The Magnetospheric Cusps: Structure and Dynamics
The Magnetospheric Cusps: Structure and Dynamics

Edited by
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The cusps have traditionally been described as narrow funnel-shaped regions that provide a focus of the Chapman–Ferraro currents that flow on the magnetopause, a boundary between the cavity dominated by the geomagnetic field (i.e., the magnetosphere) and the external region of the interplanetary medium. From low-altitude satellite and ground-based measurements the cusps appear to behave in much the manner predicted for the responses of the narrow funnel-shaped structures to changes in the upstream interplanetary medium. Measurements at higher altitudes have been reported by past and recent missions such as the Russian Interball satellites, the US/NASA Hawkeye, Polar, and IMAGE satellites, and the joint European Space Agency/NASA Cluster suite of four satellites, all in mid- to high-altitude polar orbits. From these measurements, it has become clear that the cusps are no longer confined to narrow regions near local noon but appear to encompass a large portion of the dayside high-latitude magnetosphere. An unexpected result is that the cusps appear to be a major source region of energetic charged particles for the magnetosphere.

We try in this collection of papers to address the question “What is the Cusp?” We consider what is its role in coupling the solar wind to the magnetosphere as well as its role in charged particle transport and energization within the magnetosphere. In the literature we have had the cusp known by many names. These names appear again in papers of this Special Issue.

Boundary Cusp [BL]
Cusp Throat [CT]
Exterior Cusp [ET]
Stagnant Exterior Cusp [SEC]
Turbulent Boundary Layer [TBL]
Cusp Proper [CP]
Double Cusp
Sash
True Cusp [TC]

The cusp has been reported as a single region but also as a double region each with unique properties. Multiple simultaneous cusps are discussed as well. Within the cusp there are features that have been called the following:

Cusp Diamagnetic Cavity [CDC]
Diamagnetic Bubble [DB]
Outer Throat [OT]/Inner Throat [IT]
Temporal and/or Spatial Energy Steps
Cusp Energetic Particle events [CEP]
Outer Cusp [OC]/Inner Cusp [IC]
Plasma Ball [PB]

The Turbulent Boundary Layer [TBL] has been further divided into an outer TBL zone [OZ], middle TBL zone [MZ], and inner TBL zone [IZ].

Do these many names mean that we understand the cusp and its underlying physical principles or do they indicate a lack of understanding? In this collection of papers arguments are advanced, based on observations and theory, that cusp features are entirely produced and driven by the incoming solar wind and interplanetary magnetic field structure while other papers argue that much of the turbulence, structure, and resulting particle acceleration are produced locally within the cusp. In one of the papers the cusp is depicted as a very narrow region connected to the subsolar merging site and associated with the last closed field line, whereas a couple of statistical studies reported here present evidence demonstrating that the cusp is a vast dayside region of shocked solar wind plasma existing inside the magnetopause. The reader will encounter a paper that argues that most or all of the features of the low altitude particle signatures associated with the cusp are produced by temporal changes while the authors of another paper argue that these same features are spatial and frozen in time. To assist the readers of these papers the editors have encouraged each author to define early in their paper what distinguishes their cusp from other surrounding regions of the dayside high-latitude magnetosphere. The title of this special issue is “The Magnetospheric Cusps: Structure and Dynamics”. The guest editors for this Special Issue of Surveys in Geophysics are Professor Theodore A. Fritz of Boston University, Boston, MA, USA and Dr. Shing F. Fung of the NASA Goddard Space Flight Center, Greenbelt, MD, USA. As editors of this special issue our main goal has been to provide a comprehensive set of overview papers that focus on the properties of the cusp as a function of altitude and the effects of the adjoining magnetopause boundary layer. A number of topical papers of high interest have also been included in this volume. The core papers for this issue have been drawn from a special session held at the spring meeting of the American Geophysical Union in May 2002. The session was entitled “Turbulence and Dynamics at the High Altitude Cusp and Dayside Magnetopause Boundary Layer” and the convenors were Dr. Jiasheng Chen and Professor Theodore A. Fritz. The editors would like to acknowledge and express their appreciation to the following individuals who devoted their time and effort to reviewing the papers in this collection: James L. Burch, Jiasheng Chen, Nancy U. Crooker, Timothy E. Eastman, Joseph F. Fennell, Richard C. Elphic, Charles C. Goodrich, Patrick T. Newell, Nelson C. Maynard, Richard W. McEntire, Douglas Menietti, Barbara Popielawska, Patricia H.
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CLUSTER OBSERVATIONS OF THE CUSP: MAGNETIC STRUCTURE AND DYNAMICS


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Abstract. This paper reviews Cluster observations of the high altitude and exterior (outer) cusp, and adjacent regions in terms of new multi-spacecraft analysis and the geometry of the surrounding boundary layers. Several crossings are described in terms of the regions sampled, the boundary dynamics and the electric current signatures observed. A companion paper in this issue focuses on the detailed plasma distributions of the boundary layers. The polar Cluster orbits take the four spacecraft in a changing formation out of the magnetosphere, on the northern leg, and into the magnetosphere, on the southern leg, of the orbits. During February to April the orbits are centred on a few hours of local noon and, on the northern leg, generally pass consecutively through the northern lobe and the cusp at mid- to high-altitudes. Depending upon conditions, the spacecraft often sample the outer cusp region, near the magnetopause, and the dayside and tail boundary layer regions adjacent to the central cusp. On the southern, inbound leg the sequence is reversed. Cluster has therefore sampled the boundaries around the high altitude cusp and nearby magnetopause under a variety of conditions. The instruments onboard provide unprecedented resolution of the plasma and field properties of the region, and the simultaneous, four-spacecraft coverage achieved by Cluster is unique. The spacecraft array forms a nearly regular tetrahedral configuration in the cusp and already the mission has covered this region on multiple spatial scales (100–2000 km). This multi-spacecraft coverage allows spatial and temporal features to be distinguished to a large degree and, in particular, enables the macroscopic properties of the boundary layers to be identified: the orientation, motion and thickness, and the associated current layers. We review the results of this analysis for a number of selected crossings from both the North and South cusp regions. Several key results have been found or have confirmed earlier work: (1) evidence for magnetically defined boundaries at both the outer cusp/magnetosheath interface and the inner cusp/lobe or cusp/dayside magnetosphere interface, as would support the existence
of a distinct exterior cusp region; (2) evidence for an associated indentation region on the magnetopause across the outer cusp; (3) well defined plasma boundaries at the edges of the mid- to high-altitude cusp “throat”, and well defined magnetic boundaries in the high-altitude “throat”, consistent with a funnel geometry; (4) direct control of the cusp position, and its extent, by the IMF, both in the dawn/dusk and North/South directions. The exterior cusp, in particular, is highly dependent on the external conditions prevailing. The magnetic field geometry is sometimes complex, but often the current layer has a well defined thickness ranging from a few hundred (for the inner cusp boundaries) to 1000 km. Motion of the inner cusp boundaries can occur at speeds up to 60 km/s, but typically 10–20 km/s. These speeds appear to represent global motion of the cusp in some cases, but also could arise from expansion or narrowing in others. The mid- to high-altitude cusp usually contains enhanced ULF wave activity, and the exterior cusp usually is associated with a substantial reduction in field magnitude.

**Keywords:** boundary dynamics, clustermagnetospheric cusps

**Abbreviations:** ACE – advanced composition explorer; GSE – geocentric solar ecliptic; GSM – geocentric solar magnetic; IMF – interplanetary magnetic field; LT – local time; MVA – minimum variation analysis; $R_E$ – earth’s radius; ULF – ultra-low frequency; UT – universal time

### 1. Introduction

The region associated with the Earth’s magnetospheric cusps is one of the most complex in the magnetosphere, in terms of both its morphology and the processes operating. The cusps are believed to be the main places of transport of plasma into the magnetosphere and therefore contain (modified) magnetosheath plasma (e.g. Frank, 1971; Newell and Meng, 1988). Their extent and location are known to respond to the IMF and solar wind pressure (Newell et al., 1989; Woch and Lundin, 1992; Newell and Meng, 1994; Yamauchi and Lundin, 1994; Yamauchi et al., 1996; Savin et al., 1998; Fedorov et al., 2000; Dubinin et al., 2002). The cusps, however, have an often complex magnetic topology, whose direct relation to processes occurring elsewhere on the magnetopause and in the adjacent magnetosheath is not fully understood. There is often a combination of processes operating, having both local and remote effects. Adding to this complexity are the facts that the region is of large ($R_E$) spatial extent, containing a variety of distinct structures having both plasma and field specific characteristics, but is highly dynamic and often with changes in magnetic topology. This makes measurements of the region extremely difficult to interpret. The magnetic and plasma structures surrounding the cusps often depend on prevailing conditions. The boundaries surrounding the region have therefore not been well characterised. In particular, the relation between a possible, distinct exterior cusp, as part of the high altitude cusp region, and an indentation on the magnetopause (Spreiter et al., 1968; Haerendel et al., 1978; Vasyliunas et al.,
1979) is not well formulated. A more comprehensive review of these earlier studies can be found in a companion paper in this issue (Lavraud et al., 2003).

The four-spacecraft Cluster mission is currently returning co-ordinated, multi-point information on the region of the cusps at unprecedented detail. It has the potential to resolve cusp structure, first investigated during the early Hawkeye and HEOS missions (e.g., see Paschmann et al., 1976; Haerendel et al., 1978; Farrell and Van Allen, 1990; Kessel et al., 1996; Dunlop et al., 2000; Eastman et al., 2000) over 30 years ago, and more recently re-explored with the Polar mission (e.g. Grande et al., 1997; Russell, 2000; Scudder et al., 2002, Fritz et al., 2003) as well as the Interball mission (Savin et al., 1998; Fedorov et al., 2000; Dubinin et al., 2002). The orbital dynamics is designed so as to place the spacecraft array into a nearly regular tetrahedral configuration in the location of the cusps. Both the high capabilities of the onboard instruments and the tetrahedral spacecraft configuration permit very accurate and precise determination of the physical particle and wave phenomena and small-scale dynamical analysis. Many cusp crossings have been recorded by Cluster, during 2001 and 2002, covering a variety of ambient conditions, and these have sampled the cusp region with a range of spatial scales (100–2000 km). Nevertheless, the analysis of Cluster data requires particular interpretation, currently at a phenomenological level. A number of four-spacecraft techniques have been devised to combine the multi-point dataset (see Paschmann and Daly, 1988). These techniques can determine such properties as thin boundary layers, their orientation and motion, and the nature of associated current layers, and are in development to explore further applications. Two techniques in particular are described below, the Curlo-meter (Dunlop and Balogh, 1993; Robert and Roux, 1993; Robert et al., 1998) and Discontinuity Analyser (DA) (Dunlop et al., 1997; Dunlop and Woodward, 1998, 1999). The application of these techniques is defined by the comparative spatial and temporal scales.

During the mission, the spacecraft are maintained in a closely separated array formation (at mean distances which, over the mission, have ranged between 100 and 6000 km), having a repeating evolution every orbit. Manoeuvres are performed at six-monthly to yearly intervals. The orbit is shown, for example, in Figure 2 (described in Section 3), for a typical dayside orientation of the line of apsides, in comparison with the T89 (Tsyganenko, 1989) model field, shown for guidance. Different dipole orientations occur with respect to the orbit for other passes. The orbits are inertial, having identical periods for all spacecraft and a polar orientation, with a rising argument of perigee. Perigee and apogee are at 4 and 19.6 \( R_E \), respectively. Cluster therefore samples the cusp at both high and mid altitudes during different phases of the orbit. In the plot, the configuration formed by the relative locations of each spacecraft, at different times around the orbit, is shown scaled up by a factor of 20. Not only does this spacecraft configura-
tion distort dramatically around the orbit, but its scale size varies also. Therefore, the array of four spacecraft samples the magnetic field in very different ways at different positions. This has the consequence that some combinations of the four-point measurements are more fruitful than others, depending upon the structures present. It is critical to know, for instance, what are the comparative inter-spacecraft separations with respect to the characteristic scale size of the structures present. Usually the analysis will involve crude estimates of scale (degree of stationarity or relative size, large or small-scale structures), inferred from the measured, time series variations. Fortunately, different magnetospheric phenomena often produce anisotropic structures that can be described in terms of similar global frames of reference, for example, corresponding to a flow, field, or boundary aligned co-ordinate system (Dunlop et al., 1993). The multi-spacecraft methods generally give better results than single spacecraft methods, and they give much better defined local systems of reference.

This paper reviews the analysis of a few comparative events taken from the data set, concentrating primarily on the dynamics and magnetic structure of the boundaries. A companion paper (Lavraud et al., 2003) deals with the plasma characteristics observed within key regions of the cusp, partly in the context of the magnetic boundaries. Section 2, below, summarises the four spacecraft techniques used to order the data; Section 3 then introduces each event, describing their basic properties and the solar wind/magnetosheath context, and Section 4 discusses their characteristics, interpreted from the four-spacecraft locations. Section 3 concentrates on the sampling context to characterise each event, using multi-spacecraft crossings where appropriate, whereas Section 4 discusses how well this character may be quantified by the four-spacecraft analysis, and understood in terms of the response of the region to the external conditions. In Section 5, this interpretation is summarised.

2. Measurements and techniques

2.1. Cluster instrumentation

The data used in this paper have been taken by the magnetometer and plasma instruments residing onboard the Cluster spacecraft. Although the analysis presented here depends primarily on the magnetic field measurements, the plasma data are shown for context. The fluxgate magnetometer (FGM) experiment is providing high time resolution magnetic field measurements from the primary sensors on all four spacecraft (Balogh et al., 2001). The experiment consists of two sensors on each spacecraft, mounted near the middle and end of a rigid 5-m boom, together with their onboard data processing units. Currently, the primary sensor is the outboard sensor, providing magnetic field measurements at 22.4 Hz (normal mode) or 67 Hz (burst mode). The instruments are
operating continuously and the data have been filtered and re-sampled onboard from an internal sampling rate of 202 Hz. The data are believed to be inter-calibrated to at least 0.1 nT accuracy overall. Here, we employ both spin resolution and high time resolution data where appropriate, which have been re-calibrated to higher accuracy where necessary.

The Cluster Ion Spectrometer (CIS) is fully described by Rème et al. (2001) and is capable of obtaining full three-dimensional ion distribution functions down to a time resolution of 4 s. The CIS experiment is composed of two complementary sensors: the COMposition and DIstribution Function analyser sensor (CODIF), which utilises a Time of Flight system in order to resolve ion masses, and the Hot Ion Analyser (HIA) that does not separate ion species but has a better angular resolution. The CIS experiment is currently providing data from both sensors on two spacecraft (1 and 3) and from CODIF only on spacecraft 4. We present data from both instruments in the present paper. The Plasma Electron And Current Experiment (PEACE, Johnstone et al., 1997) is providing low- and mid-energy electron data from all four spacecraft. It consists of two sensors, the High Energy Electron Analyser (HEEA) and the Low Energy Electron Analyser (LEEA), mounted on diametrically opposite sides of the spacecraft. They are designed to measure, in combination, the three dimensional velocity distributions of electrons in the range 0.6 eV to 26 keV. The HEEA normally measures the range 35 eV to 26 keV and the LEEA the range 0.6 eV to 1 keV, although either can be set to cover any subset of the energy range. Thus, the overlap energy range (measured by both sensors) effectively has 2-s resolution or can be used to cross calibrate the sensors. Data presented in this paper are derived using preliminary calibrations.

2.2. THE DISCONTINUITY ANALYSER (DA)

This technique characterises the macroscopic properties of boundaries or discontinuities, and determines parameters that describe the motion, geometry and orientation of these structures. The first application of this technique to Cluster data has been reported by Dunlop et al. (2002a) and here we use it only in the case of stationary, planar boundaries. The basic algorithm uses single spacecraft methods, such as Minimum Variance Analysis (Sonnerup and Cahill, 1967) or co-planarity, to determine the normals to the boundary at each spacecraft crossing point, independently. The boundary orientation and motion can then be calculated by combining the boundary crossing times, at each spacecraft, with spacecraft separation vectors and the boundary normals as determined above. Figure 1a shows the idealised case of a planar discontinuity. Boundary normals are envisaged as having been determined to be nearly parallel at each of the four spacecraft (s/c 1, 2, 3, 4). Because the normals are determined independently, parallel normals directly
imply a planar geometry over the spacecraft array and allow the boundary motion (velocity $v_n$, and acceleration $a_n$), to be determined from

$$ r_n = v_n^0 t + \frac{1}{2} a_n t^2 $$

where $r_n = \Delta r_{ij} \cdot n$, etc., and $t = t_{ij}$.

If the motion is constant over the spacecraft array ($a_n$ is found to be small), equation 1 can be used to compute $n/v_n^0$ (Russell et al., 1983). This computation of $n$ and $v_n^0$, under an assumption of constant velocity, is referred to below as a timing analysis, since the results only depend on the timing of the crossings at each spacecraft. When the results of the DA suggest

![Figure 1. (a) The application of the DA to a planar discontinuity (after Dunlop et al. (2002a)), and (b) The curlometer concept (after Dunlop et al. (2002b)).](image)
that the motion is indeed almost constant, these values can provide a consistency check for the planar-DA, either of the normals, or of the estimates of the motion. If the acceleration of the boundary is changing rapidly, $a_n$ may not well represent the boundary reversals.

Even with this simple form of the technique, Equation (1) rests on the determination of the inter-spacecraft time differences between the boundary crossings at each of the spacecraft, together with the assumption that the structure does not evolve over the time intervals. In practice, this requires that identifiable features in the time series data are stationary (can be interpreted as convected stable structures). These, often sharp (short duration), features are usually best viewed by the change in the maximum variance component of the magnetic field, following transformation to MVA co-ordinates (or in the field intensity where there is low field rotation). Typically, for magnetic discontinuities and other plasma boundaries, stationarity is only valid near these sharp boundaries. Particularly for the case of well-defined current sheets, the maximum variance component will suggest a magnetic field rotation over some finite time interval. These intervals correspond to the traversal times through the current sheet (time intervals to cross the current sheet, as represented by the shear in the magnetic field).

In the results analysed below we quote the mean normals, obtained from the individual spacecraft normals, where only planar crossings have been analysed. The mean normals, of course, will give better estimates of the boundary orientation than the spacecraft normals. We also quote the computed velocity between each independent spacecraft pair in order to identify the relative motion of the boundary, as determined from the DA. Once any change of this velocity over the spacecraft array has been found, this motion can be used to scale each traversal time through the current layer (at each spacecraft) to a boundary thickness. These estimates of boundary thickness are also quoted.

2.3. The curlometer

The description of the curlometer and its development has been referenced in the Introduction, and first application of the technique has been reported recently by Dunlop et al. (2002b). The technique directly combines simultaneous data across the different spacecraft with the position information of the spacecraft to calculate the curl of the magnetic field from Ampère’s law as an estimate of the average current density through the spacecraft configuration, using the difference approximation

$$\mu_0 \mathbf{j} \cdot (\Delta \mathbf{r}_i \times \Delta \mathbf{r}_j) = \Delta B_i \cdot \Delta \mathbf{r}_j - \Delta B_j \cdot \Delta \mathbf{r}_i$$
representing: $\mu_0 \int \mathbf{J} \cdot d\mathbf{s} = \oint \mathbf{B} \cdot d\mathbf{l}$

with $\Delta \mathbf{r}_i = \mathbf{r}_i - \mathbf{r}_1$, and similarly $\Delta \mathbf{B}_i = \mathbf{B}_i - \mathbf{B}_1$ (see Dunlop et al., 2002b). This effectively estimates the average current normal to the face $(l, i, j)$ of the tetrahedron (see Figure 1b). Since the vector defining the face is known by $\Delta \mathbf{r}_i \times \Delta \mathbf{r}_j$, the currents normal to three faces can easily be re-projected into a Cartesian co-ordinate system. Generally, this approximation requires that the spacecraft separation is much less than the scale lengths on which the current density varies. If this assumption does not hold, the estimate of $\mathbf{J}$ becomes inaccurate (but may still reflect real effects). Some check on the linearity of the spatial magnetic field gradients is therefore desirable, and it is also possible to calculate an estimate for $\text{div}(\mathbf{B})$ from

$$\text{div}(\mathbf{B})|\Delta \mathbf{r}_i \cdot \mathbf{r}_j \times \Delta \mathbf{r}_k| = |\Sigma_{\text{cyclic}} \Delta \mathbf{B}_i \cdot \Delta \mathbf{r}_j \times \Delta \mathbf{r}_k|$$

The calculation of $\text{div}(\mathbf{B})$ produces non-zero values as a consequence of non-linear spatial gradients neglected in its estimate (as well as containing the effect of timing and measurement errors). It therefore usefully measures the combined effect of the linear approximation for those diagonal terms in the dyadic $\Delta \mathbf{B}$, and both quantities are monitored routinely. The information from $\text{div}(\mathbf{B})$, however, only indirectly refers to the estimate of the error in $\mathbf{J}$. In particular, the use of $\text{div}(\mathbf{B})$ as an indicator is less valid at extreme distortions of the spacecraft tetrahedron and these configurations are avoided. The ratio $|\text{div}(\mathbf{B})|/|\text{curl}(\mathbf{B})|$ is actually used to monitor a dimensionless quantity, expressed as a percentage deviation from zero. The effect of measurement errors (uncertainties) in the determination of $\mathbf{r}$ and $\mathbf{B}$ (and time) is very critical for the calculation of $\mathbf{J}$, since it involves differences in the quantities. Their contribution to the error in $\mathbf{J}$ is also highly sensitive to both the spacecraft configuration and the magnetic structure. In the analysis below we comment on the curlometer calculation only briefly, but have checked that these qualifications on the estimate give consistent results for the analysis performed.

3. Events

We summarise here the description of particular cusp traversals, which have been covered by Cluster at mean spatial separations of 600 km (from the dayside pass in 2001) and 100 km (from the dayside pass in 2002). In the first case, the spacecraft configurations are scaled up by a factor of $\times 20$ and, in the second, by a factor of $\times 100$. Three primary events are described in some
detail, with the small separation events being presented for comparison, together with a quiet time event to show the underlying gross features of each region of the cusp. The events have been chosen to show both the extreme changes in character of the regions surrounding the cusp which have been observed and some of the different sampling configurations which have been covered by the Cluster spacecraft. We describe the properties of the events fully below, including their four-spacecraft context. The significance of the multi-point analysis is then discussed further in Section 4.

3.1. Event of 17 March 2001

Figure 2 shows a northern cusp crossing, which occurred during quiet external conditions, and during essentially northward IMF-\(B_Z\). The crossing occurred during the exit of the spacecraft from the magnetosphere on the outbound, northern leg of the Cluster orbits. In Figure 2, the spacecraft orbit and the configuration at intervals along the orbit are shown projected into the \(X,Z_{GSM}\) plane (with the inset being the corresponding \(X,Y_{GSM}\) projection). The dots on the orbit are hours of the day from zero UT at the perigee end of the segment shown. The plane of the orbit lies almost at magnetic noon, just on the dawn-side for the whole pass until the final magnetopause exit at 09:20 UT (confirmed by the magnetic field and ion data shown in Figures 3 and 4).

Figure 3 shows the magnetic field data compared with the Tsyganenko model field (T89, for \(K_p = 1\)). The underlying trends in \(B_Z\) and \(B_Y\) follow the model closely until the spacecraft are near the magnetopause. The magnetic field is directed down (South) and slightly duskward, as required for this location, and defines the “throat” of the cusp as field aligned. [Note that for convenience of description, we will refer to the mid- to high-altitude region (say between 5 and 10 \(R_E\) radial distance, if the sub-solar magnetopause is placed at 11 \(R_E\)) as the cusp throat and the outer, high-latitude region (the “mouth” of the cusp) as the exterior cusp. We recognise here that other authors, referred to above, have introduced a variety of definitions, and we will try to build a consistent plasma and field description around these geometrical terms as we proceed]. After about 08:00 UT, the field turns from southward to northward, corresponding to the passage through dayside field lines. During this period, the model deviates significantly from the \(B_X\) component, the component expected to be most sensitive to the precise conditions near the magnetopause boundary. The observed deviation simply means that near the external cusp region the field points less northward than predicted by this model. This is plausibly explained as an effect of the high-altitude cusp structure on surrounding magnetic field lines (in both the lobe and closed dayside regions), which is not included in the earlier T89 model and which has been addressed by Tsyganenko and Russell (1999).
In addition to the DC trend seen in Figure 3, there are a number of features. Entry into the cusp throat at 05:05 UT (5 \( R_E \)) is seen as an increase in ULF fluctuations on all spacecraft traces. The character of these fluctuations in fact changes as the passage proceeds through the region (Cargill et al; private communication), particularly after about 06:25 UT. The spacecraft configurations in Figure 2 show that they are arranged with spacecraft 1 and 3 outermost along the throat and spacecraft 2 and 4 innermost. Close inspection of the individual traces in \(|B|\) (best seen on the plot in \( B_Z \)), for example, reveals that spacecraft 1 sees the weakest field, spacecraft 3 a stronger field, spacecraft 2 the next strongest, and spacecraft 4 the strongest. This trend is followed through the throat into the dayside region, as expected from the model field and these spacecraft locations.

Figure 4 shows the ion spectrograms and the density and velocity moments, measured by the CIS-HIA instrument, together with the FGM

*Figure 2.* The event of 17 March 2001, which corresponds to a northern cusp crossing during the outbound leg of the orbits. This dayside orientation of the Cluster orbits is projected into the \( Z, X_{GSM} \) plane on the main axes. The spatial configurations of the spacecraft are shown at a sequence of times around the orbit and scaled (enlarged) by a factor of 20. The inset shows the corresponding \( X, Y_{GSM} \) projection of the configuration between the labelled times. The spacecraft are colour coded as follows: s/c1 (black), s/c2 (red), s/c3 (green), s/c4 (magenta); with spacecraft 1 corresponding to the orbit shown. Blue dots around the orbit correspond to hourly intervals starting from 00:00 UT. Also shown are model field lines, taken from the Tsyganenko model (Tsyganenko, 1989). The magnetopause position (Sibeck et al., 1991) for the conditions observed by ACE is also shown, so that the spacecraft are expected to exit into the magnetosheath at around 09:30 UT (as predicted on the plot).
magnetic field, from spacecraft 1. Also shown is the ACE-IMF, suitably lagged for solar wind convection (Lepping et al., 1995), as taken from the observed bulk velocity (not shown). The lag times are all given in the figure captions. The plasma data mainly show an entry into and through the cusp throat and then dayside plasma sheet (closed magnetosphere) and out into the magnetosheath, confirming the interpretation from the magnetic field data. After about 05:05 UT and before 06:25 UT, the ions show a broadband signature at magnetosheath energies (top panel). We interpret this as corresponding to passage through the cusp throat. The band fades through a

\[ \text{Figure 3.} \] The corresponding multi-spacecraft, vector magnetic field plot for the event in Figure 2 is plotted with the four spacecraft traces overlain. The colours for each superimposed trace correspond to the spacecraft colours defined in Figure 2. At high field the traces separate in the order described in the text and the vertical dashed blue lines refer to the boundaries described in the text, separating the regions indicated. The dashed blue lines are the T89 model field values along the orbits (only s/c 1 is shown) and have been calculated for low magnetic activity.
boundary region, starting from about 06 UT, where the density begins to fall from 10 cm$^{-3}$ to the low densities expected for the dayside plasma sheet (0.2–0.3 cm$^{-3}$). During this transition, there is an onset of a high-energy band

Figure 4. Multi-panel plot of the plasma and field information from Cluster and ACE, with vertical dashed lines indicating the corresponding features to those in Figure 3. From top to bottom these are: the ion energy spectrogram, density, velocity and magnetic field from Cluster, and the lagged ACE magnetic field representing the IMF. The lag time is computed as a simple convection time, using the ACE solar wind velocity, and is 82 min in this case.
of ions (between 5 and 10 keV). The spacecraft therefore appear to traverse the dayside region after about 06:25 UT, which is filled with trapped plasma sheet ions on closed field lines (not shown, see the companion paper by Lavraud et al., 2003). After 07 UT and until the magnetopause exit at 09:20 UT the ion density remains low with no significant bulk flow (during this period the GSM magnetic field turns from southward to northward). These gross features are characteristic of the regions traversed in all the events shown in this paper.

Within the interval through the throat (between 05:15 and 06:15 UT) there are a number of additional transient signatures. Some of these relate to dispersive signatures in the plasma data (Vontrat-Reberac et al., 2003) and some to transient, impulsive signatures, which can be correlated with plasma flows in the ionosphere (Marchaudon et al., 2003). The latter are associated with brief, southward (and dawnward) turnings of the IMF during the pass. On one occasion (06:40 UT) the spacecraft appear to be taken back into the throat region from the dayside (plasma sheet). Such an occurrence would be expected for a southward (or sunward) motion of the equatorward edge of the cusp, perhaps due to erosion of the dayside magnetopause. Such transient motions also appear more dramatically in the other events discussed below. The event here, however, has few clear boundary crossings within the cusp structure to confirm such motions or to confirm spatial as opposed to temporal effects. Nevertheless, the spacecraft sequence through a number of features in the time series data gives timing information, which confirms the expected order in passing from one region into another. For example, spacecraft 3 (green) exits first from the cusp throat, followed by 2, then 1 and 4 together, as implied by the orientation of the spacecraft configuration with respect to the cusp throat. Again, observation of these trends is useful in developing the interpretations below.

This event therefore corresponds to a traversal across the mid- to high-altitude throat region, followed by a passage through magnetospheric field lines near the dayside boundary, before a final exit into the magnetosheath. The event is chosen, and described first, because these quiet, external conditions produce a classic pass through the region, where the cusp location appears to be close to that predicted by the Tsyganenko model and the slow change in magnetic field topology can clearly be seen. The spacecraft pass out into the magnetosheath almost as indicated in Figure 2, drawn relative to the model field lines, which apparently change orientation from the southward/tailward throat alignment to the northward, dayside alignment, along the orbit. The event thus serves as a good template for the other events, some of which occurred during more dynamic conditions, often with repeated large-scale cusp motion, which adds to the observed signature. The pass is similar to that described in Section 3.3 below, in particular, but appears to be deeper within the dayside region.
3.2. Events of 13 and 20 February 2001 and 4 April 2001

Figure 5 shows the orbit and spacecraft configurations for two inbound traversals through the southern cusp regions for different IMF conditions. The first of these events has been briefly studied by Cargill et al. (2001), from the point of view of the magnetic field measurements, and both have been comparatively studied by Cargill et al. (2003) in combination with PEACE and CIS data. The crossings occurred during the entry of the spacecraft into the magnetosphere on the inbound, southern leg of the Cluster orbits. During the period of entry into the magnetosphere, the IMF was varying in some components. In the first case the field was more variable, but predominantly southward. In the second case it was dawnward and had turned southwards before entry into the cusp region and magnetosphere (at 23:00 UT, see Figure 7). The magnetic field magnitude (as measured by the FGM instru-

![Figure 5](image-url)

*Figure 5. (a) The event of 13 February 2001, which corresponds to a southern cusp crossing, during an inbound leg of the orbit, ending at 24:00 UT. The orbit and spacecraft configurations (top panel) are drawn in the same format as for Figure 2, together with insets showing the X,Y GSM projection of the configuration at cusp entry. Projected magnetic field vectors, as measured by FGM, are also shown around the orbit. The bottom panel shows the corresponding measured magnetic field magnitude for all spacecraft traces overlain with the same colour coding. The presumed, exterior cusp entry is indicated on the orbit track. (b) The event of 20 February 2001, which corresponds to a southern cusp crossing during an inbound leg of the orbit in the same format as for (a).*
ment) for a 1-h interval around the cusp traversals is shown in the bottom panels of Figure 5 and the projected field direction is added along the orbit tracks in the top panels. In each case, entry into what we define as an “exterior” cusp region appears to be directly from the magnetosheath and is identified here by both a depression in the magnetic field magnitude and an increase in the magnetic field fluctuations. These features are clearly visible in both events. The approximate position of the initial cusp entry in each case is indicated on the orbit.

Figure 5a, for example, shows that on 13 February the spacecraft entered the cusp from the magnetosheath (or boundary layer) at about 20:00:30 UT. Figure 5b shows that on 20 February the spacecraft entered the cusp from the magnetosheath (or boundary layer) at about 23:20:30 UT (these times refer to the end of the transition, seen as a decrease in |B|). One of the projected spacecraft configurations is drawn for these times in the top panels of each Figure. The main exits from the low field region (into the magnetosphere) occurred at 20:07 UT for 13 February 2001 and at 23:33 UT for 20 February 2001. These are both interpreted as an exit from the rear of the cusp-throat region into the plasma mantle, and subsequently into the tail lobe. These exits appear to be directly from a low field (diamagnetic) region. The insets in the figures show the projected spacecraft configurations into the X,Y_GSM plane for both events. From these and the main projections in Figure 5, it is apparent that both events have very similar nominal locations with respect to the magnetosphere: in fact, both lie slightly duskwards of noon. The four spacecraft, vector magnetic field data from both events (on an expanded scale focussing on the cusp entry and exit) are shown in Figure 6 (showing entry and exits by the dashed vertical lines).

As mentioned, the crossings through the exterior cusp region are characterised by a reduced field magnitude, but it is also apparent from Figure 6 that large magnetic shears (changes in the field direction: second and third panels from the bottom) are also present, particularly for 20 February 2001. In the case of 20 February 2001, the traversal is complicated by a brief exit back into the magnetosheath or an adjacent boundary region at 23:25 UT, but with a cusp re-entry at 23:26:30 UT. In both cases, just prior to the initial cusp entry, the magnetosheath field is dawnward, but is consistently southwards (in line with the IMF) only in the case of 13 February 2001 (see Figure 7). For 20 February 2001, the orientation turns southwards before the first entry, but remains predominantly dawnward at the re-entry (just before 23:26:30 UT). Thus, differences between the observed IMF and local magnetosheath conditions at these latitudes can be significant. In both events, the final exit appears to be into the tailward magnetosphere (mantle region), showing a duskward as well as a southward field, implying an exit into the duskside mantle region.
Figure 7 shows the ion spectrograms and the density and velocity moments measured by the CIS-HIA instrument, together with the FGM magnetic field, from spacecraft 3 for 13 February 2001 and 20 February 2001. Also shown is the ACE-IMF, already mentioned above, suitably lagged for solar wind convection (note the correlation with the magnetosheath trend seen at Cluster before cusp entry) as for the 17 March 2001 event. From these figures it is seen that the plasma ion distributions show a more extended...
structure than the magnetic field. It is also clear that the plasma moments show no evidence of the "stagnant" regions observed in the events discussed by Lavraud et al. (2002, 2003). In both cases, however, the southward and dawnward directed IMF (and magnetosheath field) is likely to result in significant and perhaps continual magnetic reconnection across the dayside magnetopause, and the result of such field line merging is likely to be that field lines are continually swept tailward across the cusp. In the case of 13 February 2001, the ion velocity data show a continual southward component, which in the magnetosheath is consistent with the southward location and flow around the magnetopause, and in the cusp is consistent with the

Figure 7. Plots of the Cluster ion spectra and moments and magnetic field, together with lagged ACE-IMF data in the same format as Figure 4, (a) for 13 February 2001 and (b) for 20 February 2001. The lag times used for the ACE magnetic field are: 53 min 20 s, for 13 February 2001, and 73 min 20 s for 20 February 2001.
convection of reconnected field lines persisting into the plasma mantle. In the case of 20 February 2001, however, the IMF and magnetosheath field had a dominating dawnward component (more so in GSE coordinates), so that we expect this convection of reconnected field and flow to have a significant dawnward component, as observed. On entry to and exit from the cusp region there are clear deflections in the velocity, particularly at the cusp entry from the magnetosheath, which shows a strong deflection into \(-Y_{\text{GSE}}\). The electron spectrograms (not shown), measured by the PEACE instrument, for the cusp entries also show no sharp signatures. There is, however, a drop in the flux of the high-energy band (above 100 eV) on entry (possibly representing lower temperature), and an increase in energy of the low-energy band on exit before a slow transition into the mantle. Although overall there is only a slow change electron and ion distribution, the sharp exit from the cusp into the mantle region, seen by the magnetic field, is well visible (in the case of 13 February 2001). For example, the ion density changes by a factor of 2 on spacecraft 3.

Although entry to, and exit from, the low field cusp region appear to be clear from these data signatures, close inspection of the full magnetic shear reveals that the spacecraft crossing order does not imply a simple outward motion of the boundaries across the spacecraft array. This is particularly so in the case on entry. For instance, the spacecraft configurations for both days (Figures 5 to 7) show that spacecraft 1 (black) is leading (and innermost), with the other spacecraft lying in a plane which is oriented close to the nominal magnetopause. Taking a model magnetopause boundary orientation, therefore, and simple outward motion of the boundary, it would be expected that spacecraft 1 enters and exits the cusp region first, with the order of the other spacecraft depending upon the actual boundary orientation and relative motions. It is fairly clear (Figure 6) that spacecraft 1 appears to be the first to exit the low \(|B|\) region of the exterior cusp into the magnetospheric lobes (mantle) at 20:07 UT (13 February 2001) and 23:33 UT (20 February 2001). In fact, the spacecraft crossing order in both events (spacecraft: 1, 4, 3/2) implies the cusp-throat motion is both northwards (outwards) and dawnswards across the spacecraft array. This motion is possibly consistent with a stress-induced motion arising from the dawnwards directed magnetosheath field (and consistent with the IMF orientation upstream), for instance. The entry to the cusp from the magnetosheath, however, is obscured by changes in the magnetic field direction so that the implication of the crossing order of the spacecraft is somewhat more confused. Even the assumption that the dawnwards directed magnetosheath field also results in a significant dawnwards motion of the cusp, on entry, is insufficient to explain the crossing order. It is possible, however, that an indentation in the cusp/magnetosheath boundary could suitably affect the spacecraft crossing order (see Section 4).
Further analysis of the boundary dynamics of the whole traversal, together with a possible narrowing or expansion of the cusp region, are discussed in Section 4. The details of the magnetic fluctuations and other magnetic structure throughout the traversal are not discussed here, but are dealt with by Cargill et al. (2003). We comment here, however, that the 20 February 2001 event does not correspond to clearly southward IMF conditions, and shows a more turbulent and twisted magnetic field configuration within the cusp. A third southern cusp traversal, corresponding to 4 April 2001, is shown in Figure 8 in the same format as the previous examples. Here, entry from the magnetosheath occurred at around 19:44 UT, with final exit into the mantle at around 20:28 UT (timings from spacecraft 1). This event shows a more extended signature than for either of the previous two, but has very similar character; we do not discuss it in detail. There is a brief exit back into the magnetosheath at 20:08 UT (similar to that seen on 20 February 2001). At the inner cusp boundary, on exit into the tail lobe, spacecraft 1 exits the

Figure 8. The event of 4 April 2001, which corresponds to a southern cusp crossing during and inbound leg of the orbit in the same format as for Figure 5.
cusp on a couple of occasions before all spacecraft finally exit into the lobe. The magnetic field again shows a rapidly changing orientation throughout this long encounter (see Figure 9). This event is of interest since the spacecraft crossing order appears to be clearer than for the previous events, and fits a simple traversal through the cusp region during an outward motion of the magnetopause, overall (the brief exit at 20:08 UT shows a nested signature consistent with a simple reversal in this motion of the boundary). For instance, spacecraft 1 enters each region first, followed by the others in the expected order (i.e. spacecraft two and three together and four trailing on the cusp entry) for a boundary nominally aligned with the magnetopause. The possibility that the more confused crossing order, seen during the previous two events, is due to dawnward motion (arising from the apparent $B_Y$ induced stress) is therefore given more credence by this counter example.

Figure 9. The four spacecraft vector magnetic field in GSM co-ordinates for 4 April 2001, showing the key regions discussed in the text.
3.3. Event of 26 February 2001

Figure 10 shows the orbit and spacecraft configuration for a traversal, which occurred during more dynamic conditions, corresponding to a southward IMF (\(-B_z\)), but also fairly radial (i.e. strong \(B_x\)) component. These conditions produced a complex series of boundary crossings through the different regions adjacent to the cusp. The event occurred during an outbound, northern exit of the spacecraft from the magnetosphere, as shown in the top panel of Figure 10. The cusp traversal separates into a passage through two distinct plasma regions. The first appears to correspond to a mid- to high-altitude (i.e. within the “throat” of the cusp) traversal. The second corresponds to a dynamic interval during which several entries to and exits from the high-altitude (or an exterior) cusp and dayside magnetosphere occur before the exit into the magnetosheath (also via multiple crossings). During the traversal the cusp boundaries appear to undergo some reconfiguration in the form of possible erosion (and recovery) of the equatorward boundary and large-scale motion of the whole high-altitude region. In Section 4 we concentrate on summarising the analysis of the time interval after 05:30 UT,

![Figure 10](image_url)

*Figure 10*. The event of the 26th February 2001, which corresponds to a northern cusp crossing during an outbound leg of the orbit in the same format as for Figure 5.
when repeated motion of high-altitude cusp resulted in the spacecraft encountering the dayside magnetospheric boundary, and then magnetosheath.

The spacecraft entered the cusp throat at around 04:08 UT, as suggested by increased ULF wave activity, apparent as increased fluctuations in $|B|$ in the lower panel of Figure 10. The spacecraft traversed the throat during the next hour, and appeared to move to higher altitudes during this time in a manner almost as inferred by the model field lines and orbit track, shown in the top panel of Figure 10. In consequence, the field magnitude slowly falls on all spacecraft during this time, as expected for a slow movement up the throat. The spacecraft configuration near 04 UT (top panel) indeed shows that the spacecraft form a sequence in order of relative position outward along the cusp throat: 4(magenta), 2(red), 3(green), 1(black) from the lowest (highest field) to highest (lowest field) position. The multi-spacecraft traces separate, in terms of decreasing field magnitude, according to the same sequence (4,2,3,1). They follow this trend until about 05:20 UT, when the magnetic field configuration changes. After this time, the sequence of crossings in and out of the cusp can be seen as changes in the magnetic fluctuations.

Figure 11 shows the ion data in conjunction with the magnetic field data from spacecraft 1 and the (lagged) IMF measured by ACE in the same format as Figure 7. The key difficulty with interpreting this event is that the IMF($-B_Z$) is variable, but often southward, and $B_X$ is often strongly negative, giving an almost radially aligned field during the passage through the cusp. The orbit naturally moves from dawn to dusk (remaining within an hour of local noon) during the exit from the magnetosphere, but is almost at magnetic noon at 05:00 UT. The actual spacecraft location will therefore be sensitive to any dawn–dusk motion of the cusp as well as to any North–South motion. In combination, these facts make any correlation with IMF conditions very hazardous, and the high variability evident in this pass probably results from the IMF configuration in the solar wind. Nevertheless, both the CIS data shown in Figure 11 and the PEACE data (Figure 13, see later) indicate that the spacecraft pass through distinct plasma boundaries at 05:12 and 05:21 UT.

The ion energy time spectrogram shown in the top panel of Figure 11, for example, suggests that the Cluster spacecraft enter a distinct region (adjacent to the cusp) after about 05:12 UT, presumably on the equatorward edge of the throat. After this time, they appear to exit into a region made up of high energy, bi-directional electrons and high-energy trapped (loss cone in the distribution functions) ions, and therefore we interpret it as the dayside magnetosphere (or plasma sheet). The bulk density falls slowly during the approach to this boundary (presumably within the cusp throat) and then falls dramatically on exit into the dayside region. The