Cluster observations of the exterior cusp and its surrounding boundaries under northward IMF

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[1] We have studied in detail multi-spacecraft observations of the exterior cusp on 04 February 2001, during a steady northward Interplanetary Magnetic Field (IMF) interval. At a radial distance of 11 Re, Cluster encountered a well-bounded region where the magnetic field exhibited very low diamagnetic values and the ions displayed high levels of isotropisation. We refer to this region as the Stagnant Exterior Cusp (SEC). Its equatorward edge is magnetopause like, whereas on the poleward side of the SEC, high-speed plasma jets were observed consistent with a reconnection site poleward of the cusp. The SEC/magnetosheath boundary is characterized by abrupt changes in the magnetic field and plasma parameters that satisfy the Walén test, and by an S-shaped magnetic hodogram. The latter may suggest the presence of an intermediate/slow transition. *INDEX TERMS:* 2724 Magnetospheric Physics: Magnetopause, cusp, and boundary layers; 2784 Solar wind/magnetosphere interactions; 2109 Interplanetary Physics: Discontinuities. **Citation:** Lavraud, B., et al., Cluster observations of the exterior cusp and its surrounding boundaries under northward IMF, *Geophys. Res. Lett.*, *29*(20), 1995, doi:10.1029/2002GL015464, 2002.

1. Introduction

[2] The existence of the magnetospheric cusps was revealed by the early magnetospheric model of *Chapman and Ferraro* [1930]. This predicted the possible entry of magnetosheath plasma into the magnetosphere through the subsequent null points present at the poles of each hemisphere. Two main explanations have been proposed to account for the solar wind plasma entry into the magnetosphere: diffusion processes and magnetic reconnection.

[3] Based on HEOS 2 data, *Paschmann et al.* [1976] proposed the existence of a plasma 'entry layer', adjacent to the magnetopause near the cusp, that would constitute the prime location for solar plasma entry into the magnetosphere. *Haerendel et al.* [1978] proposed an overall picture of the distant polar cusp. Rather than assuming the existence of a neutral magnetic point inferred from all magnetospheric models, they proposed the presence of an extended region over ~4–6 hrs LT at the magnetopause. The data showed perturbed field and flow, suggesting existence of eddies in the plasma flow and possible diffusion at the boundaries of this 'stagnation region.'

[4] Such a picture suggests the presence of an external boundary between the stagnation region and the magnetosheath, as discussed by *Hansen et al.* [1976]. The interpretation of the overall topology of the cusp, and its terminology, has changed in the literature, partly because reconnection [*Dungey*, 1961] is now widely assumed to be the main process allowing for solar wind plasma entry into the magnetosphere. According to *Russell* [2000], the exterior cusp is located outside the magnetopause and is characterized by a drop in magnetic field strength (together with typically large changes in magnetic field direction, such a definition is often used in the high altitude cusp). The region is directly bounded, outward from the magnetosphere, by a cusp/magnetosheath interface which has also been studied by *Savin et al.* [1998]. An alternative view has been proposed by *Chen et al.* [1997] which consists of both an interior cusp, earthward of the magnetopause, and an exterior cusp outside the magnetopause and bounded by the magnetosheath. This interior cusp was described in that study to be the region of magnetic depletion. The region we deal with here resembles the early stagnation region of *Haerendel et al.* [1978]. Because it is part of the exterior cusp, we refer to it descriptively as the Stagnant Exterior Cusp (SEC) in this paper. Its properties show particularly weak magnetic field (<20 nT) and highly isotropic ion distribution functions. Whether this part of the exterior cusp is a detached region or is an extension of the cusp itself will not be addressed in this paper. The event we focus on here, 04 February 2001, is chosen because the spacecraft cleanly encountered the SEC and its surrounding boundaries.

2. Cluster Orbit and Instrumentation

[5] Figure 1 shows a schematic of the Cluster spacecraft orbit (spacecraft 1) and tetrahedron configuration (at 21:00 UT) for the 04 February event. The spacecraft crossing of the exterior cusp occurred near local noon (~12:30 MLT). We use data from the Cluster Ion Spectrometry (CIS) and the Flux Gate Magnetometer (FGM) instruments. The CIS instruments measure full 3D ion distribution functions and moments [*Rème et al.*, 2001], with a resolution up to the

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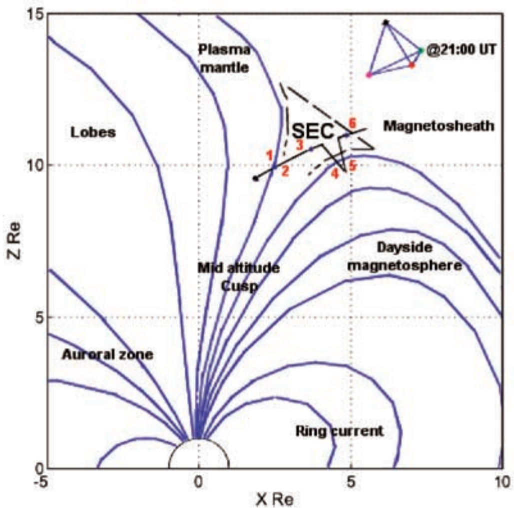

Figure 1. Schematic of the Cluster orbit and tetrahedron configuration (on top at 21:00 UT, it is enlarged by a factor of 20 for clarity) during the interval 19:30–22:30 UT, projected in the X,Z_{GSM} plane. The spacecraft positions are colored as follows: spacecraft 1 (black), spacecraft 2 (red), spacecraft 3 (green), spacecraft 4 (magenta). The field lines are sketched to fit the data but are adapted from the *Tsyganenko* [1989] model at low latitudes for context. The dashed line schematically represents the extent of the SEC, by implication from the boundary crossings.

spin rate (~4 sec), while the FGM experiment can provide high time resolution (22.4 and 67 Hz) magnetic field measurements [*Balogh et al.*, 2001]. The CIS instruments on spacecraft 1, 3 and 4 and the FGM instruments on all four spacecraft were operating during this event.

3. Observations and Analysis

[6] Figure 2 shows CIS and FGM data from spacecraft 1. The IMF (measured by ACE) has been shifted by 4800 seconds to account for the solar wind convection time, calculated from correlation between ACE and FGM data when Cluster is in the adjacent magnetosheath. The IMF was mainly directed northward, with average values of Bx ~−2 nT, By ~0–2 nT and Bz ~ 3 nT. The solar wind dynamic pressure is low, varying between 0.45 and 0.65 nPa during the interval. This figure shows that the Cluster spacecraft were in the low density (N ~ 0.03 cm-3) northern lobes until 19:55 UT. They then entered the high-altitude/exterior (since the distance is around 10.5 Re) cusp where high speed plasma jets can be seen on magnetospheric field lines, with bulk speed larger than 200 km/s (labeled region 1 in Figures 1 and 2). The spacecraft then encountered a region with slower plasma flows but with a similar level of fluctuation in velocity and magnetic field (labeled 2), from 20:40 UT until the entry into the SEC.

[7] We present in Figure 3 two-dimensional cuts of the ion distribution function from HIA at six different times: number I is in the high-altitude cusp where plasma jets are recorded, II is in the region showing fluctuations, III is inside the SEC, IV and V are inside the SEC/magnetosheath boundary and number VI is in the unperturbed magnetosheath. The entry into the SEC is clear from around 21:20 UT (label 3), it is mostly characterized by highly isotropic ion distribution functions, and both density and temperature are high (Figures 2 and 3III). The magnetic field is very weak, and accordingly, the β values are high in the SEC (Figures 2e and 2f). Distribution 3III is typical of the SEC region from around 21:20 UT until the exit in the magnetosheath, except for a brief entry into the dayside magnetosphere at ~21:42 UT. This distribution function (III) is in contrast with the one in the slow flow region characterised by fluctuations, that shows clear counterstreaming ions (label 2, distribution 3II). The spacecraft stayed in the SEC region until 22:02 UT, when they exited into the magnetosheath (see Figure 3 VI).

[8] A brief entry into the dayside magnetosphere occurred between 21:41–21:45 UT (Figure 2, labels 4 and 5). Combined use of the Minimum Variance Analysis and the planar Discontinuity Analysis techniques, using four spacecraft high resolution magnetic field, yield the following boundary normals and speed for the two successive encounters: n = (−0.43, 0.57, 0.71), Vn = +11.4 km/s and n = (−0.10, −0.13, 0.99), Vn = −10.1 km/s. The ratio of intermediate to minimum eigenvalues is >6 for the three crossings analyzed in this paper, indicating good normal determinations. The spacecraft signatures show a well-defined nested structure together with a clear reversal of

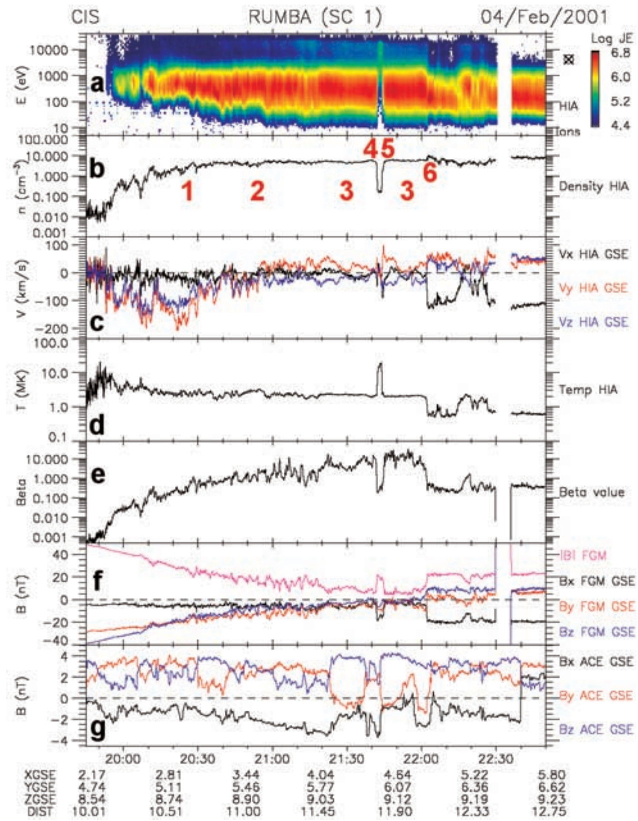

Figure 2. Panel a shows an energy-time spectrogram of all ions from the CIS/HIA instrument onboard spacecraft 1 on 04 February 2001. Panels b, c, d, e, and f respectively display the density, the bulk velocity components in GSE, the ion temperature, the β value, and the FGM magnetic field components in GSE and its magnitude. Panel g shows the lagged Solar Wind ACE magnetic field data in GSE.

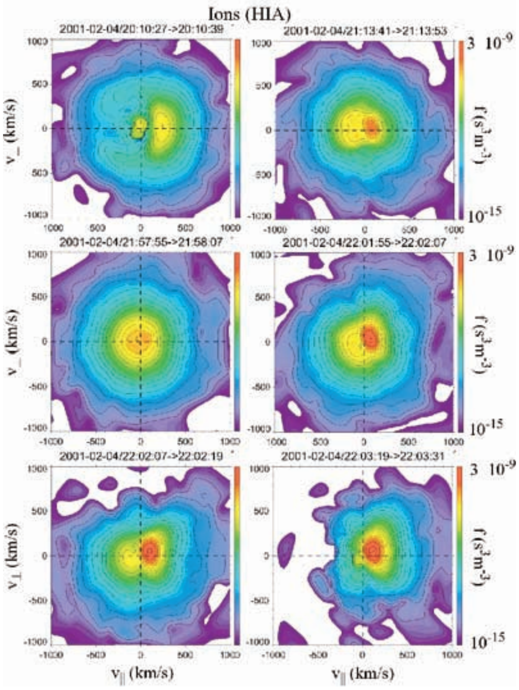

Figure 3. Two-dimensional cuts of the ions distribution function in the ($V_\parallel$, $V_\perp$) plane.

the motion along the normal direction. The drastically different magnetopause normals for the inbound and outbound crossings imply that the spacecraft entered the magnetosphere at 4 and exited at 5 (Figure 1). Such crossings were apparently caused by a transient tailward, and then equatorward motion of the indented magnetopause. At these boundaries, the normal component of the magnetic field was nearly zero (not shown). The spacecraft exit afterwards from the SEC into the unperturbed magnetosheath at 22:02 UT through a very sharp boundary (label 6 in Figures 1 and 2). The analysis of the boundary dynamics shows a normal n = (0.65, 0.45, 0.61) with a velocity of −8.8 km/s. Crossing from the magnetosheath into the SEC, both the flow speed and the magnetic field magnitude decrease drastically, while the β value and the temperature increase abruptly (see Figure 2).

4. Discussions

[9] The observations presented in the last section indicate that for northward IMF, there is a region in the exterior cusp where the magnetic field is extremely weak and the plasma is hot and nearly stagnant. The particle distribution consists of a single isotropic population and the magnetic field displays nearly no low-frequency turbulence. The Stagnant Exterior Cusp (SEC) is surrounded by sharp boundaries both on its day (equatorward) side, compatible with an indented magnetopause and a funnel like topology, and with the outer unperturbed magnetosheath. The SEC is also separated from the lobes by a more turbulent region with counterstreaming ion populations and plasma jets that are indicative of a plasma injection site tailward of the cusp. The ion energy dispersion seen in Figure 2a from 19:55 UT to 21:UT is also consistent with this feature. We now discuss the SEC/magnetosheath boundary in more detail as well as the possible origin of the stagnant plasma in the SEC.

4.1. SEC/Magnetosheath Boundary Structure

[10] The magnetosheath and the SEC are separated by a sharp boundary across which the plasma temperature and velocity, as well as the magnetic field strength and direction, change abruptly. To examine the spatial structure of this boundary in more detail, Figure 4 shows a zoom-in of the boundary with magnetic field (8 Hz) data from all 4 spacecraft and the normal ion velocity from 3 spacecraft (in MVA coordinates of spacecraft 1). It is seen that the normal components of both the velocity (∼−20 km/s) and the magnetic field (∼−3 nT) point inward. The latter is consistent with a reconnection site poleward of the spacecraft while the former indicates plasma transport across this boundary.

[11] We have performed the Walén test (see Figure 5) to investigate whether the flow and field changes across this boundary are consistent with a rotational discontinuity (RD). A good de-Hoffmann Teller frame (moving at [4, 31, −32] km/s) was found for this boundary, and the flow speed in this frame is 91% of the Alfven speed, in excellent agreement with expectations from an RD. The positive slope of the regression line implies that the normal magnetic field points earthward, consistent with the magnetic field measurements, and with reconnection occurring tailward of the spacecraft.

[12] However, although the magnetosheath/SEC boundary is primarily consistent with an RD resulting from lobe

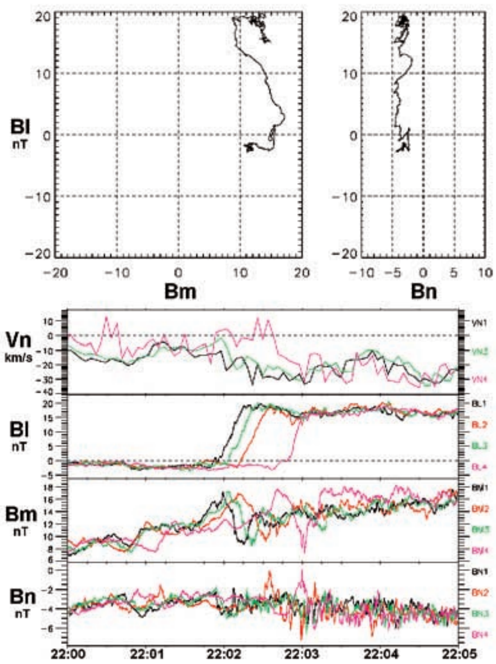

Figure 4. In the bottom plot, first panel shows spacecraft 1, 3 and 4 ion normal velocity. The three next panels show the four spacecraft FGM magnetic field data components in the LMN coordinates (Maximum, medium and minimum variance respectively), computed with the MVA technique (spacecraft curves are color coded as in Figure 1). The top figures show spacecraft 1 magnetic field data in an L-M (left) and L-N (right) hodogram representation.

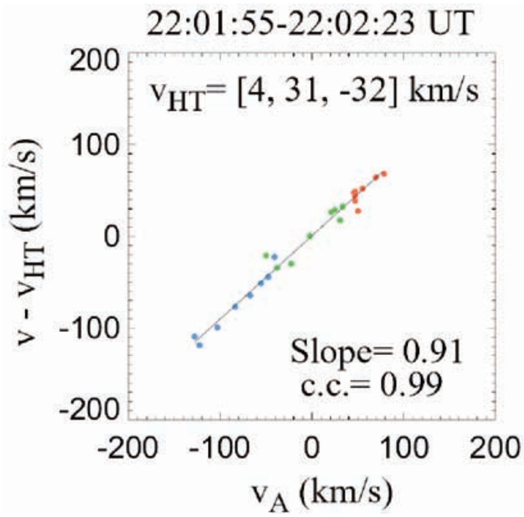

Figure 5. Walén test across the SEC/magnetosheath boundary showing the relationship between the flow velocity in the deHoffmann-Teller frame and the Alfven velocity. The results are consistent with the presence of a rotational discontinuity at this boundary.

reconnection, the large plasma parameter and field jump across this boundary are not consistent with the hot SEC isotropic distribution being the result of local entry of magnetosheath across a simple RD. The magnetic hodogram of this boundary is S-shaped and this structure appears to be spatial as it is detected by all 4 spacecraft (Figure 4). Such a hodogram is suggestive of intermediate or slow mode shocks [*Hau and Sonnerup*, 1990; *Karimabadi et al.*, 1995; *Dubinin et al.*, 2002]. The density decrease across this boundary from the magnetosheath to the SEC at first seems inconsistent with a slow transition interpretation. However, this density enhancement detected on spacecraft 1 and 3, just adjacent to the boundary, is not detected by spacecraft 4 later, revealing the possible convective nature of this structure. It is noted that the field transition is non-coplanar which is consistent with a strong intermediate transition. Thus, the structure of this boundary is still not fully understood.

[13] With a normal boundary speed of −8.8 km/s and a current sheet crossing duration of ~25 s, the boundary thickness is ~220 km. This corresponds to ~5 gyroradii of the thermal magnetosheath ions. If one were to obtain the boundary normal speed from Vht · n, one obtains a speed of −3 km/s and a thickness of 75 km or 2 gyroradii.

4.2. Source of the SEC Plasma

[14] The ion energy dispersion and the gradual decrease of the ion temperature (Figures 2a and 2d) as one moves from the lobe to the SEC suggest that the SEC ions enter this region via a reconnection site. The evolution of the ion distributions in Figure 3 shows that the jet distribution is hot due to time-of-flight effect where only the high-energy particles can reach the poleward most reconnected field lines (Figure 3I). As one moves to more equatorward field lines, the distributions contain more and more low-energy ions, some of which mirror at lower altitudes and return (Figure 3II) [*Fuselier et al.*, 2000]. The temperature levels off to the SEC level where the distributions appear nearly isotropic. However, how distribution 3II evolves into distribution 3III with an even weaker field is not clear.

[15] The ion distributions sampled in the SEC/magnetosheath boundary consist of counterstreaming (incoming) cold magnetosheath and (outgoing) hot SEC ions (Figures 3IV and 3V). This indicates that the SEC population is pre-existing. In other words, the incoming part of the plasma inside the SEC may not be the simple/unique result of the heating and slowing down of magnetosheath plasma across the boundary. Also, it is not clear why the global temperature during the whole cusp crossing is ~4 times greater than in the adjacent magnetosheath. This however shows that a heating process must be involved at some points.

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