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Magnetospheric Cusps under Extreme Conditions: Cluster Observations and MHD Simulations Compared

George Siscoe · Zerefşan Kaymaz · Yulia V. Bogdanova

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Abstract MHD simulations are here applied to aid in the interpretation of three apparent cusp encounters by the Cluster 4 spacecraft in unusual places when the magnetosphere was under extreme solar wind and interplanetary magnetic field (IMF) conditions associated with the passage of magnetic clouds imbedded within fast ICMEs. At the time of each cusp encounter the IMF was very strong, generally northward in one case, generally equatorial in a second case, and generally southward in the third case. In the southward IMF case, the MHD models locate the origin of the cusp-like plasma by showing that the position of the spacecraft at the time of encounter was engulfed in a tongue of high-pressure plasma extending from the magnetopause into the magnetosphere. This tongue points to the northern-hemisphere cusp as the source of the feature. In the equatorial IMF case an elevated-pressure feature that apparently marked a cusp encounter in the computations coincided, however, with a passage in the solar wind of a dynamic pressure pulse, thus giving an alternative interpretation of the feature. However, Cluster data unambiguously identified the event as an encounter with magnetosheath-like plasma. Given that the Cluster observations classify the event as a true encounter with a cusp-like plasma feature (and not a compression event), the model simulations can be interpreted as identifying the origin of the feature to have been the northern-hemisphere cusp even though — and this is the interesting point — the observation point was in the southern hemisphere. In the northward IMF case, neither cusp (defined as a magnetic funnel linking the magnetopause to the Earth) was directly connected to the observation point. Instead, this encounter of magnetosheath-like plasma appears to be an instance of boundary-layer formation by means of the Song – Russell mechanism in which two-point

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G. Siscoe (✉)
Center for Space Physics, Boston University, Boston, MA, USA
e-mail: siscoe@bu.edu

Z. Kaymaz
Faculty of Aeronautics and Astronautics, Istanbul Technical University, Istanbul, Turkey
e-mail: zerefsan@itu.edu.tr

Y.V. Bogdanova
Mullard Space Science Laboratory, University College London, Surrey, UK
e-mail: jb@mssl.ucl.ac.uk

magnetic reconnection entrains magnetosheath plasma on closed field lines when the IMF is northward.

1. Introduction

Bogdanova *et al.* (2007) have presented data from the Cluster mission that reveal properties of the polar cusp in Earth's magnetosphere during two of the CME events that are the focus of this special issue. Here we compare for these same two events Cluster data against corresponding outputs of two MHD magnetospheric simulation codes. The simulations provide global context to aid in interpreting Cluster measurements, and for their part the Cluster measurements test the capability of the MHD models to reproduce plasma parameters along the Cluster orbit.

Two MHD models are used to make the model – data comparisons: the BATSRUS code developed at the University of Michigan and the Open GGCM code developed most recently at the University of New Hampshire. The versions of the models used here are those in residence at the Community Coordinated Modeling Center (CCMC), which ran the codes using inputs provided by us for this study and placed the results on the publicly accessible CCMC Web site.

2. Strong Northward IMF and High Dynamic Pressure

Figure 1 shows a plot of the dynamic pressure of the solar wind (ρV^2) and the y- and z-components of the interplanetary magnetic field (IMF) as measured by the ACE spacecraft for a two-hour time interval during the 7 November 2004, ICME when the Cluster spacecraft encountered cusp-like plasma in an unusual place. It is an interval of high dynamic pressure and strong northward IMF. However, conditions are not steady. The dynamic pressure varies by a factor of about 4 (from ~10 to ~40 nPa) in an irregular saw-tooth-shaped curve that peaks at 19.5 hours, while the magnetic field y-component flips back and forth eight times during the interval between positive and negative values and the z-component flips five times. Nonetheless, with regard to the z-component, the interval divides into a northward-dominated interval prior to about 20.3 hours and a negative-dominated interval afterward.

Figure 2 shows the position of the Cluster 4 spacecraft when it encountered evident cusp-like plasma as distinguished by magnetosheath-like densities and temperatures. The notable detail in this figure is that the cusp is located deep within the magnetosphere, sandwiched between a dense plasma sheet and field lines from the northern open polar cap. As it measured cusp-like plasma, Cluster 4 moved tailward in x from about $0.5R_{\mathrm{e}}$ (Earth radii) to $-0.3R_{\mathrm{e}}$, inward in y from about $-2.9R_{\mathrm{e}}$ to $-2.1R_{\mathrm{e}}$, and outward in z from about $3.1R_{\mathrm{e}}$ to $4.3R_{\mathrm{e}}$. This observation poses a global-context issue for MHD modeling to address: namely, what is the relation between the cusp-like plasma that Cluster 4 measured and the global geometry of the cusp, plasma sheet, and open polar cap field lines at this time? In particular, is it possible (according to the models) under the given solar wind and IMF conditions for cusp-like plasma to have been present at essentially the local time of the dawn terminator at a distance of less than $5R_{\mathrm{e}}$ from Earth?

To answer the posed question, we review properties of magnetospheric geometry that are peculiar to strong dynamic pressure and strong northward IMF — the two conditions that make the interval under consideration special. A strong dynamic pressure obviously puts the magnetosphere in a state of unusual compression, and a strong northward IMF puts the

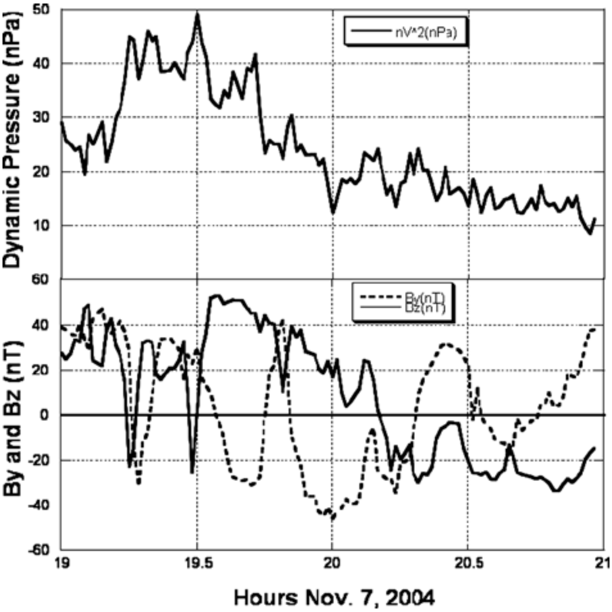

Figure 1 Solar wind dynamic pressure (ρV^2) and the y- and z-components of the IMF measured by the ACE spacecraft during a two-hour interval within the ICME event of 7 November 2004. The times correspond to conditions at Earth obtained by advecting the parameters from the ACE spacecraft using the measured solar wind speed.

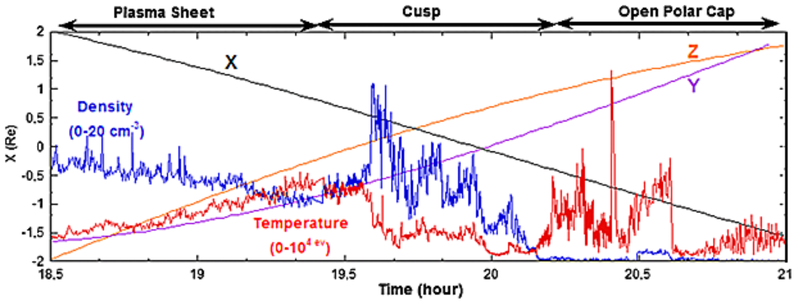

Figure 2 Cluster 4 orbit parameters during the cusp encounter on 7 November 2004, indicated by magnetosheath-like proton densities and temperatures as measured by the Cluster Ion Spectrometer (CIS) experiment. The scales for the density and temperature data plots are 0 to 20 cm^{-3} and 0 to 10^4 eV, respectively, from bottom to top. The temperature is the average of the parallel temperature and the two perpendicular temperatures. The plots of Cluster 4 orbit parameters (but not the data) are taken from the CCMC (http://ccmc.gsfc.nasa.gov) listed under Global Magnetospheric Model Results, run number 062506-3.

magnetosphere in a state of an extreme northward IMF condition, characterized by simultaneous or sequential north-and-south lobe magnetic reconnection and consequent accretion of a closed-field-line dayside boundary layer consisting of magnetosheath plasma (Song and Russell, 1992). States of elevated compression and accreted closed-field-line boundary layer are illustrated in Figure 3. In examining this figure, it should be kept in mind that here the two extreme conditions are displayed separately (high pressure on the top and strong northward IMF on the bottom), whereas they occur together in the event under study.

In the strong-dynamic-pressure half of Figure 3 (top), the magnetopause (identified by the last closed field line) lies at about $8R_e$ and the bow shock at about $10R_e$. The magnetopause normally lies at about $10R_e$, as in the bottom half of the figure. The $8R_e$ magnetopause in

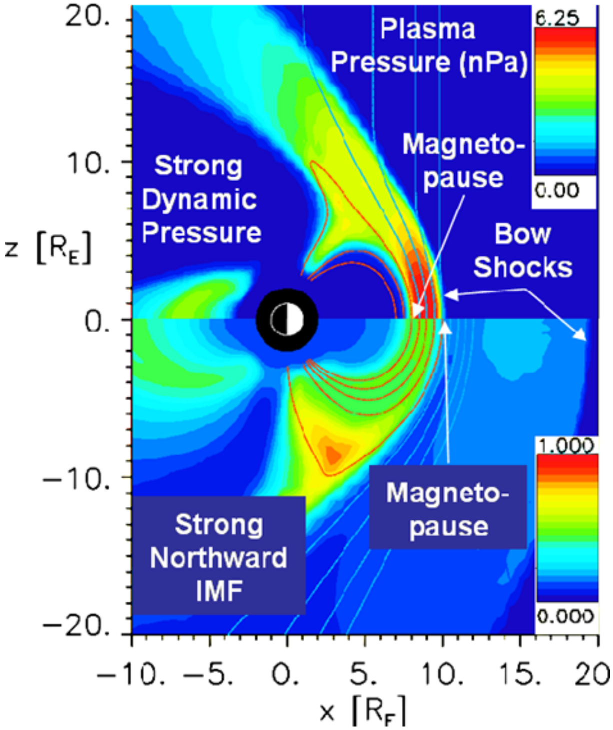

Figure 3 Profiles of the magnetosphere in the noon – midnight meridian plane for two extreme conditions (strong dynamic pressure, top, and strong northward IMF, bottom) as seen in color contours of plasma pressure. Color bars give pressure in units of nPa. The images are from the "General Purpose Runs for Education and Research" listed by the CCMC (http://ccmc.gsfc.nasa.gov) listed under Global Magnetosphere Model Results; runs 112305_1 (top: $V = 400\ \mathrm{km\,s^{-1}}$; $n = 30\ \mathrm{cm^{-3}}$; $B_x = 0$, $B_y = 0$, $B_z = 5$ nT) and 120505_1 (bottom: $V = 400\ \mathrm{km\,s^{-1}}$; $n = 5\ \mathrm{cm^{-3}}$; $B_x = 0$, $B_y = 0$, $B_z = 20$ nT). These runs were made by the Open GGCM code.

this case is a result of high dynamic pressure without the assistance of a southward IMF, which can also displace the magnetopause Earthward through "erosion" (as shown in the following for the event under study). The bow shock in the bottom half lies at about $19R_\mathrm{e}$ because here the Alfvén Mach number is very low. The dynamic pressures in the two cases are 8.0 nPa (top) and 1.3 nPa (bottom).

As mentioned, a basic feature of the magnetosphere under northward IMF is a boundary layer of magnetosheath plasma on closed field lines, which is well seen in the strong northward IMF (bottom) half of Figure 3. This feature results from simultaneous or sequential north and south reconnection of magnetosheath field lines with the magnetic field in both lobes of the magnetotail. The process has been described by Song and Russell (1992) and demonstrated with MHD simulations by Siscoe and Siebert (2003) and Li *et al.* (2005). The reconnection sites lie tailward of the cusps, which causes the cusps to reside on closed field lines, as both the top and bottom halves of Figure 3 show.

The differences that one sees in the boundary layer in the two halves of Figure 3 result from the top half showing a high-β situation and the bottom half a low-β situation. Thus, in the top half the reconnection rate (roughly proportional to the Alfvén speed) is relatively low, resulting in a thin boundary layer, whereas the reconnection rate in the bottom half is relatively high, resulting in a thick boundary layer.

Figure 3 illustrates the general situation that the Cluster 4 spacecraft probably encountered on 7 November 2004 — compressed magnetosphere and a layer of magnetosheath-like plasma coating the dayside magnetopause on closed field lines. To go from this general picture to a determination of the origin of plasma along the specific Cluster trajectory on 7 November 2004 — in particular, to tell whether the plasma comes from the magnetosheath or the plasma sheet — it is useful to make contour plots of specific entropy since this quan-

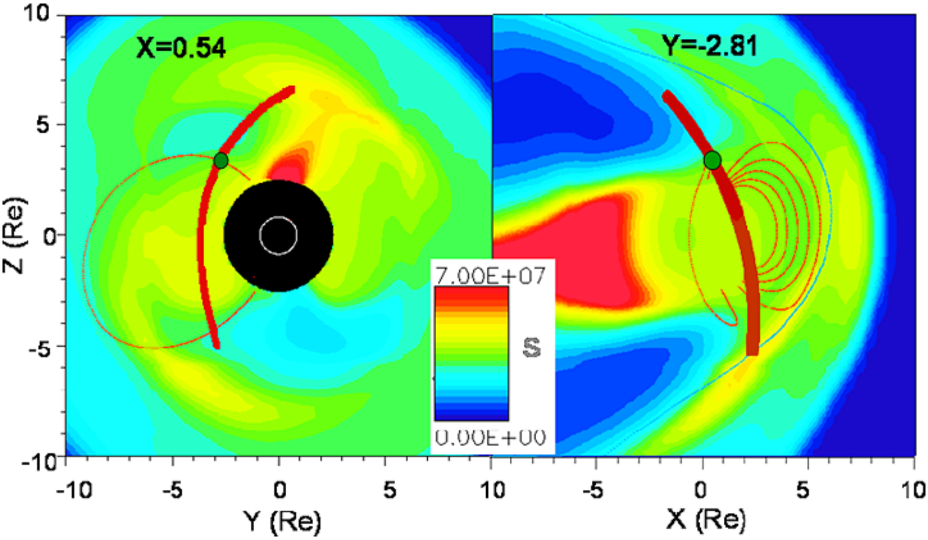

Figure 4 Contours in yz- and xz-planes of the entropy parameter $S = T/n^{3/2}$ (km^2) at the time Cluster 4 encountered magnetosheath-like plasma on 7 November 2004. The thick arc shows a segment of the spacecraft orbit on which the spacecraft was moving northward. Green circles mark its position at the time it encountered cusp-like plasma. The magnetic field lines were all initiated in the viewing planes but are otherwise projected onto the viewing planes. One field line goes through the location of the spacecraft. The images are from the CCMC (http://ccmc.gsfc.nasa.gov) listed under Global Magnetosphere Model Results, run number 062506_3. This run was made by the BATSRUS code.

tity tends to be uniform in plasmas that share a common origin. Instead of specific entropy itself, however, we use a quantity to which it is logarithmically related, $T/n^{3/2}$, where T is temperature and n is number density. (More generally, this expression is T/n^{γ} where γ is the ratio of specific heats. The MHD code uses $\gamma = 5/3$, as is appropriate to an idealized, monatomic gas.) In terms of this quantity one can see that the three intervals designated in Figure 2 as “Plasma Sheet,” “Cusp,” and “Open Polar Cap” correspond to high, low, and very high ranges of $T/n^{3/2}$, respectively.

A global picture of the situation is given in Figure 4, which shows contours of the entropy parameter $S = T/n^{3/2}$ in yz- and xz-planes at 19:35 UT as computed by the BATSRUS code at CCMC using ACE solar wind and IMF data as input. The thick arc in each view traces a segment of the orbit of Cluster 4. At the mentioned time the spacecraft was located at $X = 0.54R_\mathrm{e}$ and $Y = -2.81R_\mathrm{e}$ (indicated by green circles in the figure) and was moving northward along its orbit. Also shown is a magnetic field line through the marked spacecraft location. This time, 19:35 UT, is when Cluster 4 measured magnetosheath-like plasma, which was tentatively interpreted as a signature of the cusp.

In light of Figure 4, what appears to be the most probable interpretation of the Cluster 4 “cusp-encounter” event of Figure 2 goes as follows: The left panel shows that the spacecraft was not in the cusp as defined by a topologically cylindrical volume of magnetic field lines that goes from the magnetopause directly to the ionosphere, bearing magnetosheath-like plasma. Such a feature is indeed seen; it is the highest entropy feature in the left panel. The high entropy in the cusp arises from dissipation in the BATSRUS MHD code that produces magnetic reconnection. In this northward IMF situation, field lines reconnect tailward of the cusp. Reconnection feeds high-entropy plasma into the cusp but not into the layer of entrained magnetosheath plasma equatorward of the cusps, which merely grows by accretion of magnetosheath plasma as northward magnetosheath field lines reconnect with tail-lobe field lines in both hemispheres. This accounts for the difference in entropy between plasma in the cusp and in the layer of trapped magnetosheath. Thus, contours of the entropy parameter, $T/n^{3/2}$, are able to show that the cusp is well separated from the spacecraft.

The magnetosheath-like plasma that Cluster 4 encountered has an entropy value in Figure 4 that indeed matches that in the magnetosheath. This equality of entropy in the two places is perhaps best seen in the right-hand panel of the figure, which shows continuity of entropy between the position of the spacecraft and the layer of plasma on closed field lines just inside the magnetopause. This layer was accreted from magnetosheath plasma at an earlier time when the entropy in the magnetosheath was less than at the high-compression time illustrated in the figure, which is why the entropy goes up across the magnetopause. The right panel also shows that, before the spacecraft reached the magnetosheath-like plasma, it was immersed in a plasma domain that connects continuously to the plasma sheet in the tail, which is the reason for the "Plasma Sheet" label for this interval in Figure 2. After the magnetosheath-like plasma interval, the spacecraft enters the volume of open field lines that form the northern hemisphere tail lobe, as is confirmed by actual field line tracing. It might interest code developers to note that the entropy in the open field line volume computed by the model is much too low compared to Cluster observations, but this observation is not relevant to the present purpose of identifying plasma regimes. Whether by high entropy or low entropy, the entry of the spacecraft into the volume of open field lines is distinctly marked in the model.

To summarize this 4 November 2004, event from the viewpoint of MHD modeling, we have seen that Cluster 4 indeed encountered an interval of magnetosheath-like plasma that could have been but was not the signature of the cusp *per se* deep in the magnetosphere near the dawn terminator. Instead, according to a reading of model-computed entropy contours, it was an encounter with magnetosheath plasma probably on closed field lines accreted from the magnetosheath through the Song – Russell mechanism of two-point reconnection of magnetosheath field lines with tail lobe field lines in both hemispheres and subsequent convection tailward within the magnetosphere under the general dayside-to-nightside magnetosheath pressure gradient. The latter point about tailward convection, which is part of the Song and Russell (1992) scenario and shown in Li *et al.* (2005), follows in the present analysis from model-computed contours of velocity (not shown) that put the field line through the spacecraft in the domain of plasma moving tailward at about 50 km s^{-1}.

3. Strong Southward IMF and Elevated Dynamic Pressure

On 10 November 2004, the Cluster spacecraft encountered the cusp twice in a two-hour time interval, once in the southern hemisphere and once in the northern hemisphere. Throughout this time a magnetic cloud was passing over the Earth with a strong and rotating magnetic field such that during the first cusp encounter the field was nearly equatorial and during the second encounter it was strongly southward. Figure 5 shows the interplanetary conditions in a three-hour interval containing the two encounters and adds the information that during the first encounter the dynamic pressure was high but less so during the second encounter (merely "elevated").

Figure 6 shows the thermal pressure as determined with data from the Cluster 4 spacecraft and as computed by the two MHD codes Open GGCM and BATSRUS. The proton thermal pressure measured by the Cluster 4 spacecraft has been multiplied by the factor 1.1

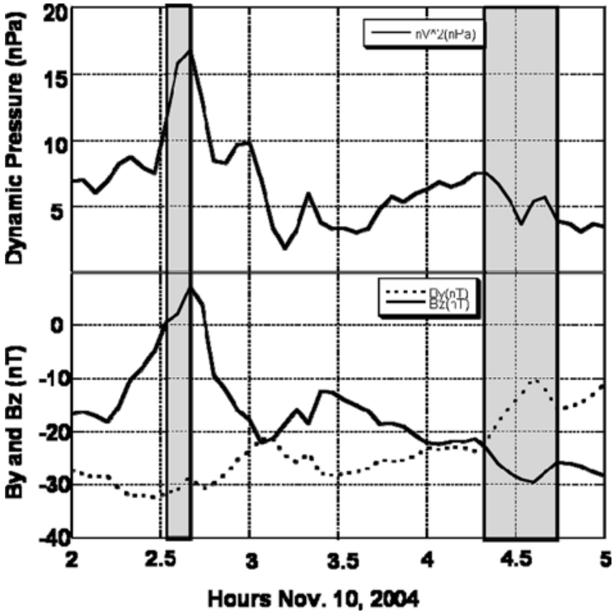

Figure 5 Solar wind dynamic pressure (ρV^2) and the y- and z-components of the IMF measured by the ACE spacecraft during a three-hour interval within the magnetic cloud of 10 November 2004. The times correspond to conditions at Earth obtained by propagating the parameters from the ACE spacecraft to Earth using the measured solar wind speed.

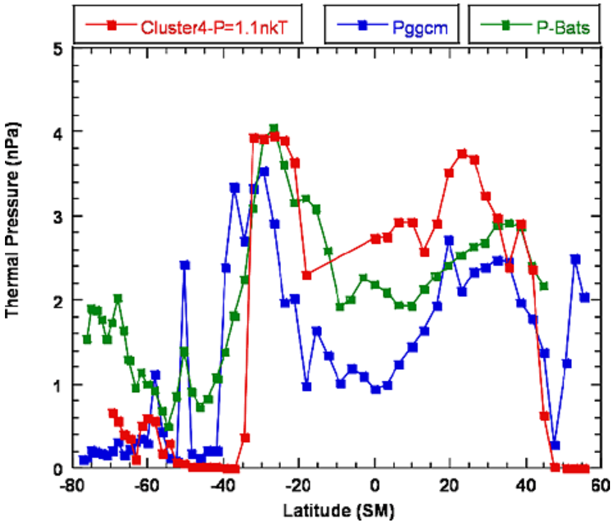

Figure 6 Thermal pressure measured by the Cluster 4 spacecraft (increased by 10% to allow for electron pressure) and computed by the Open GGCM and BATSRUS MHD codes at the CCMC (http://ccmc.gsfc.nasa.gov) listed under Global Magnetosphere Model Results, run numbers 013106_2 and 013106_1, respectively.

to allow for a typical 10% contribution from electrons. The pressure exhibits two peaks, corresponding to two cusp encounters. The first one around 30° south latitude corresponds to the first shaded region in Figure 5 during which the IMF was strong and equatorial, and the second one around 30° north latitude corresponds to the second shaded region in Figure 5 during which the IMF was strong and southward. The (x, y, z) GSM coordinates of the Cluster 4 spacecraft when the two peaks in pressure were measured are $(2.69, -3.81, -1.13)$ and $(0.79, -2.85, 3.31)$, respectively. Thus as in the northward IMF case previously discussed, the cusp signature occurred close to Earth and, in the northward case, near the terminator.

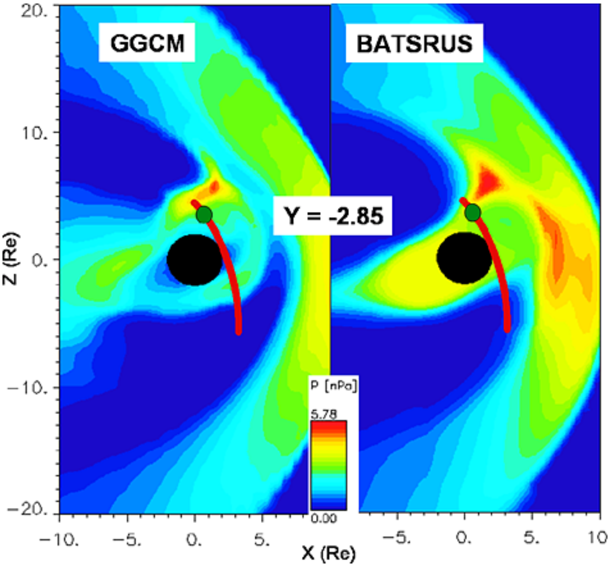

Figure 7 Contours in xz-plane ($y = -2.85$) of computed thermal pressure at the time Cluster 4 encountered a northern-hemisphere pressure peak on 10 November 2004. Computational results from both the Open GGCM and BATSRUS codes are shown. The thick arcs show a segment of the spacecraft orbit on which the spacecraft was moving northward. Green circles mark its position at the time it encountered the pressure peak. The images are from the CCMC (http://ccmc.gsfc.nasa.gov) listed under Global Magnetosphere Model Results, run numbers 013106_2 and 013106_1, respectively.

The peaks in the pressure measured by the Cluster spacecraft have corresponding peaks in the pressures computed by the two MHD codes. The peaks agree not only in position (approximately) but in amplitude. Moreover, the two computed peaks are mutually consistent, which adds to the likelihood that the MHD codes have correctly computed the magnetospheric state of affairs for this event. Thus, the global context that they provide may be assumed to simulate the one in which the Cluster 4 spacecraft found itself at this time.

In the second encounter when the spacecraft was in the northern dawn quadrant of the magnetosphere and the IMF was strongly southward but also significantly westward, the expected location of the northern hemisphere cusp was in the same quadrant as the spacecraft, unlike the northward IMF case on 7 November 2004, previously discussed. Figure 7 shows contours of pressure in the xz-plane through the y position of the spacecraft at the time of peak recorded pressure (*i.e.*, $y = -2.85$).

The geometry of the northern-hemisphere cusp is unmistakably depicted in both panels. The southern-hemisphere cusp has been shifted in a positive y direction (owing to the negative IMF y-component), and so lies beyond the plane of the figure. Although the match between the peaks in the pressure measured by the spacecraft and computed by the MHD codes is not one of perfect congruence (the peak comes a little later in the codes than in the data, as Figure 6 shows), it is close enough to verify that the peak in pressure that the spacecraft measured at this time indeed marked a fairly direct encounter with the northern-hemisphere cusp.

4. Strong Equatorial IMF and Strong Dynamic Pressure

Two hours earlier, while it was in the southern hemisphere, the spacecraft recorded a peak in pressure that was at first interpreted as an encounter with the southern hemisphere cusp. The IMF at this time was strong and pointed in the negative y direction ($\sim - 30$ nT), and slightly northward, as Figure 5 shows. The dynamic pressure was also high ($\sim$15 nPa). The spacecraft was in the southern-dawn quadrant of the magnetosphere. Therefore, the

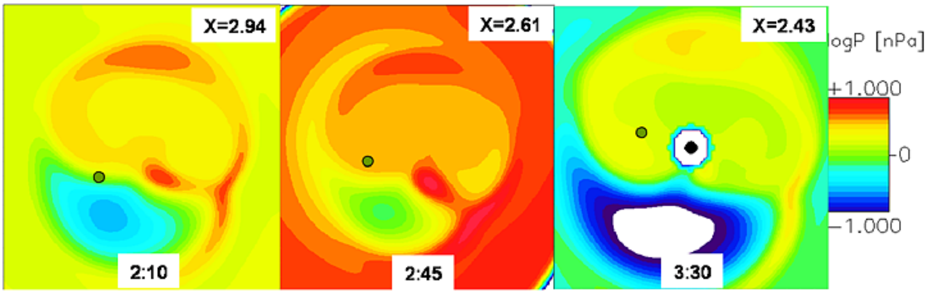

Figure 8 Contours of the base-ten logarithm of pressure in nPa in the *yz*-plane that contains the Cluster 4 spacecraft for the three specified times on 10 November 2004. Each plane goes from $-10R_e$ to $+10R_e$ in the *y* and *z* directions. The location of the spacecraft is marked by a green circle. The simultaneous *x* position is indicated in each time frame. The images are from the BATSRUS code run by the CCMC (http://ccmc.gsfc.nasa.gov) listed under Global Magnetosphere Model Results, run number 013106_1.

southern cusp should have been shifted away from it in the dusk direction. The northern cusp should have been shifted toward it, but the spacecraft was in the southern hemisphere, and so presumably closer to the southern cusp.

To address the question of the origin of the cusp observed in the southern hemisphere, Figure 8 shows a sequence of pressure profiles (on a logarithmic scale) in *yz*-planes at the *x* positions of the spacecraft at the times noted. The images were made with the BATSRUS MHD code. The Open GGCM code gives a similar but not identical result. The times were selected to show the global situation 1. before the southern-cusp encounter when the pressure was low (2:10 UT), 2. at the peak pressure of the southern-hemisphere cusp encounter (2:45 UT), and 3. after the peak pressure (3:30 UT).

The sequence of images in Figure 8 reveals a complicated story in which the southern-hemisphere pressure feature of Figure 6 is seen to result from a combination of changes in time of the global environment and changes in space of the spacecraft. The north – south asymmetry of the images is due to the season tilt of the dipole away from the Sun in the northern hemisphere. The clockwise skewing of the color contours results from the strong negative *y* component of the IMF.

At the time of the first image (2:10 UT) the spacecraft was emerging from the open field lines of the southern polar cap. Just ahead of it lay the closed-field-line volume of the magnetosphere (shifted northward because of the tilt of the dipole relative to the solar wind flow direction) with appreciable pressure owing to trapped plasma and rimmed by a high-pressure ribbon in which the northern and southern cusps stand out as distinct pressure features as does the southern-hemisphere imprint of the magnetospheric sash (Siscoe *et al.*, 2005). (The northern-hemisphere sash is displaced tailward owing to the dipole tilt and has a reduced pressure compared to the southern-hemisphere sash.) From the continuity of the high-pressure ribbon, it appears as if it is being fed plasma from both cusps. By the time the spacecraft had reached the position of the high-pressure ribbon (2:45 UT), the high-dynamic-pressure feature seen in Figure 5 associated with a noncompressive density enhancement (NCDE) (Gosling *et al.*, 1977) has caused the internal pressure of the magnetosphere to increase globally. Thus, even had the spacecraft not crossed the high-pressure ribbon at this time, it would have experienced a pressure rise. As it happened, however, its entry into the closed-field-line volume of the magnetosphere coincided with the pressurization of the whole magnetosphere by the passing NCDE. The NCDE lasted only a short time (less than 20 minutes) and decompression of the magnetosphere then followed. By the time of the third image in Figure 8 at 3:30 UT, the event was wholly over and pressure throughout the magnetosphere had dropped to less than pre-event levels, consistent with a drop in the dynamic pressure of the solar wind (Figure 5).

As far as one can tell from MHD simulations, therefore, it is unclear whether the pressure peak that the Cluster 4 satellite observed around 2:40 UT was a crossing of a high-pressure plasma ribbon being fed by one or both cusps (*i.e.*, a "cusp-encounter" interpretation) or whether it was a result of a short compression – decompression event involving the whole magnetosphere caused by an coincidental passing of a NCDE just as the spacecraft entered the region of trapped magnetospheric plasma. But the Cluster 4 data are unambiguous regarding the presence of plasma with magnetosheath temperatures at this time (Bogdanova *et al.*, 2007). Thus, between the data and the simulations, we may conclude that the spacecraft encountered a plasma boundary layer receiving magnetosheath plasma from one or both of the cusps. The plot corresponding to Figure 8 using contours of entropy (not shown) reveal that the plasma at the position of the spacecraft is connected to the northern cusp and separated from the southern cusp. This is confirmed by the Open GGCM code. The conclusion based on the MHD simulations, therefore, is that the northern cusp is the proximate origin of the magnetosheath-like plasma that Cluster observed between 2:30 and 2:40 UT in the southern hemisphere.

5. Summary

MHD simulations provide global context to aid the interpretation of single-point measurements. Of course, this use of MHD simulations is well known and has been applied successfully in many case studies. Here it has been applied to cases in which the magnetosphere is under extreme solar wind and IMF conditions associated with the passage of magnetic clouds imbedded within fast ICMEs. This circumstance has resulted in the Cluster 4 spacecraft observing magnetosheath-like plasma that is usually associated with the dayside magnetospheric cusps in unusual places, namely, within $5R_e$ of Earth and closer to the dawn terminator than to the noon meridian. Thus, in the present application, MHD simulations can address the issue of the global geometry that allows magnetosheath-like plasma to get to the unusual places as observed.

Three encounters have been studied of magnetosheath-like plasma apparently within the magnetosphere. In all cases the IMF was very strong. In one case it was generally northward, in a second case generally southward, and in the third case generally equatorial (in the negative y direction). The solar wind dynamic pressure was also strong in each case, especially so in the northward IMF case.

Techniques used to determine the geometry responsible for magnetosheath-like plasma getting to the places observed included making contours of a function of specific entropy to verify that the plasma at the observation point in question was magnetosheath-like in the computations as well as in the data, verifying that the observation point was near the boundary between open and closed field lines, and making contours of plasma pressure to trace the link between the plasma at the observation point to one or the other polar cusp.

Only in the case with southward IMF was the identification of the origin of the magnetosheath-like plasma straightforward and unambiguous. Here the computed northern-hemisphere cusp as identified by an extension of plasma pressure from the magnetopause into the magnetosphere actually engulfed the spacecraft position. In the northward IMF case, neither cusp was directly connected to the observation point. Instead, the observed magnetosheath-like plasma was interpreted to be an instance of boundary-layer formation by means of two-point magnetic reconnection as happens when the IMF is northward (the Song – Russell mechanism). Entropy was used as a diagnostic in this instance. The equatorial IMF case was complicated by a coincidental passage of a dynamic pressure pulse, which gave an alternative interpretation to the pressure pulse that marked the cusp-encounter event in the computations. But by taking the Cluster data to have unambiguously identified the event as an encounter with magnetosheath-like plasma, the simulations show by means of continuity of entropy contours that the origin was the northern-hemisphere cusp even though the observation point was in the opposite hemisphere.

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