetic field turbulence, strong continuous magnetic field fluctuations over a broad range of frequencies from <0.01 Hz to up to a few of kHz, inside the so-called Turbulent Boundary Layer (TBL). This layer was observed near the interface between high-altitude/exterior cusp and magnetopause (e.g., Savin, Buchner, et al., 2002; Savin, Zelenyi, et al., 2002, and references therein; Yordanova et al., 2004). It was suggested that the turbulence involves the fluctuations of physical parameters at many different scales which interact non-linearly to produce self-organized structures in the form of vortices via inverse energy cascade between two or three-dimensional dispersive modes that are nonlinearly interacting (e.g., Pokhotelov et al., 1996). Zimbardo et al. (2008) discussed two different sources that can produce a typical power-low turbulence spectrum which is a manifestation of the energy cascading from the large to small scales. As turbulence is seen as the co-existence and interaction of coherent structures at multiple scales, it is essential to estimate the scale of structures that concentrate most of the power and where interactions are localized. Thus, the Cluster multi-point measurements have a clear advantage in comparison with single spacecraft measurements in studying turbulence. Early in the mission, Keith et al. (2005) presented Cluster observations of fully developed turbulence in the external cusp while the energy cascading from the low to high frequencies via wave modes interacting non-linearly via three-wave processes have been discussed by Blecki et al. (2005).

Coherent small-scale vortex structures have been investigated by Sundkvist, Krasoselskikh, et al. (2005), Sundkvist and Bale (2008), and Romanov (2013). Sundkvist, Krasoselskikh, et al. (2005), presented a discovery of the short-scale drift-kinetic Alfvén (DKA) vortices in the high-altitude cusp region, estimating its characteristics and spatial origin. It was noted that the cusp provides suitable conditions for the formation of DKAs due to the nonlinear interaction of coupled finite-amplitude low-frequency drift and kinetic Alfvén waves, existing in non-uniform plasma with sheared flows and density gradients. The presented analysis showed that the observed broad-band fluctuations had an Alfvénic nature, that coupled drift and kinetic Alfvén waves were present and that a significant part of the low-frequency spectrum could be attributed to coherent DKA vortex structures. Due to small inter-spacecraft separation, some of these structures were seen passing through the spacecraft with the closest separation. It has been shown that the DKA vortex has a transverse radial scale of the order $(2-3)\rho_p$, where ρ_p is the ion gyroradius of ~25 km, and that the vortices propagate along (across) the magnetic field lines with a speed comparable to the Alfvén speed V_A ($[0.01-0.1]V_A$). It was suggested that similar to the large-scale Kelvin-Helmholtz vortices at the magnetopause, the DKA vortices play an important role in the energy and plasma transport between solar wind and magnetosphere.

In a further study, Sundkvist and Bale (2008) used the observations in the cusp to study drift ion-scale vortices and their coupling to Alfvén waves in inhomogeneous plasma to address the question of how plasma is transported across a confining magnetic field, with the candidates being low-frequency waves and coherent structures. It was shown that some vortices were driven by a strong density gradient in a boundary layer with a scale size comparable with the vortex diameter of ~48 km, and were observed simultaneously with a strong and localized Alfvénic perturbation. Vortices were also observed off the gradient, which was interpreted in terms that symmetry-breaking conditions in the inhomogeneous plasma can lead to both cross-field and cross-boundary anomalous transport of particles and energy.
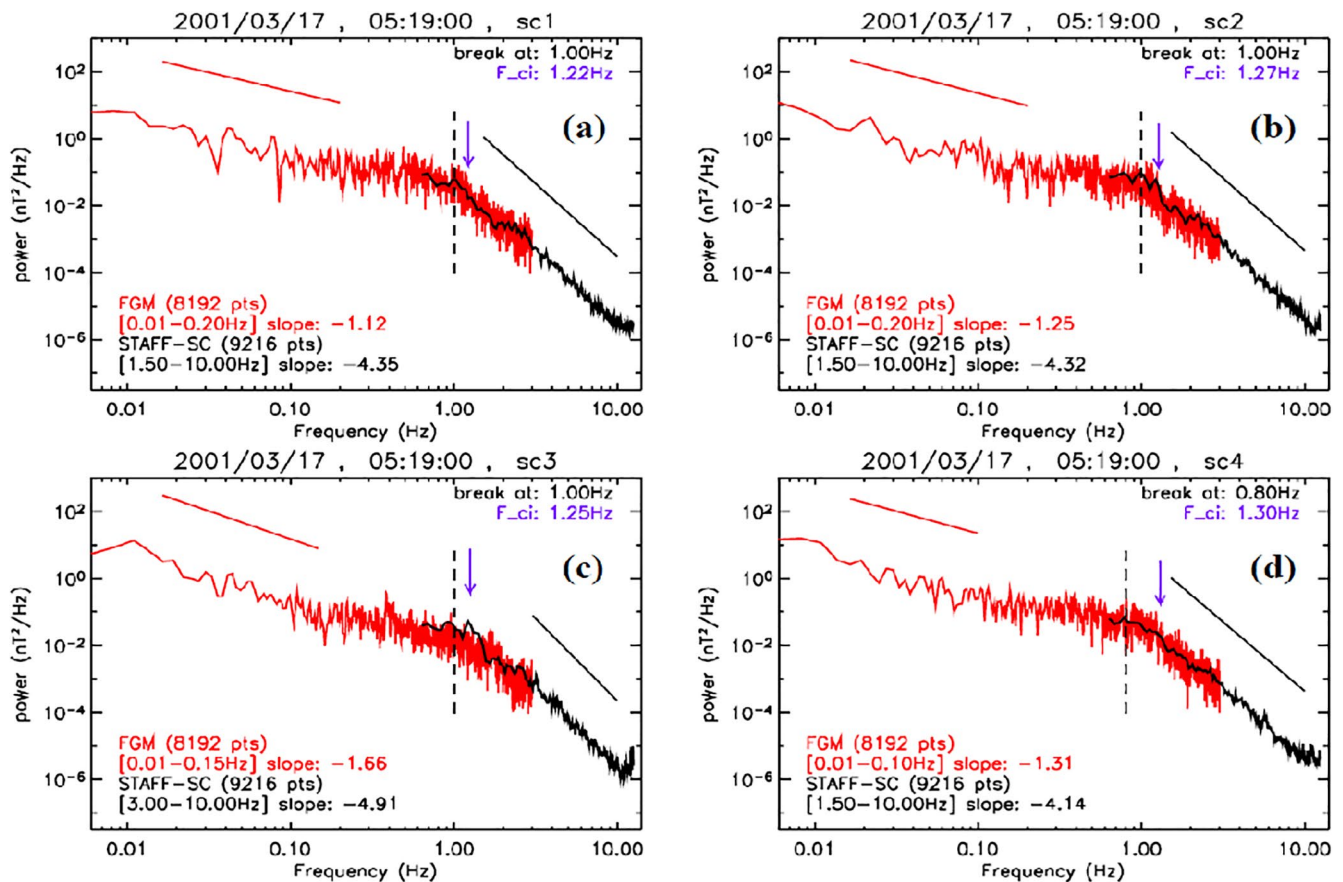
Figure 15. The power spectrum of magnetic field observations observed on four Cluster spacecraft by the Flux Gate Magnetometers (FGM; red) and Spatio Temporal Analysis of Field Fluctuations (STAFF; black) instruments. Power law slopes are shown above the spectra. See Nykyri et al. (2006) for more details.

Romanov (2013) estimated the turbulence strength inside the cusp and magnetosheath by the ratio of the magnetic field fluctuations' power in the frequency band 0.01–11 Hz to the energy of the background magnetic field. It was shown that the high-altitude cusp is highly turbulent, with the ratio reaching ~40%–50% in some regions inside the cusp while being ~20% at the outer boundary of the cusp. The degree of oscillation coherence also has been estimated based on the data from four satellites, which was relatively high, showing that the turbulent structures, considered within limited time intervals (estimated to be of a time scale of ~90s), is orderly arranged. Different types of stable vortex structures have been detected during ~70% of their total time inside the cusp. Analysis of the wave vector spectra specific features suggested an entropy growth with increasing wave number, indicating a cascade energy transfer across the spectrum from large to small scales.

Nykyri et al. (2006) investigated magnetic field turbulence over the frequency range 0.01–10 Hz inside the high altitude cusp region under northward IMF. The observations showed that the magnetic field power spectra had power laws with both single and double slopes at different times. In addition, strong power peaks close to the ion cyclotron frequency and its harmonics were sometimes observed, suggesting coexistence of discreet wave modes and turbulence. Figure 15 shows an example of the broadband magnetic field power spectra with a clear break dividing the spectra into two different power regimes, with a break point frequency being close to the ion cyclotron frequency. Analysis of all intervals showed that the power spectral index was in the range (−1.0 to −2.7) in the frequency range below the spectral breakpoint and in the range (−2.9 to −5.2) above the spectral breakpoint. It was argued that power spectra was dominated by the propagating temporal fluctuations from the different sources. There was no correlation found between the power spectral slopes and plasma parameters and at times power indices differed by 100% when observed simultaneously by different spacecraft with inter-spacecraft separation of ~600 km. The analysis also re-

vealed that in both regimes, above and below the break frequency, the fluctuations are mostly transverse. It was proposed that the plasma injections from lobe reconnection provide free power for the fluctuations to grow. Two different generation mechanisms of the doubled sloped spectra have been considered and it was suggested that the spectral break point may be partially caused by the damping of obliquely propagating kinetic Alfvén waves and partly by cyclotron damping of ion cyclotron waves. The results of this analysis also have been discussed in Zimbardo et al. (2008).

The power spectral indices for the double power law have been confirmed by Wang et al. (2014) in the study of the magnetic field turbulence with small inter-spacecraft separation up to 127 km in the exterior cusp under northward IMF. The analyzed power spectra had a double slope with a scaling coefficient of −1.7 below the proton cyclotron frequency, resembling a classical Kolmogorov power law, the break point near the cyclotron frequency, and then steeper power law with the scaling coefficient of (−2.8 to −2.0) up tp 10 Hz. The analysis of the fluctuations, including mode identification via k-filtering technique, showed that the observed fluctuations corresponded to the kinetic Alfvén waves propagating quasi-perpendicular to the background magnetic field waves. It was proposed that most possibly the kinetic Alfvén waves were produced via resonance mode conversion and these waves were identified as the most possible origin of turbulence.

Echim et al. (2007) investigated the statistical properties of magnetic field fluctuations in the cusp and surrounding regions at different scales in order to understand the physics of the cascade of energy transfer in the high-altitude cusp, and at the places below (magnetospheric lobes) and above (magnetosheath), concentrating on the intermittency of magnetic field fluctuations. The authors defined intermittency to be related to a sudden occurrence, in space or time, of large amplitude variations of plasma variables, including magnetic field intensity. It was noted that in the energy turbulent cascade intermittency occurs when the coherent turbulent structures are not space-filling at all scales or when the energy transfer rate between scales is not constant but varies intermittently. The analysis showed that at lower altitudes the magnetosphere is in a non-intermittent turbulent state and the fluctuations are random. Inside the high-altitude cusp, closer to the interface with the magnetopause and magnetosheath, there is a clear intermittent behavior at scales smaller than around 60 s (or 170 km). The wavelet analysis (Figure 16) enabled the identification of the events that produce sudden variations in the magnetic field and of the scales that have the most power, and it can be seen that events for scales below 65 s are non-uniformly distributed through the cusp and that intermittency is absent for the scales greater than that time. It was suggested that the turbulent cusp can be considered as a transition from an intermittent turbulent state of the magnetosheath to a non-intermittent turbulent state of the magnetosphere and that cusp turbulence can be caused by non-linear interactions of plasma coherent structures.

9. Summary

Better understanding the cusp was one of the objectives of the Cluster mission and the fact is, Cluster has been quite successful in exploring the physics at play in that region of the magnetosphere, unveiling the coupling processes between the solar wind/IMF and the geomagnetic field. Its numerous achievements were reached by two peculiarities of the mission: its multipoint nature and its comprehensive instrumentation. To the credit of its 3D capability, we can cite the latitudinal dynamics of the cusp, the transition phase following an IMF rotation, and the evidence that double or multiple cusp crossings could arise from either the motion of the whole structure (temporal effect) or by several sources of magnetosheath plasma (spatial effect, namely double cusp). The Cluster cusp measurements were often used to deduce large-scale reconnection geometry at the magnetopause, and its temporal and spatial variations. With its instrumentation and multi-point measurements, Cluster has allowed to characterize the exterior cusp, its magnetic geometry and interface with the magnetosheath, to study energetic particles inside the cusp and their possible sources, to characterize wave modes and wave characteristics, to investigate the on-going particle-wave interactions, as well as to study the turbulence inside the cusp.

What Cluster did not allow for though, is to probe the full longitudinal extend and dynamics of the cusp. To do so, the spacecraft should have been placed in more or less parallel orbits so that they fly at the same latitude but at different longitude or local times, like the Swarm A and C spacecraft (Friis-Christensen
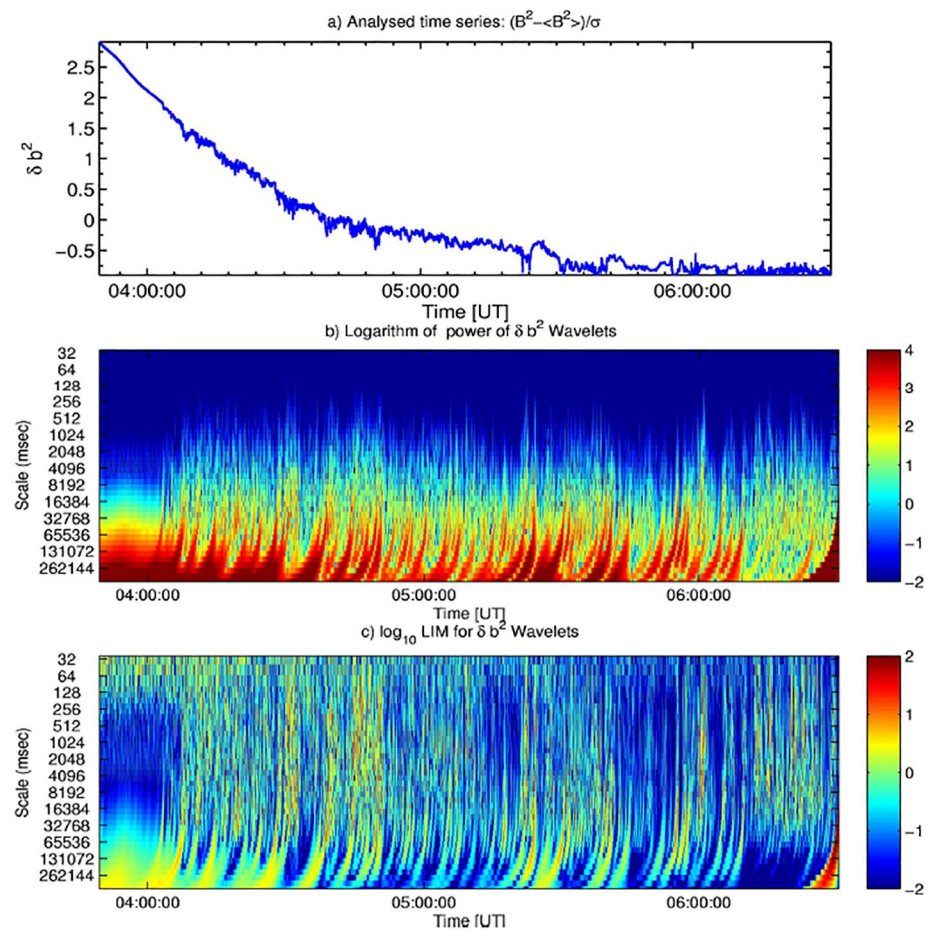
Figure 16. Haar wavelet analysis of B^2 fluctuations: (a) the analyzed time series; (b) logarithm of the power of δb^2 wavelets; (c) the local intermittency measure. One can see change in power at around 04:00 UT and 06:10 UT, when Cluster was exiting lobes to the cusp and cusp to the magnetosheath respectively. See Echim et al. (2007) for more details.

et al., 2008), but with a total separation in local time of order of 3 h or more. This could serve as an inspiration for future magnetospheric mission.

Data Availability Statement

All Cluster data used in the cited papers and reproduced figures are available through the Science Cluster Archive at https://csa.esac.esa.int/csa-web/. Lengths to reconnection site shown in Figure 9 are from Trattner et al., 2005.

References

Adamson, E., & Nykyri, K. (2011). 3-D mesoscale MHD simulations of a cusp-like magnetic configuration: Method and first results. *Annals of Geophysics*, *29*, 759–770. https://doi.org/10.5194/angeo-29-759-2011

Agarwal, P., Varma, P., & Tiwari, M. S. (2011a). Effects of density, temperature and velocity gradients on inertial Alfvén wave in cusp region. *Planetary and Space Science*, *59*(13), 1516–1523. https://doi.org/10.1016/j.pss.2011.06.016

Agarwal, P., Varma, P., & Tiwari, M. S. (2011b). Study of inertial kinetic Alfvén waves around cusp region. *Planetary and Space Science*, *59*(4), 306–311. https://doi.org/10.1016/j.pss.2010.11.006

Anderson, K. A., & Ness, N. F. (1966). Correlation of magnetic fields and energetic electrons on the IMP 1 satellite. *Journal of Geophysical Research*, *71*(15), 3705–3727. https://doi.org/10.1029/JZ071i015p03705

André, M. (1997). Waves and wave-particle interactions in the auroral region. *Journal of Atmospheric and Terrestrial Physics*, *59*, 1687–1712. https://doi.org/10.1016/S1364-6826(96)00173-3

André, M., Norqvist, P., Andersson, L., Eliasson, L., Eriksson, A. I., Blomberg, L., et al. (1998). Ion energization mechanisms at 1700 km in the auroral region. *Journal of Geophysical Research*, *103*(A3), 4199–4222. https://doi.org/10.1029/97JA00855

André, M., Temerin, M., & Gorney, D. (1986). Resonant generation of ion waves on auroral field lines by positive slopes in ion velocity space. *Journal of Geophysical Research*, *91*, 3145–3151. https://doi.org/10.1029/JA091iA03p03145

Asikainen, T. (2010). *Energetic particles in the cusp: A Cluster/RAPID view*. In H. Laakso, M. Taylor, & C. Escoubet (Eds.), The cluster active archive. Astrophysics and space science proceedings. Springer. https://doi.org/10.1007/978-90-481-3499-1_29

Asikainen, T., & Mursula, K. (2005). Energetic particle fluxes in the exterior cusp and he high- latitude dayside magnetosphere: Statistical results from the Cluster/RAPID instrument. *Annals of Geophysics*, *23*, 2217–2230. https://doi.org/10.5194/angeo-23-2217-2005

Asikainen, T., & Mursula, K. (2006). Reconnection and energetic particles at the edge of the exterior cusp. *Annals of Geophysics*, *24*, 1949–1956. https://doi.org/10.5194/angeo-24-1949-2006

Balan, N., Alleyne, H., Walker, S., Reme, H., Lucek, E., Cornilleau-Wehrlin, N., et al. (2007). Response of the magnetosheath-cusp region to a coronal mass ejection. *Journal of Geophysical Research*, *112*, A12211. https://doi.org/10.1029/2006ja012122

Balogh, A., Carr, C. M., Acuña, M. H., Dunlop, M. W., Beek, T. J., Brown, P., et al. (2001). The Cluster Magnetic Field Investigation: Overview of in-flight performance and initial results. *Annals of Geophysics*, *19*, 1207–1217. https://doi.org/10.5194/angeo-19-1207-2001

Balogh, A., Dunlop, M. W., Cowley, S. W. H., Southwood, D.J., Thomlinson, J. G., Glassmeier, K. H., et al. (1997). The cluster magnetic field investigation. *Space Science Reviews*, *79*, 65–91. https://doi.org/10.1023/A:1004970907748

Berchem, J., Richard, R., Escoubet, P., Wing, S., & Pitout, F. (2014). Dawn-dusk asymmetry in solar wind ion entry and dayside precipitation: Results from large-scale simulations. *Journal of Geophysical Research: Space Physics*, *119*, 1549–1562. https://doi.org/10.1002/2013JA019427

Berchem, J., Richard, R. L., Escoubet, C. P., Wing, S., & Pitout, F. (2016). Asymmetrical response of dayside ion precipitation to a large rotation of the IMF. *Journal of Geophysical Research: Space Physics*, *121*, 263–273. https://doi.org/10.1002/2015JA021969

Bingham, R., Kellett, B. J., Cairns, R. A., Dendy, R. O., & Shukla, P. K. (1999). Wave generation by ion horseshoe distributions on auroral field lines. *Geophysical Research Letters*, *26*, 2713–2716. https://doi.org/10.1029/1999GL900582

Blecki, J., Wronowski, R., Savin, S., Cornilleau-Wehrlin, N., Parrot, M., Nemecek, Z., et al (2005). Low frequency plasma waves in the outer polar CUSP – A review of observations from prognoz 8, magion 4, interball 1 and cluster satellites. *Surveys in Geophysics*, *26*(1–3), 177–191. https://doi.org/10.1007/s10712-005-1876-2

Boakes, P. D., Nakamura, R., Volwerk, M., & Milan, S. E. (2014). ECLAT cluster spacecraft magnetotail plasma region identifications (2001–2009). *Dataset Papers in Science*. https://doi.org/10.1155/2014/684305

Bogdanova, Y. V., Fazakerley, A. N., Owen, C. J., Klecker, B., Cornilleau-Wehrlin, N., Grison, B., et al. (2004). Correlation between suprathermal electron bursts, BBELF waves and local ion heating in the mid-altitude cleft/LLBL observed by Cluster. *Journal of Geophysical Research*, *109*(A12). https://doi.org/10.1029/2004JA010554

Bogdanova, Y. V., Klecker, B., Paschmann, G., Kistler, L. M., Mouikis, C., Moebius, E., et al. (2004). Investigation of the source region of ionospheric oxygen outflow in the cleft/cusp using multi-spacecraft observations by CIS onboard Cluster. *Advances in Space Research*, *34*(11), 2459–2464. https://doi.org/10.1016/j.asr.2004.02.014

Bogdanova, Y. V., Owen, C. J., Dunlop, M. W., Frey, H. U., Wild, J. A., Fazakerley, A. N., et al. (2005). On the formation of the high-altitude stagnant cusp: Cluster observations. *Geophysical Research Letters*, *32*, L12101. https://doi.org/10.1029/2005gl022813

Bogdanova, Y. V., Owen, C. J., Dunlop, M. W., Wild, J. A., Davies, J. A., Lahiff, A. D., et al. (2008). Formation of the low-latitude boundary layer and cusp under the northward IMF: Simultaneous observations by cluster and double star. *Journal of Geophysical Research*, *113*, A07S07. https://doi.org/10.1029/2007ja012762

Bogdanova, Y. V., Owen, C. J., Fazakerley, A. N., Klecker, B., & Rème, H. (2006). Statistical study of the location and size of the electron edge of the low-latitude boundary layer as observed by cluster at mid-altitudes. *Annals of Geophysics*, *24*, 2645–2665. https://doi.org/10.5194/angeo-24-2645-2006

Bogdanova, Y. V., Owen, C. J., Siscoe, G., Fazakerley, A. N., Dandouras, I., Marghitu, O., et al. (2007a). Cluster observations of the magnetospheric low-latitude boundary layer and cusp during extreme solar wind and interplanetary magnetic field conditions: I. 10 November 2004 ICME. *Solar Physics*, *244*, 201–232. https://doi.org/10.1007/s11207-007-0417-1

Bogdanova, Y. V., Owen, C. J., Siscoe, G., Fazakerley, A. N., Dandouras, I., Marghitu, O., et al. (2007b). Cluster observations of the magnetospheric low-latitude boundary layer and cusp during extreme solar wind and interplanetary magnetic field conditions: II. 7 November 2004 ICME and statistical survey. *Solar Physics*, *244*, 233–261. https://doi.org/10.1007/s11207-007-0418-0

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

Bosqued, J. M., Escoubet, C. P., Frey, H. U., Dunlop, M. W., Berchem, J., Marchaudon, A., et al. (2005). Multipoint observations of transient reconnection signatures in the cusp precipitation: A Cluster-IMAGE detailed case study. *Journal of Geophysical Research*, *110*, A03219. https://doi.org/10.1029/2004ja010621

Bouhram, M., Klecker, B., Miyake, W., Rème, H., Sauvaud, J.-A., Malingre, M., et al. (2004). On the altitude dependence of transversely heated O+ distributions in the cusp/cleft. *Annals of Geophysics*, *22*, 1787–1798. https://doi.org/10.5194/angeo-22-1787-2004

Bouhram, M., Malingre, M., Jasperse, J. R., Dubouloz, N., & Sauvaud, J.-A. (2003). Modeling transverse heating and outflow of ionospheric ions from the dayside cusp/cleft. 2 Applications. *Annals of Geophysics*, *21*, 1773–1791. https://doi.org/10.5194/angeo-21-1773-2003

Burch, J. L. (1972). Precipitation of low-energy electrons at high latitudes: Effects of interplanetary magnetic field and dipole tilt angle. *Journal of Geophysical Research*, *77*(34), 6696–6707. https://doi.org/10.1029/ja077i034p06696

Burch, J. L., Menietti, J. D., & Barfield, J. N. (1986). DE-1 observations of solar wind/magnetosphere coupling processes in the polar cusp. In Y. Kamide, J. A. Slavin, & Publisher (Eds.), *Solar wind-magnetosphere coupling* (p. 441). Terra Scientific Publishing Company. https://doi.org/10.1007/978-90-277-2303-1_32

Cai, H. T., McCrea, I. W., Dunlop, M. W., Davies, J. A., Bogdanova, Y. V., Pitout, F., et al. (2009). Cusp observations during a sequence of fast IMF B_z reversals. *Annals of Geophysics*, *27*, 2721–2737. https://doi.org/10.5194/angeo-27-2721-2009

Cargill, P. J., Dunlop, M. W., Balogh, A., & FGM Team. (2001). First Cluster results of the magnetic field structure of the mid- and high-altitude cusps. *Annals of Geophysics*, *19*, 1533–1543. https://doi.org/10.5194/angeo-19-1533-2001

Cargill, P. J., Dunlop, M. W., Lavraud, B., Elphic, R. C., Holland, D. L., Nykyri, K., et al. (2004). CLUSTER encounters with the high altitude cusp: Boundary structure and magnetic field depletions. *Annals of Geophysics*, *22*, 1739–1754. https://doi.org/10.5194/angeo-22-1739-2004

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*, 321–366. https://doi.org/10.1007/s11214-005-3835-0

Cattell, C., Johnson, L., Bergmann, D., Klumpar, D., Carlson, C., McFadden, J., et al. (2002). FAST observations of discrete electrostatic waves in association with down-going ion beams in the auroral zone. *Journal of Geophysical Research*, *107*(A9), 12–1–12–7, https://doi.org/10.1029/2001JA000254

Cerisier, J. -C., Marchaudon, A., Bosqued, J. -M., McWilliams, K., Frey, H. U., Bouhram, M., et al. (2005). Ionospheric signatures of plasma injections in the cusp triggered by solar wind pressure pulses. *Journal of Geophysical Research*, *110*, A08204. https://doi.org/10.1029/2004JA010962

Chang, S. W., Scudder, D., Fuselier, S. A., Fennell, J. F., Trattner, K. J., Pickett, J. S., et al. (1998). Cusp energetic ions: A bow shock source. *Geophysical Research Letters*, *6*, 531–534. https://doi.org/10.1029/98GL52808

Chang, T., Crew, G. B., Hershkowitz, N., Jasperse, J. R., Retterer, J. M., & Winningham, J. D. (1986). Transverse acceleration of oxygen ions by electromagnetic ion cyclotron resonance with broad band left-hand polarized waves. *Geophysical Research Letters*, *13*, 636–639. https://doi.org/10.1029/GL013i007p00636

Chapman, S., & Ferraro, V. C. A. (1931). A new theory of magnetic storms. *Terrestrial Magnetism and Atmospheric Electricity*, *36*(3), 171–186. https://doi.org/10.1029/TE036i003p00171

Chaston, C. C., Peticolas, L. M., Carlson, C. W., McFadden, J. P., Mozer, F., Wilber, M., et al. (2005). Energy deposition by Alfvèn waves into the dayside auroral oval: Cluster and FAST observations. *Journal of Geophysical Research*, *110*(A2), A02211. https://doi.org/10.1029/2004JA010483

Chen, J. (2008). Evidence for particle acceleration in the magnetospheric cusp. *Annals of Geophysics*, *26*, 1993–1997. https://doi.org/10.5194/angeo-26-1993-2008

Chen, J., Fritz, T. A., Sheldon, R. B., Spence, H. E., Spjeldvik, W. N., Fennell, J. F., et al. (1998). Cusp energetic particle events: Implications for a major acceleration region of the magnetosphere. *Journal of Geophysical Research*, *103*, 67078. https://doi.org/10.1029/97JA02246?

Chen, J., & Fritz, T. A. (2005). High-altitude cusp: The extremely dynamic region in geospace. *Surveys in Geophysics*, *26*, 71–93. https://doi.org/10.1007/s10712-005-1873-5

Chen, S.-H., Boardsen, S. A., Fung, S. F., Green, J. L., Kessel, R. L., Tan, L. C., et al. (1997). Exterior and interior polar cusps: Observations from Hawkeye. *Journal of Geophysical Research*, *102*(A6), 11335–11347. https://doi.org/10.1029/97JA00743

Connor, H. J., Raeder, J., & Trattner, K. J. (2012). Dynamic modeling of cusp ion structures. *Journal of Geophysical Research*, *117*, A04203. https://doi.org/10.1029/2011JA017203

Cornilleau-Wehrlin, N., Chanteur, G., Perraut, S., Rezeau, L., Robert, P., Roux, A., et al (2003). First results obtained by the Cluster STAFF experiment. *Annals of Geophysics*, *21*, 437–456. https://doi.org/10.5194/angeo-21-437-2003

Cowley, S. W. H., & Lockwood, M. (1992). Excitation and decay of solar wind-driven flows in the magnetosphere-ionosphere system. *Annals of Geophysics*, *10*, 103–115.

Crooker, N. U. (1979). Dayside merging and cusp geometry. *Journal of Geophysical Research*, *84*(A3), 951–959. https://doi.org/10.1029/JA084iA03p00951

Dandouras, I. (2021). Ion outflow and escape in the Terrestrial Magnetosphere: Cluster Advances. *Journal of Geophysical Research: Space Physics.*[preprint].

D'Angelo, N. (1977). Plasma waves and instabilities at the polar cusp: A review. *Reviews of Geophysics*, *15*, 299–307. https://doi.org/10.1029/RG015i003p00299

Décréau, P. M. E., Fergeau, P., Krannosels'kikh, V., Leveque, M., Martin, Ph., Randriamboarsion, O., et al. (1997). Whisper, a resonance sounder and wave analyser: Performances and perspectives for the Cluster mission. *Space Science Reviews*, *79*, 157–193. https://doi.org/10.1023/A:1004931326404

Delcourt, D. C., & Sauvaud, J. A. (1998). Recirculation of plasma sheet particles into the high-latitude boundary layer. *Journal of Geophysical Research*, *103*, 26521. https://doi.org/10.1029/98JA02392

Delcourt, D. C., & Sauvaud, J. A. (1999). Populating cusp and boundary layers by energetic (hundreds of keV) equatorial particles. *Journal of Geophysical Research*, *104*, 22635–22648. https://doi.org/10.1029/1999JA900251

Duan, S.-P., Liu, Z.-X., Cao, J.-B., Shi, J.-K., Lu, L., Li, Z.-Y., et al. (2006). Analysis of the interaction between low-frequency waves and ions in the high-altitude cusp region observed by satellite cluster. *Chinese Physics Letters*, *23*, 1351–1354. https://doi.org/10.1088/0256-307X/23/5/079

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

Dungey, J. W. (1965). Null points in space plasma. In *Proceedings of the plasma space science symposium* (pp. 160–169). Springer. https://doi.org/10.1007/978-94-011-7542-5_12

Dunlop, M. W., Balogh, A., Glassmeier, K.-H., & Robert, P. (2002). Four-point Cluster application of magnetic field analysis tools: The Curlometer. *Journal of Geophysical Research*, *107*(A11), 1384. https://doi.org/10.1029/2001JA005088

Dunlop, M. W., Cargill, P. J., Stubbs, T. J., & Wooliams, P. (2000). The high-altitude cusps: HEOS-2. *Journal of Geophysical Research*, *105*(A12), 27509–27517. https://doi.org/10.1029/2000JA900084

Dunlop, M. W., Lavraud, B., Cargill, P., Taylor, M. G. G. T., Balogh, A., Reme, H., et al. (2005). Cluster observations of the cusp: Magnetic structure and dynamics surveys in geophysis. *Surveys in Geophysics*, *26*, 5–55. https://doi.org/10.1007/s10712-005-1871-7

Eastman, T. E., Boardsen, S. A., Chen, S.-H., & Fung, S. F. (2000). Configuration of high-latitude and high-altitude boundary layers. *Journal of Geophysical Research*, *105*(A10), 23221–23238. https://doi.org/10.1029/1999JA900269

Echim, M. M., Lamy, H., & Chang, T. (2007). Multi-point observations of intermittency in the cusp regions. *Nonlinear Processes in Geophysics*, *14*, 525–534. https://doi.org/10.5194/npg-14-525-2007

Engebretson, M. J., Kahlstorf, C. R. G., Murr, D. L., Posch, J. L., Keiling, A., Lavraud, B., et al. (2012). Cluster observations of band-limited Pc 1 waves associated with streaming H+ and O+ ions in the high-altitude plasma mantle. *Journal of Geophysical Research*, *117*, A10219. https://doi.org/10.1029/2012JA017982

Escoubet, C. P., & Bosqued, J. M. (1989). The influence of IMF-Bz and/or AE on the polar cusp: An overview of observations from the Aureol-3 satellite, *Planetary Space Science*, *37*, 609–626. https://doi.org/10.1016/0032-0633(89)90100-1

Escoubet, C. P., Fehringer, M., & Goldstein, M. (2001). The Cluster mission. *Annals of Geophysics*, *19*, 1197–1200. https://doi.org/10.5194/angeo-19-1197-2001

Escoubet, C. P., Bosqued, J. M., Berchem, J. M., Trattner, K. J., Taylor, M. G. G. T., Pitout, F., et al. (2006). Temporal evolution of a staircase ion signature observed by Cluster in the mid-altitude polar cusp. *Geophysical Research Letters*, *33*, L07108. https://doi.org/10.1029/2005GL025598

Escoubet, C. P., Berchem, J. M., Bosqued, J. M., Trattner, K. J., Taylor, M. G. G. T., Pitout, F., et al. (2007). Two sources of magnetosheath ions observed by Cluster in the mid-altitude polar cusp. *Advances in Space Research*, *41*, 1528–1536 https://doi.org/10.1016/j.asr.2007.04.031

Escoubet, C. P., Berchem, J. M., Bosqued, J. M., Trattner, K. J., Taylor, M. G. G. T., Pitout, F., et al. (2008). Effect of a northward turning of the interplanetary magnetic field on cusp precipitation as observed by Cluster. *Journal of Geophysical Research*, *113*, A07S13. https://doi.org/10.1029/2007JA012771

Escoubet, C. P., Berchem, J. M., Trattner, K. J., Pitout, F., Richard, R., Taylor, M. G. G. T., et al. (2013). Double cusp encounter by Cluster: Double cusp or motion of the cusp? *Annals of Geophysics*, *31*, 713–723. https://doi.org/10.5194/angeo-31-713-2013

Farrugia, C. J., Lund, E., Sandholt, P. E., Wild, J. A., Cowley, S. W. H., Balogh, A., et al. (2004). Pulsed flows at the high-altitude cusp poleward boundary, and associated ionospheric convection and particle signatures, during a Cluster - FAST - SuperDARN - Søndrestrøm conjunction under a southwest IMF. *Annals of Geophysics*, *22*, 2891–2905. https://doi.org/10.5194/angeo-22-2891-2004

Fear, R. C., Fazakerley, A. N., Owen, C. J., Lahiff, A. D., Lucek, E. A., Balogh, A., et al. (2005). Cluster observations of boundary layer structure and a flux transfer event near the cusp. *Annals of Geophysics*, *23*, 2605–2620. https://doi.org/10.5194/angeo-23-2605-2005

Forslund, D. W., Kindel, J. M., & Stroscio, M. A. (1979). Current driven electromagnetic ion cyclotron instability. *Journal of Plasma Physics*, *21*, 127–139. https://doi.org/10.1017/S0022377800021693

Förster, M., & Haaland, S. (2015). Interhemispheric differences in ionospheric convection: Cluster EDI observations revisited. *Journal of Geophysical Research: Space Physics*, *120*. https://doi.org/10.1002/2014JA020774

Frank, L. A. (1971). Plasmas in the Earth's polar magnetosphere. *Journal of Geophysical Research*, *76*, 5202. https://doi.org/10.1029/JA076i022p05202

Frey, H. U., Mende, S. B., Immel, T. J., Fuselier, S. A., Claflin, E. S., Gerard, J.-C., & Hubert, B. (2002). Proton aurora in the cusp. *Journal of Geophysical Research*, *107*(A7), SMP2-1–SMP2-17. https://doi.org/10.1029/2001JA900161

Frey, H. U., Mende, S. B., Immel, T. J., Fuselier, S. A., Claflin, E. S., Gerard, J.-C., et al. (2019). Dayside Aurora. *Space Science Reviews*, *215*, 51. https://doi.org/10.1007/s11214-019-0617-7

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

Friis-Christensen, E., Lühr, H., Knudsen, D., & Haagmans, R. (2008). Swarm – An Earth Observation Mission investigating Geospace. *Advances in Space Research*, *41*, 210–216. https://doi.org/10.1016/j.asr.2006.10.008

Fritz, T. A. (2001). The cusp as a source of magnetospheric energetic particles, currents, and electric fields: A new paradigm. *Space Science Reviews*, *95*, 469–488. https://doi.org/10.1023/A:1005286908441

Fritz, T. A. (2010). Perspectives gained from a combination of polar, Cluster and ISEE energetic particle measurements in the dayside cusp. In H. Laakso, M. Taylor, & C. Escoubet (Eds.), *The cluster Active archive. Astrophysics and space science proceedings*. Springer. https://doi.org/10.1007/978-90-481-3499-1_28

Fritz, T. A. and S. F. Fung, (2005), *The magnetospheric cusps: Structure and dynamics*, Springer, https://doi.org/10.1007/1-4020-3605-1

Fritz, T. A., Walsh, B. M., Klida, M., & Chen, J. (2012). The cusp as a source of magnetospheric particles. *Journal of Atmospheric and Solar-Terrestrial Physics*, *87–88*, 39–46. https://doi.org/10.1016/j.jastp.2011.10.016

Fu, S. Y., Zong, Q. G., Pu, Z. P., Xiao, C. J., Korth, A., Daly, P., & Reme, H. (2005). Energetic particles observed in the Cusp region during a Storm recovery Phase. *Surveys in Geophysics*, *26*, 241–254. https://doi.org/10.1007/s10712-005-1881-5

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

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*, 8275–8291. https://doi.org/10.1029/2018JA025435

Génot, V., Beigbeder, L., Popescu, D., Dufourg, N., Gangloff, M., Bouchemit, M., et al. (2018). Science data visualization in planetary and heliospheric contexts with 3D view. *Planetary and Space Science*, *150*, 111–130. https://doi.org/10.1016/j.pss.2017.09.007

Gosling, J. T., Thomsen, M. F., Bame, S. J., Onsager, T. G., & Russell, C. T. (1990). The electron edge of the low latitude boundary layer during accelerated flow events. *Geophysical Research Letters*, *17*, 1833–1836. https://doi.org/10.1029/GL017i011p01833

Grandin, M., Turc, L., Battarbee, M., Ganse, U., Johlander, A., Pfau-Kempf, Y., et al. (2020). Hybrid-Vlasov simulation of auroral proton precipitation in the cusps: Comparison of northward and southward interplanetary magnetic field driving. *Journal of Space Weather Space Climate*, *10*, 51. https://doi.org/10.1051/swsc/2020053

Grison, B., Escoubet, C. P., Santolík, O., Cornilleau-Wehrlin, N., & Khotyaintsev, Y. (2014). Wave number determination of Pc 1–2 mantle waves considering He^{++} ions: A Cluster study. *Journal of Geophysical Research: Space Physics*, *119*. https://doi.org/10.1002/2013JA019719

Grison, B., Sahraoui, F., Lavraud, B., Chust, T., Cornilleau-Wehrlin, N., Reme, H., et al. (2005). Wave particle interactions in the high-altitude cusp: A Cluster study. *Annals of Geophysics*, *23*, 3699–3713. https://doi.org/10.5194/angeo-23-3699-2005

Gurnett, D. A., Huff, R. L., & Kirchner, D. L. (1997). The wide-band plasma wave investigation. *Space Science Reviews*, *79*, 195–208. https://doi.org/10.1023/A:1004966823678

Gustafsson, G., André, M., Carozzi, T., Eriksson, A. I., Fälthammar, C. -G., Grard, R., et al. (2001). First results of electric field and density observations by Cluster EFW based on initial months of operation. *Annals of Geophysics*, *19*, 1219–1240. https://doi.org/10.5194/angeo-19-1219-2001

Haerendel, G. (1978). Microscopic plasma processes related to reconnection. *Journal of Atmospheric and Terrestrial Physics*, *40*, 343–353. https://doi.org/10.1016/0021-9169(78)90051-X

Haerendel, G., Paschmann, G., Sckopke, N., Rosenbauer, H., & Hedgecock, P. C. (1978). The frontside boundary layer of the magnetopause and the problem of reconnection. *Journal of Geophysical Research*, *83*, 3195–3216. https://doi.org/10.1029/JA083iA07p03195

Hansen, A. M., Bahnsen, A., & D'Angelo, N. (1976). The cusp-magnetosheath interface. *Journal of Geophysical Research*, *81*(4), 556–561. https://doi.org/10.1029/JA081i004p00556

Harten, R., & Clark, K. (1995). The design features of the GGS Wind and Polar spacecraft. *Space Science Reviews*, *71*, 23. https://doi.org/10.1007/BF00751324

Hasegawa, H., Retinò, A., Vaivads, A., Khotyaintsev, Y., Nakamura, R., Takada, T., et al. (2008). Retreat and reformation of X-line during quasi-continuous tailward-of-the-cusp reconnection under northward IMF. *Geophysical Research Letters*, *35*, L15104. https://doi.org/10.1029/2008GL034767

Heikkila, W. J., & Winningham, J. D. (1971). Penetration of magnetosheath plasma to low altitudes through the dayside magnetospheric cusps. *Journal of Geophysical Research*, *76*(4), 883–891. https://doi.org/10.1029/JA076i004p00883

Hu, R., Bogdanova, Y. V., Owen, C. J., Foullon, C., Fazakerley, A. N., & Rème, H. (2008). Cluster observations of the midaltitude cusp under strong northward interplanetary magnetic field. *Journal of Geophysical Research*, *113*, A07S05. https://doi.org/10.1029/2007JA012726

Jacobsen, K. S., & Moen, J. I. (2010). On the correlation between Broad-Band ELF wave power and ion fluxes in the cusp. *Annals of Geophysics*, *28*, 1249–1261. https://doi.org/10.5194/angeo-28-1249-2010

Janhunen, P., Olsson, A., Vaivads, A., & Peterson, W. K. (2003). Generation of Bernstein waves by ion shell distributions in the auroral region. *Annals of Geophysics*, *21*, 881–891. https://doi.org/10.5194/angeo-21-881-2003

Johnstone, A. D., Alsop, C., Burge, S., Carter, P. J., Coates, A. J., Coker, A. J., et al. (1997). PEACE: A plasma electron and current experiment. *Space Science Reviews*, *79*, 351. https://doi.org/10.1023/A:1004938001388

Kawashema, N., & Fukushima, N. (1964). Model experiment for the interaction of solar plasma stream and geomagnetic field. *Planetary and Space Science*, *12*(12), 1187–1201. https://doi.org/10.1016/0032-0633(64)90165-5

Keith, W. R., Winningham, J. D., Goldstein, M. L., Wilber, M., Rème, H., Fritz, T. A., et al. (2005). Observations of a unique cusp signature at low and mid altitudes. *Surveys in Geophysics*, *26*(1–3), 307–339. https://doi.org/10.1007/s10712-005-1885-1

Keith, W. R., & Stubbs, T. J. (2008). Identification of spacecraft conjunctions in the cusp. *Advances in Space Research*, *41*(10), 1562–1570. https://doi.org/10.1016/j.asr.2007.09.030

Khotyaintsev, Y., Vaivads, A., Ogawa, Y., Popielawska, B., André, M., Buchert, S., et al. (2004). Cluster observations of high-frequency waves in the exterior cusp. *Annals of Geophysics*, *22*, 2403–2411. https://doi.org/10.5194/angeo-22-2403-2004

Kivelson, M. G., Russell, C. T., Neugebauer, M., Scarf, F. L., & Fredricks, R. W. (1973). Dependence of the polar cusp on the north-south component of the interplanetary magnetic field. *Journal of Geophysical Research*, *78*(19), 3761–3772. https://doi.org/10.1029/JA078i019p03761

Korth, A., Echer, E., Zong, Q.-G., Guarnieri, F. L., Fraenz, M., & Mouikis, C. G. (2011). The response of the polar cusp to a high-speed solar wind stream studied by a multispacecraft wavelet analysis. *Journal of Atmospheric and Solar-Terrestrial Physics*, *73*(1), 52–60. https://doi.org/10.1016/j.jastp.2009.10.004

Lakhina, G. S. (1990). Generation of ULF waves in the polar cusp region by velocity shear-driven kinetic Alfvén modes. *Astrophysics and Space Science*, *165*, 153–161. https://doi.org/10.1007/BF00653667

Lavraud, B., & Cargill, P. J. (2005). Cluster reveals the magnetospheric cusps. *Astronomy and Geophysics*, *46*, 1–321.35. https://doi.org/10.1046/j.1468-4004.2003.46132

Lavraud, B., Dunlop, M. W., Phan, T. D., Rème, H., Bosqued, J.-M., Dandouras, I., et al. (2002). Cluster observations of the exterior cusp and its surrounding boundaries under northward IMF. *Geophysical Research Letters*, *29*(20), 1995. https://doi.org/10.1029/2002GL015464

Lavraud, B., Dunlop, M. W., Phan, T. D., Rème, H., Bosqued, J.-M., Dandouras, I., et al. (2005). Cluster observes the high-altitude cusp region. *Surveys in Geophysics*, *26*(1–3), 135–174. https://doi.org/10.1007/s10712-005-1875-3

Lavraud, B., Fedorov, A., Budnik, E., Grigoriev, A., Cargill, P. J., Dunlop, M. W., et al. (2004). Cluster survey of the high-altitude cusp properties: A three-year statistical study. *Annals of Geophysics*, *22*(8), 3009–3019. https://doi.org/10.5194/angeo-22-3009-2004

Lavraud, B., Fedorov, A., Budnik, E., Thomsen, M. F., Grigoriev, A., Cargill, P. J., et al. (2005). High-altitude cusp flow dependence on IMF orientation: A 3-year Cluster statistical study. *Journal of Geophysical Research*, *110*, A02209. https://doi.org/10.1029/2004JA010804

Lavraud, B., Phan, T. D., Dunlop, M. W., Taylor, M. G. G. T., Cargill, P. J., Bosque, J.-M., et al. (2004). The exterior cusp and its boundary with the magnetosheath: Cluster multi-event analysis. *Annals of Geophysics*, *22*, 3039–3054. https://doi.org/10.5194/angeo-22-3039-2004

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*, *111*, A05211. https://doi.org/10.1029/2005JA011266

Le, G., Blanco-Cano, X., Russell, C. T., Zhou, X.-W., Mozer, F., Trattner, K. J., et al. (2001). Electromagnetic ion cyclotron waves in the high altitude cusp: Polar observations. *Journal of Geophysical Research*, *106*, 19067–19079. https://doi.org/10.1029/2000JA900163

Le, G., Zheng, Y., Russell, C. T., Pfaff, R. F., Slavin, J. A., Lin, N., et al. (2008). Flux transfer events simultaneously observed by Polar and Cluster: Flux rope in the subsolar region and flux tube addition to the polar cusp. *Journal of Geophysical Research*, *113*, A01205. https://doi.org/10.1029/2007JA012377

Levy, R. H., Petscheck, E., & Siscoe, G. L. (1964). Aerodynamic aspects of the magnetospheric flow. *AIAA Journal*, *2*, 2065–2076. https://doi.org/10.2514/3.2745

Lin, C., Burch, J., & Winningham, J. (1986). Near-conjugate observations of polar cusp electron precipitation using DE 1 and DE 2. *Journal of Geophysical Research*, *91*, 11186–11202. https://doi.org/10.1029/ja091ia10p11186

Lin, N., Maksimovic, E. S., Lee, J., Mcfadden, G., Parks, M., Wilber, M., et al. (2006). VLF/ELF wave activity in the vicinity of the polar cusp: Cluster observations. *Annals of Geophysics*, *24*, 1993–2004. https://doi.org/10.5194/angeo-24-1993-2006

Lockwood, M., Denig, W. F., Farmer, A. D., Davda, V. N., Cowley, S. W. H., & Luhr, H. (1993). *Nature*, *361*(6411), 424–427. https://doi.org/10.1038/361424a0

Lockwood, M., Opgenoorth, van, Eyken, A. P., Fazakerley, A., Bosqued, J.-M., Denig, W., et al. (2001). Coordinated Cluster, ground-based instrumentation and low-altitude satellite observations of transient poleward-moving events in the ionosphere and in the tail lobe. *Annals of Geophysics*, *19*, 1589–1612. https://doi.org/10.5194/angeo-19-1589-2001

Marchaudon, A., Cerisier, J.-C., Bosqued, J.-M., Owen, C. J., Fazakerley, A. N., & Lahiff, A. D. (2006). On the structure of field-aligned currents in the mid-altitude cusp. *Annals of Geophysics*, *24*, 3391–3401. https://doi.org/10.5194/angeo-24-3391-2006

Marchaudon, A., Cerisier, J.-C., Dunlop, M. W., Pitout, F., Bosqued, J.-M., & Fazakerley, A. N. (2009). Shape, size, velocity and field-aligned currents of dayside plasma injections: A multi-altitude study. *Annals of Geophysics*, *27*, 1251–1266. https://doi.org/10.5194/angeo-27-1251-2009

Marchaudon, A., Cerisier, J.-C., Bosqued, J.-M., Dunlop, M., Wild, J., Decreau, P., et al. (2004). Transient plasma injections in the dayside magnetosphere: One-to-one correlated observations by Cluster and SuperDARN. *Annals of Geophysics*, *22*, 141–158. https://doi.org/10.5194/angeo-22-141-2004

Matsui, H., Puhl-Quinn, P. A., Torbert, R. B., Baumjohann, W., Farrugia, C. J., Mouikis, C. G., et al. (2007). Cluster observations of broad-band ULF waves near the dayside polar cap boundary: Two detailed multi-instrument event studies. *Journal of Geophysical Research*, *112*(A7), A07218. https://doi.org/10.1029/2007JA012251

Maynard, N. C., Aggson, T. L., Basinska, E. M., Burke, W. J., Craven, P., Peterson, W. K., et al. (1991). Magnetospheric boundary dynamics: DE 1 and DE 2 observations near the magnetopause and cusp. *Journal of Geophysical Research*, *96*(A3), 3505–3522. https://doi.org/10.1029/90JA02167

Maynard, N. C., Ober, D. M., Burke, W. J., Scudder, J. D., Lester, M., Dunlop, M. W., et al. (2003). Polar, Cluster and SuperDARN evidence for high latitude merging during southward IMF: Temporal/spatial evolution. *Annales Geophysicae*, *21*(12), 2233–2258. https://doi.org/10.5194/angeo-21-2233-2003

Mead, G. D. (1964). Deformation of the geomagnetic field by the solar wind. *Journal of Geophysical Research*, *69*(7), 1181–1195. https://doi.org/10.1029/JZ069i007p01181

Mead, G. D. (1967). Neutral points on the boundary of the closed magnetosphere. *Space Science Reviews*, *7*, 158–165. https://doi.org/10.1007/BF00215593

Miyashita, Y., Shinohara, I., Fujimoto, M., Hasegawa, H., Hosokawa, K., Takada, T., & Hori, T., et al. (2011). A powerful tool for browsing quick-look data in solar-terrestrial physics: "Conjunction Event Finder". *Earth Planets and Space*, *63*, e1–e4. https://doi.org/10.5047/eps.2011.01.003

Moen, J., Holtet, J., Pedersen, A., Lybekk, B., Svenes, K., Oksavik, K., et al. (2001). Cluster boundary layer measurements and optical observations at magnetically conjugate sites. *Annals of Geophysics*, *19*, 1655–1668. https://doi.org/10.5194/angeo-19-1655-2001

Měrka, J., Šafránková, J., & Němeček, Z. (2002). Cusp-like plasma in high altitudes: A statistical study of the width and location of the cusp from Magion-4. *Annals of Geophysics*, *20*, 311–320. https://doi.org/10.5194/angeo-20-311-2002

Ness, N. F. (1969). The geomagnetic tail. *Reviews of Geophysics*, *7*, 97–127. https://doi.org/10.1029/rg007i001p00097

Newell, P. T., & Meng, C.-I. (1988a). Hemispherical asymmetry in cusp precipitation near solstices. *Journal of Geophysical Research*, *93*, 2643–2648. https://doi.org/10.1029/JA093iA04p02643

Newell, P. T., & Meng, C.-I. (1988b). The cusp and the cleft/boundary layer: Low-altitude identification and statistical local time variation. *Journal of Geophysical Research*, *93*(14), 549. https://doi.org/10.1029/JA093iA12p14549

Newell, P. T., & Meng, C.-I. (1989). Dipole tilt angle effects on the latitude of the cusp and cleft/low-latitude boundary layer. *Journal of Geophysical Research*, *94*, 6949. https://doi.org/10.1029/JA094iA06p06949

Newell, P. T., & Meng, C.-I. (1994). Ionospheric projections of magnetospheric regions under low and high solar wind conditions. *Journal of Geophysical Research*, *99*, 273–286. https://doi.org/10.1029/93JA02273

Newell, P. T., Meng, C.-I., Sibeck, D., & Lepping, R. (1989). Some low-altitude cusp dependencies on the interplanetary magnetic field. *Journal of Geophysical Research*, *94*, 8921. https://doi.org/10.1029/JA094iA07p08921

Norqvist, P., André, M., & Tyrland, M. (1998). A statistical study of ion energization mechanisms in the auroral region. *Journal of Geophysical Research*, *103*(A10), 23459–23473. https://doi.org/10.1029/98JA02076

Nykyri, K., Cargill, P. J., Lucek, E. A., Horbury, T. S., Balogh, A., Lavraud, B., et al. (2003). Ion cyclotron waves in the high altitude cusp: CLUSTER observations at varying spacecraft separations. *Geophysical Research Letters*, *30*(24). https://doi.org/10.1029/2003GL018594

Nykyri, K., Cargill, P., Lucek, E., Horbury, T., Lavraud, B., Balogh, A., et al. (2004). Cluster observations of magnetic field fluctuations in the high-altitude cusp. *Annals of Geophysics*, *22*, 2413–2429. https://doi.org/10.5194/angeo-22-2413-2004

Nykyri, K., Grison, B., Cargill, P. J., Lavraud, B., Lucek, E., Dandouras, I., et al. (2006). *Origin of the turbulent spectra in the high-altitude cusp: Cluster spacecraft observations* (pp. 1057–1075). https://doi.org/10.5194/angeo-24-1057-2006

Nykyri, K., Otto, A., Adamson, E., Dougal, E., & Mumme, J. (2011). Cluster observations of a cusp diamagnetic cavity: Structure, size, and dynamics. *Journal of Geophysical Research*, *116*, A03228. https://doi.org/10.1029/2010JA015897

Nykyri, K., Otto, A., Adamson, E., Kronberg, E., & Daly, P. (2012). On the origin of high-energy particles in the cusp diamagnetic cavity. *Journal of Atmospheric and Solar-Terrestrial Physics*, *87–88*, 70–81. https://doi.org/10.1016/j.jastp.2011.08.012

Nykyri, K., Otto, A., Adamson, E., & Tjulin, A. (2011). On the origin of fluctuations in the cusp diamagnetic cavity. *Journal of Geophysical Research*, *116*, A06208. https://doi.org/10.1029/2010JA015888

Onishchenko, O. G., Pokhotelov, O. A., Krasnoselskikh, V. V., & Shatalov, S. I. (2009). Drift-Alfvén waves in space plasmas–Theory and mode identification. *Annals of Geophysics*, *27*, 639–644. https://doi.org/10.5194/angeo-27-639-2009

Palmroth, M., Laasko, H., & Pulkkinen, T. I. (2001). Location of high-altitude cusp during steady solar wind conditions. *Journal of Geophysical Research*, *106*, 21109. https://doi.org/10.1029/2001JA900073

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*, *113*, A01220. https://doi.org/10.1029/2006JA012123

Paschmann, G., Quinn, J. M., Torbert, R. B., Vaith, H., McIlwain, C. E., Haerendel, G., et al. (1997). The electron drift instrument for Cluster. *Space Science Reviews*, *79*, 233–269. https://doi.org/10.1023/A:1004917512774

Paschmann, G., Quinn, J. M., Torbert, R. B., Vaith, H., McIlwain, C. E., Haerendel, G., et al. (2001). The electron drift instrument on Cluster: Overview of first results. *Annals of Geophysics*, *19*, 1273–1288. https://doi.org/10.5194/angeo-19-1273-2001

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

Petschek, H. E. (1964). Magnetic field annihilation. In *NASA Symposium on Physics of Solar Flares* (Vol. 50, pp. 425–429). NASA Special Publication.

Pettigrew, E. D., Shepherd, S. G., & Ruohoniemi, J. M. (2010). Climatological patterns of high-latitude convection in the Northern and Southern hemispheres: Dipole tilt dependencies and interhemispheric comparisons. *Journal of Geophysical Research*, *115*(A7). https://doi.org/10.1029/2009JA014956

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). https://doi.org/10.1029/2003GL016885

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

Pickett, J. S., Franz, J. R., Scudder, J. D., Menietti, J. D., Gurnett, D. A., Hospodarsk, G. B., et al. (2001). Plasma waves observed in the cusp turbulent boundary layer: An analysis of high time resolution wave and particle measurements from the Polar spacecraft. *Journal of Geophysical Research*, *106*, 19081–19100. https://doi.org/10.1029/2000JA003012

Pinçon, J. L., & Motschmann, U. (1998). Multispacecraft filtering: General framework. In: *Analysis methods for multi-spacecraft data* (pp. 65–78). International Space Science Institute.

Pitout, F., Bosqued, J.-M., Alcaydé, D., Denig, W. F., & Rème, H. (2001). Observations of the cusp region under northward IMF. *Annals of Geophysics*, *19*, 1641–1653. https://doi.org/10.5194/angeo-19-1641-2001

Pitout, F., Escoubet, C. P., Bogdanova, Y. V., Georgescu, E., Fazakerley, A. N., & Rème, H. (2006). Response of the mid-altitude cusp to rapid rotations of the IMF. *Geophysical Research Letters*, *33*, L11107. https://doi.org/10.1029/2005GL025460

Pitout, F., Escoubet, C. P., Klecker, B., & Dandouras, I. (2009). Cluster survey of the middle altitude cusp: 2. large-scale morphology. *Annals of Geophysics*, *27*, 1875–1886. https://doi.org/10.5194/angeo-27-1875-2009

Pitout, F., Escoubet, C. P., Klecker, B., & Rème, H. (2006). Cluster survey of the middle altitude cusp: 1. size, location, and dynamics. *Annals of Geophysics*, *24*, 3011–3026. https://doi.org/10.5194/angeo-24-3011-2006

Pitout, F., Escoubet, C. P., Taylor, M. G. G. T., Berchem, J., & Walsh, A. P. (2012). Overlapping ion structures in the mid-altitude cusp under northward IMF: Signature of dual lobe reconnection? *Annals of Geophysics*, *30*, 489–501. https://doi.org/10.5194/angeo-30-489-2012

Pitout, F., Marchaudon, A., Trattner, K. J., Berchem, J., Laakso, H., & Escoubet, C. P. (2020). Simultaneous Polar and Cluster observations in the northern and southern middle-altitude polar cusps around equinox. *Journal of Geophysical Research: Space Physics*, *125*, e2020JA028346. https://doi.org/10.1029/2020JA028346

Pitout, F., Newell, P. T., & Buchert, S. C. (2002). Simultaneous high- and low-latitude reconnection: ESR and DMSP observations. *Annals of Geophysics*, *20*, 1311–1320. https://doi.org/10.5194/angeo-20-1311-2002

Pletnev, V. D., Skuridin, G. A., Shalimov, V. P., & Shvachunov, I. N. (1965). Dynamics of a geomagnetic trap and Origin of the Earth's Radiation Belts". *Geomagnetism and Aeronomy*, *5*, 485.

Pokhotelov, O. A., Stenflo, L., & Shukla, P. K. (1996). Nonlinear structures in the Earth's magnetosphere and atmosphere. *Plasma Physics Reports*, *22*, 852–863. https://doi.org/10.1134/1.952350

Reiff, P. H., Hill, T. W., & Burch, J. L. (1977). Solar wind plasma injection at the dayside magnetospheric cusp. *Journal of Geophysical Research*, *82*(4), 479–491. https://doi.org/10.1029/JA082i004p00479

Rème, Aoustin, C., Bosqued, J. M., Dandouras, I., Lavraud, B., Sauvaud, J. A., et al. (2001). First multispacecraft ion measurements in and near the Earth's magnetosphere with the identical Cluster ion spectrometry (CIS) experiment. *Annals of Geophysics*, *19*, 1303. https://doi.org/10.5194/angeo-19-1303-2001

Rodriguez-Canabal, J., Warhaut, M., Schmidt, R., & Bello-Mora, M. (1993). *The Cluster orbit and mission scenario, ESA SP-1159* (p. 259). Retrieved from https://ui.adsabs.harvard.edu/abs/1993ESASP1159..259R

Romanov, S. A. (2013). Magnetic turbulence in the cusp region: 3D spectra and vortex cascades. *Geomagnetism and Aeronomy*, *53*, 733–740. https://doi.org/10.1134/S0016793213060133

Rönnmark, K. (1982). *WHAMP – waves in Homogeneous, anisotropic multicomponent plasmas* (p. 179). Kiruna Geophysical Institute Report.

Rosenbauer, H., Gruenwaldt, H., Montgomery, M. D., Paschmann, G., & Skopke, N. (1975). HEOS-2 plasma observations in the distant polar magnetosphere: The plasma mantle. *Journal of Geophysical Research*, *80*(19), 2723–2737. https://doi.org/10.1029/JA080i019p02723

Rothkaehl, H., Trotignon, J. -G., Decreau, P., Błecki, J., Pitout, F., & Reme, H. (2009). HF wave activity in the low and middle-altitude polar cusp. *Advances in Space Research*, *43*(6), 948–956. https://doi.org/10.1016/j.asr.2008.07.018

Russell, C. T. (2000a). The polar cusp. *Advances in Space Research*, *25*(7–8), 1413–1424. https://doi.org/10.1016/S0273-1177(99)00653-5

Russell, C. T. (2000b). POLAR eyes the cusp, Proceedings of the Cluster II Workshop: Multiscale/multipoint plasma measurements. *ESA SP-*, *449*, 47.

Russell, C. T., Chappell, C. R., Montgomery, M. D., Neugebauer, M., & Scarf, F. L. (1971). Ogo 5 observations of the polar cusp on November 1, 1968. *Journal of Geophysical Research*, *76*(28), 6743–6764. https://doi.org/10.1029/JA076i028p06743

Sandholt, P. E., Lybekk, B., Egeland, A., Jacobson, B., Bythrow, P. F., & Hardy, D. A. (1989). Electrodynamics of the polar cusp ionosphere: A case study. *Journal of Geophysical Research*, *94*, 6713. https://doi.org/10.1029/JA094ia06p06713

Savin, S., Büchner, J., Consolini, G., Nikutowski, B., Zelenyi, L. M. E. A., et al. (2002). On the properties of turbulent boundary layer over polar cusps. *Nonlinear Processes in Geophysics*, *9*, 443–451. https://doi.org/10.5194/npg-9-443-2002

Savin, S., Zelenyi, L. M., Romanov, S., Sandahl, I., Pickett, J., Amata, E., et al. (2002). Multispacecraft tracing of turbulent boundary layer. *Advances in Space Research*, *30*, 2821–2830. https://doi.org/10.1016/S0273-1177(02)80422-7

Savin, S., Zelenyi, L., Romanov, S., Sandahl, I., Pickett, J., Amata, E., et al. (2004). Magnetosheath-cusp interface. *Annals of Geophysics*, *22*, 183–212. https://doi.org/10.5194/angeo-22-183-2004

Scarf, F. L., Fredricks, R. W., Green, I. M., & Russell, C. T. (1972). Plasma waves in the dayside polar cusp: 1, Magnetospheric observations. *Journal of Geophysical Research*, *77*(13), 2274–2293. https://doi.org/10.1029/JA077i013p02274

Shabansky, V. P. (1968). Magnetospheric processes and related geophysical phenomena. *Space Science Reviews*, *8*, 366–454. https://doi.org/10.1007/BF00184741

Sheldon, R., Harlan, E., Sullivan, J. D. T. A. F., & Chen, J. (1998). The discovery of trapped energetic electrons in the outer cusp. *Geophysical Research Letters*, *25*, 1825–1828. https://doi.org/10.1029/98GL01399

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*, *116*, A09228. https://doi.org/10.1029/2011JA016501

Shi, J., Guo, J., Dunlop, M., Zhang, T., Liu, Z., Luceket, E., et al. (2012). Inter-hemispheric asymmetry of dependence of the cusp location on dipole tilt during northward IMF conditions. *Annals of Geophysics*, *30*, 21–26. https://doi.org/10.5194/angeo-30-21-2012

Shi, J., Zhang, Z., Torkar, K., Cheng, Z., Escoubet, P., Farzakeley, A., et al. (2019). South-north hemispheric asymmetry of the FAE distribution around the cusp region: Cluster observation. *Journal of Geophysical Research - A: Space Physics*, *124*, 5342–5352. https://doi.org/10.1029/2019JA026582

Shi, J., Zhang, Z., Torkar, K., Cheng, Z., Farzakeley, A., Dunlop, M., et al. (2017). Distribution of field-aligned electron events in the high-altitude polar region: Cluster observations. *Journal of Geophysical Research: Space Physics*, *122*, 11245–11255. https://doi.org/10.1002/2017JA024360

Shi, J., Zhang, Z., Torkar, K., Dunlop, M., Fazakerley, A., Cheng, Z., & Liu, Z. (2014). Temporal and spatial scales of a high-flux electron disturbance in the cusp region: Cluster observations. *Journal of Geophysical Research: Space Physics*, *119*, 4536–4543. https://doi.org/10.1002/2013JA019560

Shi, Q. Q., Pu, Z. Y., Soucek, J., Zong, Q.-G., Fu, S. Y., Xie, L., et al. (2009). Spatial structures of magnetic depression in the Earth's high-altitude cusp: Cluster multipoint observations. *Journal of Geophysical Research*, *114*, A10202. https://doi.org/10.1029/2009JA014283

Shi, Q. Q., Zong, Q.-G., Zhang, H., Pu, Z. Y., Fu, S. Y., Xie, L., et al. (2009). Cluster observations of the entry layer equatorward of the cusp under northward interplanetary magnetic field. *Journal of Geophysical Research*, *114*, A12219. https://doi.org/10.1029/2009JA014475

Siscoe, G., Kaymaz, Z., & Bogdanova, Y. V. (2007). Magnetospheric Cusps under extreme conditions: Cluster Observations and MHD Simulations Compared. *Solar Physics*, *244*, 189–199. https://doi.org/10.1007/s11207-007-0359-7

Slapak, R., Gunell, H., & Hamrin, M. (2017). Observations of multiharmonic ion cyclotron waves due to inverse ion cyclotron damping in the northern magnetospheric cusp. *Geophysical Research Letters*, *44*, 22–29. https://doi.org/10.1002/2016GL071680

Slapak, R., Nilsson, H., Waara, M., André, M., Stenberg, G., & Barghouthi, I. A. (2011). O+ heating associated with strong wave activity in the high altitude cusp and mantle. *Annals of Geophysics*, *29*, 931–944. https://doi.org/10.5194/angeo-29-931-2011

Smith, M. F., & Lockwood, M. (1996). Earth's magnetospheric cusps. *Reviews of Geophysics*, *34*(2), 233–260. https://doi.org/10.1029/96RG00893

Song, P., & Russell, C. T. (1992). Model of the formation of the low latitude boundary layer for strongly northward interplanetary magnetic field. *Journal of Geophysical Research*, *97*, 1411. https://doi.org/10.1029/91JA02377

Spreiter, J. R., & Summers, A. L. (1967). On conditions near the neutral points on the magnetosphere boundary. *Planetary and Space Science*, *15*(4), 787–790. https://doi.org/10.1016/0032-0633(67)90050-5

Sundkvist, D., & Bale, S. D. (2008). Characteristic parameters of drift vortices coupled to Alfvén waves in an inhomogeneous space plasma. *Physical Review Letters*, *101*, 065001. https://doi.org/10.1103/PhysRevLett.101.065001

Sundkvist, D., Krasnoselskikh, V., Shukla, P. K., Vivads, A., André, M. J., Buchert, S., et al. (2005). *In situ* multi-satellite detection of coherent vortices as a manifestation of Alfvénic turbulence. *Nature*, *436*, 825–828. https://doi.org/10.1038/nature03931

Sundkvist, D., Vaivads, A., André, M. J.-E., Hobara, W. Y., Joko, S., et al. (2005). Multi-spacecraft determination of wave characteristics near the proton gyrofrequency in high-altitude cusp. *Annals of Geophysics*, *23*, 983–995. https://doi.org/10.5194/angeo-23-983-2005

Sundkvist, D., Vaivads, A., Bogdanova, Y. V., Krasnoselskikh, V. V., Fazakerley, A., & Décréau, P. M. E. (2006). Shell-instability generated waves by low energy electrons on converging magnetic field lines. *Geophysical Research Letters*, *33*, L03103. https://doi.org/10.1029/2005GL024388

Taylor, M. G. G. T., Fazakerley, A., Krauklis, I. C., Owen, C. J., Travnicek, P., Dunlop, M., et al. (2001). Four point measurements of electrons using PEACE in the high-altitude cusp. *Annals of Geophysics*, *19*, 1567–1578. https://doi.org/10.5194/angeo-19-1567-2001

Trattner, K. J., Chen, J., & Fritz, T. A. (2001). Origins of energetic ions in the cusp. *Journal of Geophysical Research*, *106*, 5967–5079. https://doi.org/10.1029/2000JA003005

Trattner, K. J., Fuselier, S. A., Peterson, W. K., Boehm, M., Klumpar, D., Carlson, C. W., & Yeoman, T. K., et al. (2002). Temporal versus spatial interpretation of cusp ion structures observed by two spacecraft. *Journal of Geophysical Research*, *107*(A10), 1287. https://doi.org/10.1029/2001JA000181

Trattner, K. J., Fuselier, S. A., Peterson, W. K., & Carlson, C. W. (2002). Spatial features observed in the cusp under steady solar wind conditions. *Journal of Geophysical Research*, *107*(A10), 1288. https://doi.org/10.1029/2001JA000262

Trattner, K. J., Fuselier, S. A., Peterson, W. K., Sauvaud, J.-A., Stenuit, H., Dubouloz, N., & Kovrazhkin, R. A. (1999). On spatial and temporal structures in the cusp. *Journal of Geophysical Research*, *104*(A12), 28411–28421. https://doi.org/10.1029/1999JA900419

Trattner, K. J., Fuselier, S. A., Petrinec, S. M., Yeoman, T. K., Escoubet, C. P., & Reme, H. (2005). Reconnection sites of spatial cusp structures. *Journal of Geophysical Research*, *110*, A04207. https://doi.org/10.1029/2004JA010722

Trattner, K. J., Fuselier, S. A., Petrinec, S. M., Yeoman, T. K., Escoubet, C. P., & Reme, H. (2008). The reconnection site of temporal cusp structures. *Journal of Geophysical Research*, *113*, A07S14. https://doi.org/10.1029/2007JA012776

Trattner, K. J., Fuselier, S. A., Yeoman, T. K., Korth, A., Fraenz, M., Mouikis, C., et al. (2003). Cusp structures: Combining multi-spacecraft observations with ground-based observations. *Annals of Geophysics*, *21*, 2031–2041. https://doi.org/10.5194/angeo-21-2031-2003

Trattner, K. J., Petrinec, S. M., Fuselier, S. A., Nykyri, K., & Kronberg, E. (2011). Cluster observations of bow shock energetic ion transport through the magnetosheath into the cusp. *Journal of Geophysical Research*, *116*, A09207. https://doi.org/10.1029/2011JA016617

Trattner, K. J., Petrinec, S. M., Peterson, W. K., Fuselier, S. A., & Reme, H. (2006). Tracing the location of the reconnection site from the northern and southern cusps. *Journal of Geophysical Research*, *111*, A11211. https://doi.org/10.1029/2006JA011673

Tsyganenko, N. A. (1995). Modeling the Earth's magnetospheric magnetic field confined within a realistic magnetopause. *Journal of Geophysical Research*, *100*, 5599–5612. https://doi.org/10.1029/94JA03193

Tsyganenko, N. A. (2009). Magnetic field and electric currents in the vicinity of polar cusps as inferred from Polar and Cluster data. *Annals of Geophysics*, *27*, 1573–1582. https://doi.org/10.5194/angeo-27-1573-2009

Tsyganenko, N. A., & Russell, C. T. (1999). Magnetic signatures of the distant polar cusps: Observations from Polar and quantitative modeling. *Journal of Geophysical Research*, *104*(A11), 24939–24955. https://doi.org/10.1029/1999JA900279

Tsyganenko, N. A., & Sitnov, M. I. (2005). Modeling the dynamics of the inner magnetosphere during strong geomagnetic storms. *Journal of Geophysical Research*, *110*, A03208. https://doi.org/10.1029/2004JA010798

Tsyganenko, N. A., & Sitnov, M. I. (2007). Magnetospheric configurations from a high-resolution data-based magnetic field model. *Journal of Geophysical Research*, *112*, A06225. https://doi.org/10.1029/2007JA012260

Twitty, C., Phan, T., Paschmann, G., Lavraud, B., Rème, H., & Dunlop, M. (2004). Cluster survey of cusp reconnection and its IMF dependence. *Geophysical Research Letters*, *31*, L19808. https://doi.org/10.1029/2004GL020646

Vaith, H., Paschmann, G., Quinn, J. M., Foerster, M., Georgescu, E., Haaland, S. E., et al. (2004). Plasma convection across the polar cap, plasma mantle and cusp: Cluster EDI observations. *Annals of Geophysics*, *22*, 2451–2461. https://doi.org/10.5194/angeo-22-2451-2004

Vogiatzis, I. I., Sarris, T. E., Sarris, E. T., Santolík, O., Dandouras, I., Robert, P., et al. (2008). Cluster observations of particle acceleration up to supra-thermal energies in the cusp region related to low-frequency wave activity—Possible implications for the substorm initiation process. *Annals of Geophysics*, *26*, 653–669. https://doi.org/10.5194/angeo-26-653-2008

Vontrat-Reberac, A., Bosqued, J. M., Taylor, M. G. G. T., Lavraud, B., Fontaine, D., Dunlop, M. W., et al. (2003). Cluster observations of the high-altitude cusp for northward interplanetary magnetic field: A case study. *Journal of Geophysical Research*, *108*, 1346. https://doi.org/10.1029/2002JA009717

Waara, M., Nilsson, H., Slapak, R., André, M., & Stenberg, G. (2012). Oxygen ion energization by waves in the high altitude cusp and mantle. *Annals of Geophysics*, *30*, 1309–1314. https://doi.org/10.5194/angeo-30-1309-2012

Waara, M., Slapak, R., Nilsson, H., Stenberg, G., André, M., & Barghouthi, I. A. (2011). Statistical evidence for O+ energization and outflow caused by wave-particle interaction in the high altitude cusp and mantle. *Annals of Geophysics*, *29*, 945–954. https://doi.org/10.5194/angeo-29-945-2011

Walsh, A. P., Haaland, S., Forsyth, C., Keesee, A. M., Kissinger, J., Li, K., et al. (2014). Dawn–dusk asymmetries in the coupled solar wind–magnetosphere–ionosphere system: A review. *Annals of Geophysics*, *32*, 705–737. https://doi.org/10.5194/angeo-32-705-2014

Walsh, B. M., & Fritz, T. A. (2011). Cluster energetic electron survey of the high-altitude cusp and adjacent regions. *Journal of Geophysical Research*, *116*, A12212. https://doi.org/10.1029/2011JA016828

Walsh, B. M., Fritz, T. A., & Chen, J. (2012). Simultaneous observations of the exterior cusp region. *Journal of Atmospheric and Solar-Terrestrial Physics*, *87–88*, 47–55. https://doi.org/10.1016/j.jastp.2011.08.011

Walsh, B. M., Fritz, T. A., Klida, M. M., & Chen, J. (2010). Energetic electrons in the exterior cusp: Identifying the source. *Annals of Geophysics*, *28*, 983–992. https://doi.org/10.5194/angeo-28-983-2010

Wang, T., Cao, J.-B., Fu, H., Liu, W., & Dunlop, M. (2014). Turbulence in the Earth's cusp region: The k-filtering analysis. *Journal of Geophysical Research: Space Physics*, *119*. https://doi.org/10.1002/2014JA019997

Wescott, E. (1962). Magnetic activity during periods of auroras at geomagnetically conjugate points. *Journal of Geophysical Research*, *67*(4), 1353–1355. https://doi.org/10.1029/JZ067i004p01353

Wilken, B., Axford, W. I., Daglis, I. A., Daly, P., Güttler, W., Ip, W.-H., et al. (1997). RAPID: The Imaging Energetic Particle Spectrometer on Cluster. *Space Science Reviews*, *79*, 399–473. https://doi.org/10.1023/A:1004994202296

Willis, D. M. (1969). The influx of charged particles at the magnetic cusps on the boundary of the magnetosphere. *Planetary and Space Science*, *17*(3), 339–348. https://doi.org/10.1016/0032-0633(69)90067-1

Wing, S., Newell, P. T., & Ruohoniemi, J. M. (2001). Double Cusp: Model prediction and observational verification. *Journal of Geophysical Research*, *106*, 25571. https://doi.org/10.1029/2000JA000402

Xiao, C., Liu, W., Shen, C., Zhang, H., & Rong, Z. (2018). Study on the curvature and gradient of the magnetic field in Earth's cusp region based on the magnetic curvature analysis method. *Journal of Geophysical Research: Space Physics*, *123*. https://doi.org/10.1029/2017JA025028

Xiao, C., Liu, W., Zhang, D., & Zhang, Z. (2020). A normalized statistical study of Earth's cusp region based on nine-years of Cluster measurements. *Earth Planetary Physics*, *4*, 266–273. https://doi.org/10.26464/epp2020031

Xiao, F., Zong, Q., Su, Z., Yang, C., He, Z., Wang, Y., & Gao, Z. (2013). Determining the mechanism of cusp proton aurora. *Nature Scientific Reports*, *3*. https://doi.org/10.1038/srep01654

Yordanova, E., Grzesiak, M., Wernik, A., Popielawska, B., & Stasiewicz, K. (2004). Multifractal structure of turbulence in the magnetospheric cusp. *Annals of Geophysics*, *22*, 2431–2440. https://doi.org/10.5194/angeo-22-2431-2004

Yordanova, E., Sundkvist, D., Buchert, S. C., André, M., Ogawa, Y., Morooka, M., et al. (2007). Energy Input from the exterior cusp into the ionosphere: Correlated ground-based and satellite observations. *Geophysical Research Letters*, *34*, L04102. https://doi.org/10.1029/2006GL028617

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*, *112*(A2), A02204. https://doi.org/10.1029/2006JA011774

Zhang, H., Fritz, T. A., Zong, Q.-G., & Daly, P. W. (2006). The high latitude boundaries under extreme solar wind conditions, a cluster perspective. *Advances in Geosciences*, *2*, 163–172. https://doi.org/10.1142/9789812707185_0013

Zhang, H., Fritz, T. A., Zong, Q.-G., & Daly, P. W. (2005). Stagnant exterior cusp region as viewed by energetic electrons and ions: A statistical study using Cluster Research with Adaptive Particle Imaging Detectors (RAPID) data. *Journal of Geophysical Research*, *110*, A05211. https://doi.org/10.1029/2004JA010562

Zhou, X.-W., & Russell, C. T. (1997). The location of the high-latitude polar cusp and the shape of the surrounding magnetopause. *Journal of Geophysical Research*, *102*(A1), 105–110. https://doi.org/10.1029/96JA02702

Zhou, X. W., Russell, C., Le, G., Fuselier, S., & Scudder, J. (1999). The polar cusp location and its dependence on dipole tilt. *Geophysical Research Letters*, *26*, 429–432. https://doi.org/10.1029/1998GL900312

Zhou, X. W., Russell, C. T., Le, G., Fuselier, S. A., & Scudder, J. D. (2000). Solar wind control of the polar cusp at high altitude. *Journal of Geophysical Research*, *105*, 245–252. https://doi.org/10.1029/1999JA900412

Zimbardo, G., Greco, A., Veltri, P., Voros, Z., & Taktakishvili, A. L. (2008). Magnetic turbulence in and around the Earth's magnetosphere. *Astrophysics and Space Sciences Transactions*, *4*, 35–40. https://doi.org/10.5194/astra-4-35-2008

Zong, Q.-G., Fritz, T. A., Daly, P. A., Korth, A., Dunlop, M., & Balogh, A. (2003). Bursty energetic electrons confined in flux ropes in the cusp region. *Planetary and Space Science*, *51*, 821–830. https://doi.org/10.1016/S0032-0633(03)00116-8

Zong, Q.-G., Fritz, T. A., Korth, A., Daly, P. W., Dunlop, M., Balogh, A., et al. (2005). Energetic Electrons as a Field Line Topology Tracer in the High Latitude Boundary/Cusp Region: Cluster Rapid Observation. *Surveys in Geophysics*, *26*(1–3), 215–240. https://doi.org/10.1007/s10712-005-1879-z

Zong, Q.-G., Fritz, T. A., Spence, H. E., Frey, H. U., & Mende, S. B. (2005). Reverse convection and cusp proton aurora: Cluster, polar and image observations. *Advances in Space Research*, *36*, 1779–1784. https://doi.org/10.1016/j.asr.2004.09.023

Zong, Q.-G., Fritz, T. A., Spence, H. E., Zhang, H., Huang, Z. Y., Pu, Z. Y., et al. (2005). Plasmoid in the high latitude boundary/cusp region observed by Cluster. *Geophysical Research Letters*, *32*, L01101. https://doi.org/10.1029/2004GL020960

Zong, Q.-G., Fritz, T. A., Wilken, B., & Daly, P. (2003). Energetic ions in the high latitude boundary layer of the magnetosphere-Rapid/Cluster observation. In P. T. Newell, & T. Onsager (Eds.), *Energetic ions in the high latitude boundary layer of the magnetosphere - RAPID/CLUSTER observation in Earth's low-latitude boundary layer*. Geophysical Monograph Series (Vol. 133, pp. 101–110). AGU. https://doi.org/10.1029/133GM10

Zong, Q.-G., Fritz, T. A., Zhang, H., Korth, A., Daly, P. W., Dunlop, M. W., et al. (2004). Triple cusps observed by Cluster—Temporal or spatial effect? *Geophysical Research Letters*, *31*, L09810. https://doi.org/10.1029/2003GL019128

Zong, Q.-G., Zong, Q.-G., Zhang, H., Fritz, T. A., Goldstein, M., Wing, S., Keith, W. R., et al. (2008). Multiple cusps during an extended northward IMF period with a significant B_y component. *Journal of Geophysical Research*, *113*, A01210. https://doi.org/10.1029/2006JA012188