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# Flux pile-up and plasma depletion at the high latitude dayside magnetopause during southward interplanetary magnetic field: a cluster event study

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**Abstract.** An event of strong flux pile-up and plasma depletion at the high latitude magnetopause tailward of the cusp has been analyzed based on observations by the suite of Cluster spacecraft. The multi-satellite analysis facilitates the separation of temporal and spatial features and provides a direct estimate for the strength of the plasma depletion layer for this event. A doubling of the magnetic field strength and a forty percent reduction of the density are found. Our analysis shows that roughly half of the total magnetic field increase occurs within  $0.6 R_E$  of the magnetopause and another quarter within a distance of  $1.2 R_E$ . In addition, the plasma depletion signatures exhibit temporal variations which we relate to magnetopause dynamics.

**Keywords.** Magnetospheric physics (Magnetopause, Cusp and boundary layers; Magnetosheath; Solar wind-magnetosphere interactions)

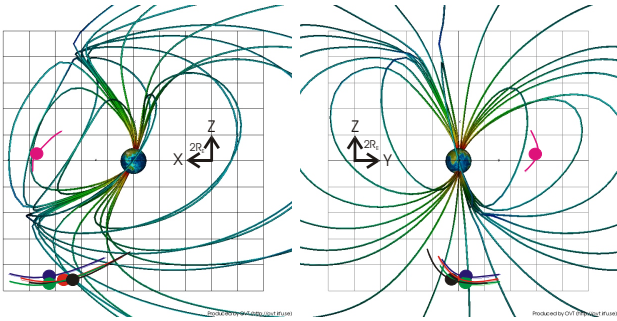
## 1 Introduction

The Earth's magnetosheath consists of shocked solar wind plasma whose flow is diverted around the obstacle of the Earth magnetic field. The plasma carries a magnetic field that drapes against the dayside magnetopause. Unless magnetic reconnection at the low-latitude magnetopause proceeds at a rate strong enough to prevent it, this is expected to lead to pile-up of magnetic flux and associated plasma depletion near the sub-solar magnetopause (e.g. Farrugia et al., 1995; Anderson et al., 1997; Siscoe et al., 2002; Wang et al., 2003). Observational evidence for a plasma depletion layer (PDL) adjacent to the subsolar magnetopause is plentiful

(e.g. Crooker et al., 1979; Fuselier et al., 1991; Song et al., 1993; Paschmann et al., 1993; Anderson and Fuselier, 1993; Anderson et al., 1994; Phan et al., 1994; Farrugia et al., 1997; Phan et al., 1997, 2003; Wang et al., 2003). The main characteristics of the layer are a decrease in density and increase in magnetic field as compared to the values immediate upstream in the magnetosheath. In addition, an increase in the ion temperature anisotropy has been observed in the layer, primarily caused by a decrease in the parallel temperature. Factors 2 enhancements for the magnetic field and slightly less for the density depletions are typical. The reported width of the layer ranges between  $0.2 R_E$  and  $1 R_E$  (Phan and Paschmann, 1995) but depends greatly on the exact definition used (Farrugia et al., 1995; Siscoe et al., 2002).

The PDL is most pronounced and most frequently observed for northward IMF orientation, when magnetic reconnection at the dayside magnetopause is often suppressed. A detailed analysis of this scenario was the subject of the two recent studies of Wang et al. (2003) and Wang et al. (2004). Their global Magneto-Hydro-Dynamic (MHD) simulations predict that a stable PDL structure forms during northward IMF conditions; that the PDL structure extends at least 6 h in MLT away from the sub-solar point and to  $40^\circ$  in latitude from the equatorial plane; and that the PDL is weaker and thicker away from the subsolar point. Fuselier et al. (2000) suggested that an extension of the PDL to high latitudes for northward IMF could play an important role in sustaining reconnection tailward of the cusp by making the flow in the layer sub-Alfvénic. Observational support for this scenario is provided by the event studies of Avakov et al. (2001), Phan et al. (2003), and Lavraud et al. (2004).

The situation for southward IMF is much less clear. Based on a boundary layer analysis of the ideal MHD equations, Farrugia et al. (1995) predict the existence of a significant



**Fig. 1.** Orbits of the Cluster (black, red, green, and blue) and Polar (magenta) satellites for 06:00–11:00 UT on 2 February 2003 in the GSM X–Z (left panel) and Y–Z planes. The background magnetospheric field lines are from the Tsyganenko-96 model with  $B_z = -7$  nT,  $P_{dyn} = 5$  nPa, and  $D_{st} = -40$ , as appropriate for the event. The figure was produced using the Orbit Visualization Tool by Stasiewicz et al. (2003).

PDL at the magnetopause for the high shear case (southward IMF) only when the upstream (solar wind) Alfvén Mach number is low. In contrast, Anderson et al. (1997) conclude from observational evidence that PDL for southward IMF occurs primarily during high solar wind density conditions, which cause the magnetosheath plasma  $\beta$  to be large. They interpret their results in terms of reconnection efficiency at the subsolar magnetopause and suggest that large Alfvén Mach number in the solar wind is what best predicts low reconnection efficiency and PDL formation for southward IMF. Results from global MHD simulations presented by Siscoe et al. (2002) show no PDL formation for southward IMF. Most recently, Maynard et al. (2004) have presented observations and global MHD simulation results that show localized PDL formation for southward IMF conditions when either a significant dipole tilt is present or the IMF has a significant X-component. They also present evidence for PDL formation tailward of the cusp during conditions with a very strong southward IMF ( $B_z < -20$  nT) and large dipole tilt. From a theoretical point of view, the physics governing reconnection at the Earth’s subsolar magnetopause is still far from well understood, including the role of magnetic flux pileup in sustaining fast, driven magnetic reconnection (Dorelli et al., 2004).

Here we present observations by the Cluster spacecraft for an event of considerable magnetic flux pile-up and associated plasma depletion at high latitude (basically tailward of the cusp) during southward IMF conditions. We also report on dynamical magnetopause structures that affect the values observed for the depletion layer.

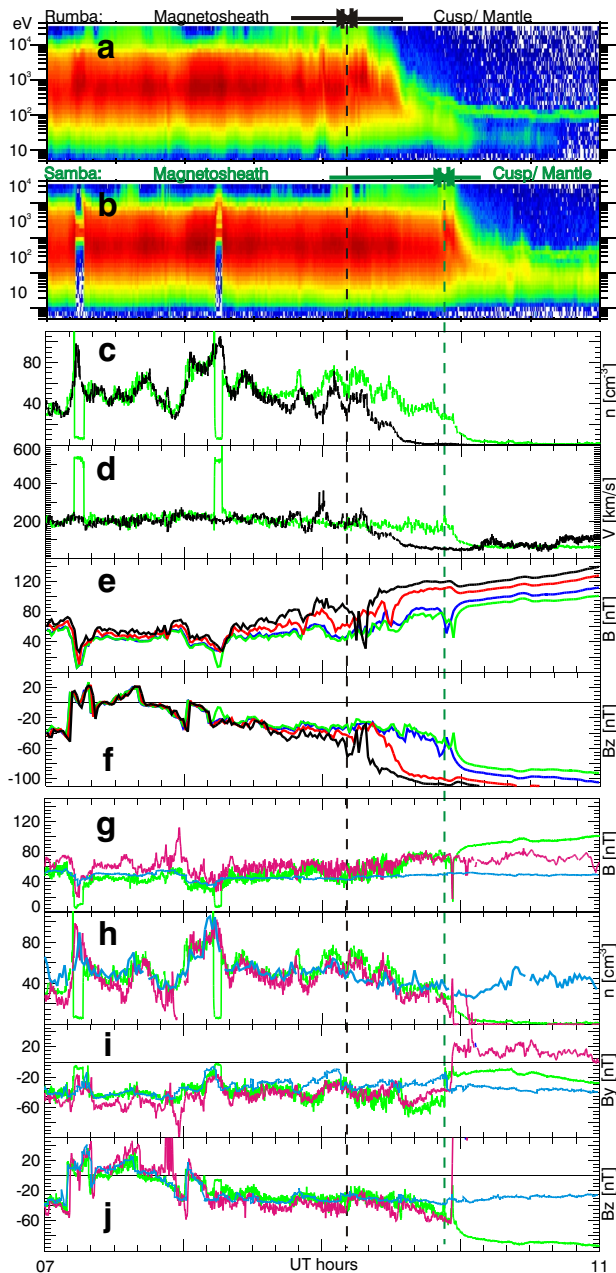
## 2 Observations

On 2 February 2003 between 06:00 UT and 11:00 UT, the Cluster spacecraft traversed the southern hemisphere, high-latitude magnetosheath along the orbits depicted in Fig. 1.

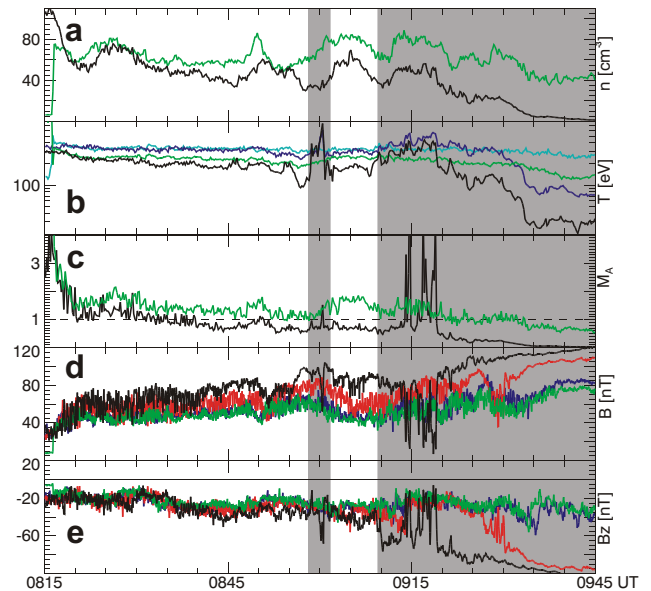
The constellation is in a stretched configuration mainly in the X-direction and remains close to the  $Y=0$  plane in the GSM coordinate system at approximately  $Z = -9 R_E$ . At 09:00 UT the separation between the leading spacecraft, Rumba (in black), and the trailing spacecraft, Samba (in green), is  $1.8 R_E$  in the X-direction,  $1.1 R_E$  in the GSM Y-direction, and  $0.3 R_E$  in the GSM Z-direction. Included in Fig. 1 is also the orbit for the Polar spacecraft (in magenta), which at this time is crossing the Equatorial plane from South to North in the afternoon dayside magnetosheath.

Figure 2 presents an overview of the Cluster magnetosheath crossing for the time interval 07:00–11:00 UT. Ion measurements from the Hot Ion Analyzer (HIA) of the Cluster Ion Spectrometry (CIS) experiment (Rème et al., 2001) are available for the Rumba and Samba satellites (panels a–d in Fig. 2) with 4 s resolution. Magnetic field vectors measured by the Cluster flux gate magnetometers (FGM) (Balogh et al., 2001) are available for all four spacecraft. For clarity, one minute magnetic field averages are used in Fig. 2 (panels e and f). At the beginning of the interval (to the left in Fig. 2), all four Cluster spacecraft are in the magnetosheath. Except for Samba experiencing two short recursions back into the solar wind around 07:15 UT and 08:15 UT, respectively, caused by sharp solar wind density increases, they stay in the magnetosheath for the next several hours. Starting with Rumba just after 09 UT and ending with Samba at around 10:00 UT, they all gradually enter through the magnetopause boundary into the cusp/plasma mantle regions. Both the density (panel c) and magnetic field observations (panels d and e) in the magnetosheath exhibit large variations. Most of these are nearly identical at all spacecraft and are observed with delays of less than a few minutes, being seen first at the outermost spacecraft (Samba and Tango furthest away from the magnetopause shown in green and blue, respectively). In addition, clear evidence for flux pile-up through most of the magnetosheath are provided by the magnetic field magnitude measurements (panel e) in that the traces for the four spacecraft are separated and ordered with respect to proximity to the magnetopause. The density (panel c) exhibits the opposite trend (Rumba, closer to the magnetopause, sees lower densities than Samba), though much less dramatically, which is evidence for plasma depletion on the magnetically compressed flux-tubes.

Panels g–j in Fig. 2 show a comparison of the observations from Cluster Samba (in green as before) with observations from the Polar (in magenta) and ACE (in cyan) spacecraft. ACE is near the L1 location far upstream of the Earth ( $X = 231 R_E$ ,  $Y = 1.6 R_E$ ,  $Z = 14 R_E$  in GSM coordinates). To account for the propagation of structures from here to the location of Cluster, a delay of 50 min has been applied to the ACE observations in Fig. 2. Furthermore, to match the values for Cluster in the magnetosheath, the densities and magnetic field values displayed for ACE both have been multiplied by a factor of 4. Similarly, the density values displayed for Polar have been multiplied by a factor of 30 to account for the fact that they are partial densities calculated from the measurements of the TIMAS instrument (Shelley et al., 1995) for the



**Fig. 2.** Satellite plasma and magnetic field observations for 2 February 2003, 07:00–11:00 UT. Panels (a) and (b) show omnidirectional energy-time spectrograms for Rumba and Samba. In panels (c)–(f) the four colors represent Rumba (black), Salsa (Red), Samba (green), and Tango (blue). Panels (c) and (d) show ion number density and velocity and panels (e) and (f) show magnetic field strength and GSM Z-component. In panels (g)–(j) green represents Samba, magenta Polar, and cyan ACE. Panel (g) displays magnetic field strength (multiplied by a factor 4 for ACE), panel (h) displays number density (multiplied by a factor 4 for ACE and 30 for Polar) and panels (i) and (j) show GSM Y and Z-components of the magnetic field (multiplied by a factor 4 for ACE). A delay of 50 min has been applied to the ACE data. The two vertical lines mark the approximate times of magnetopause entry for Rumba (black) and Samba (green).



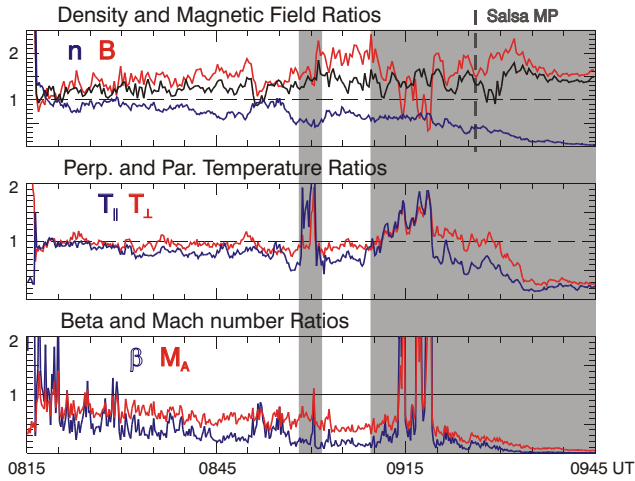
**Fig. 3.** Cluster plasma and magnetic field observations for 2 February 2003, 08:15–09:45 UT. From top to bottom are shown density, parallel and perpendicular temperatures,  $M_A$ , magnetic field strength, and GSM Z-component. Perpendicular temperatures in panel (b) are shown in purple for Rumba and in turquoise for Samba.

energy range 0.7–30 keV. Polar is in the magnetosheath until just before 10:00 UT when, within a few minutes of Samba, it enters into the magnetosphere through a rather sharp magnetopause boundary.

For the magnetosheath, an almost exact agreement is found between the density (panel h) and magnetic field variations (panels g, i, and j) observed at Samba and Polar with delays of less than a few minutes. Reflecting the fact that during the time interval from 07 UT to 10 UT Samba moves from GSM  $X=8 R_E$  to  $5 R_E$  while Polar remains roughly at  $7 R_E$ , the variations are observed first at Samba at the beginning of the interval but at Polar at the end of the interval. The coherency of the variations over  $9 R_E$  and more than  $3 R_E$ , respectively, in the GSM Z and Y directions, verifies that the density and field variations observed by Samba in the magnetosheath are caused by large-scale, propagating structures. In addition, most of the variations match variations observed at ACE, demonstrating that they are likely of solar wind origin.

We now focus on the time interval from 08:15 UT to 09:45 UT to analyze the flux pile-up and plasma depletion near the magnetopause. Figure 3 shows the density, temperature, Alfvén Mach number ( $M_A$ ), and magnetic field observations for this time interval. The large separation mainly in the X-direction between Samba and Rumba allows us to determine the magnitude of the flux pile-up and plasma depletion directly (i.e. without the spatial-temporal ambiguity of single spacecraft identifications). This is illustrated in Fig. 4, which displays the ratios between values measured at Rumba and Samba. For clarity, 20 s averages of the magnetic field





**Fig. 4.** Ratios of Rumba and Samba values for 2 February 2003, 08:15–09:45 UT. Top panel shows ratios for magnetic field strength (red) and density (blue), middle panel for parallel (blue) and perpendicular (red) temperatures, and bottom panel for  $M_A$  (red) and  $\beta$  (blue). The black curve in the top panel shows the ratio of magnetic field strength between Salsa and Samba.

measurements have been used for this figure. Also included in Fig. 4 (top panel) is the ratio of magnetic field strength between Salsa and Samba (black curve). Salsa is located between Samba and Rumba in the X-direction, approximately  $0.6 R_E$  from Rumba and  $1.2 R_E$  from Samba. Marked by grey shading on the right in both Figs. 3 and 4 is the time period after the final entry of Rumba into the cusp/mantle as evidenced by a rapid increase in temperature (Fig. 3, panel b) and magnetic field rotation (Fig. 3, panel e). The narrow grey shading in both figures marks a transient (partial) magnetopause entry by Rumba, again identified by large increase in temperature and strong magnetic field fluctuations. Salsa enters the cusp/mantle region at approximately 09:26 UT (about 15 min later than Rumba) as indicated by the sharp change in the magnetic field Z-component (Fig. 3, panel e) and this time is marked in the top panel of Fig. 4.

From 08:30 UT to 08:50 UT, the differences in density, parallel temperature, and magnetic field strength (Fig. 3, panels a, b, and d) between Rumba and Samba all increase fairly steadily. The ratios reach 1.7 and 0.7 for the magnetic field strength and density (Fig. 4, top panel), respectively, and 0.8 for the parallel temperature (Fig. 4, middle panel). The ratios for  $M_A$  and  $\beta$  (Fig. 4, bottom panel) decrease as low as 0.5 and 0.2, respectively. The Plasma flow at Rumba clearly becomes sub-Alfvénic ( $M_A < 1$  in Fig. 3, panel c). Next, from 08:50 UT to 08:57 UT, these parameters all exhibit a complex pattern, in which the differences first almost disappear (ratios close to 1 in Fig. 4) for the first roughly 5 min and then briefly resume their prior values for a few minutes before Rumba observes the transient magnetopause encounter (narrow grey shading). Finally, for a short time just prior to the final magnetopause encounter (between the narrow and wide grey shaded areas in Fig. 3 and Fig. 4), Rumba again

measures much stronger magnetic field strength and reduced density as compared to Samba. At this time, ratios reach more than 2.0 for the magnetic field strength, but less than 0.6 for the density, and 0.7 for the parallel temperature, respectively, while the ratios for  $M_A$  and  $\beta$  decrease to 0.5 and 0.2. Salsa consistently observes smaller magnetic field enhancement relative to Samba than Rumba (Fig. 4, top panel). At the time when Rumba observes maximum enhancement, the enhancement measured by Salsa is roughly a factor of 1.5. This means that about half of the total 100% increase in magnetic field occur within  $0.6 R_E$  of the magnetopause.

On the other hand, the maximum enhancement measured by Salsa, at all, is a factor of roughly 1.6, just prior to its magnetopause encounter at 09:26 UT. This could be a temporal effect, reflecting a real reduction in flux pile-up at the magnetopause since the time when it was measured by Rumba (less than 20 min earlier). There are no indications of changes at this time in the solar wind parameters (Fig. 2, panels g–j) that could have caused this (e.g. decreasing density or magnetic field strength), though. More likely, it is an effect of the shorter distance between Salsa and Samba ( $1.2 R_E$ ) than between Rumba and Samba ( $1.8 R_E$ ). This means that Samba is closer to the magnetopause at the time when Salsa encounters the magnetopause than it was when Rumba did so and may at this location already observe increased magnetic field as compared to further upstream in the magnetosheath. This interpretation implies that roughly 25% of the total increase in the magnetic field occurs already at a distance of  $1.2 R_E$  from the magnetopause.

### 3 Discussion

The comparison between the Rumba and Samba observations clearly shows significant flux pile-up and plasma depletion adjacent to the southern, high-latitude magnetopause for this case study during strong southward IMF. The magnetic field increases by a factor of 2 as compared to the value in the upstream magnetosheath proper while the plasma density and parallel temperature decrease by 40% and 20%, respectively. The combined effect of these results in a reduction of the plasma  $\beta$  by 80%. This level of depletion is as large as any of those reported for the subsolar magnetopause (Anderson et al., 1997), even when including the low magnetic shear (northward IMF) cases. This depletion even exceeds that observed at the high-latitude magnetopause in all of the recent northward IMF case studies (Avanov et al., 2001; Fuselier et al., 2002; Phan et al., 2003; Lavraud et al., 2004). According to the ACE observations (Fig. 2), the event occurs during strong southward IMF ( $B_Y \approx B_Z \approx -7$  nT) and solar wind density ( $n \approx 12 \text{ cm}^{-3}$ ) and ram pressure ( $P_{dyn} \approx 5$  nPa, not shown) that are also above normal. Whether this is enough to qualify as an example of “extreme driving of the magnetosphere” as considered in Maynard et al. (2004) is not clear, though. The Alfvén Mach number for the upstream solar wind is 6–8 (not shown), which clearly means that the event does not fulfill the prediction of Farrugia et al. (1995) that PDL formation

for southward IMF requires unusually low solar wind Mach number ( $M_A \sim 3$ ). Model predictions for the width of the PDL are all rather vague, especially for southward IMF (Farrugia et al., 1995; Siscoe et al., 2002). To our knowledge no observational results exist for the southward IMF case at such high latitudes. A width between  $0.6 R_E$  (50% magnetic field increase) and  $1.2 R_E$  (25% increase), however, is in good general agreement with observations and model predictions for the northward IMF case (Phan and Paschmann, 1995; Wang et al., 2003). Our results clearly verify that one of the effects of the flux pile-up and depletion is to make the flow near the magnetopause sub-Alfvénic, even for this high-latitude southward IMF case. The potential important role of this mechanism in the reconnection process at the dayside magnetopause for both the southward and northward IMF cases has been suggested by Anderson et al. (1997), based on subsolar observations for all IMF orientations, and Fuselier et al. (2000), based on high-latitude observations for northward IMF.

To explain the changes to the flux pile-up and depletion observed in relation with the transient magnetopause encounter at  $\sim 09:00$  UT (narrow grey shading in Figs. 3 and 4), we shall briefly discuss two different scenarios. First, we consider the possibility that the brief density enhancement observed by Samba around 08:50 UT sets the magnetopause in oscillatory motion, causing both the magnetopause encounter at Rumba and the changes just prior to it. This implies that the density increase would first, effectively, move Rumba further away from the magnetopause, out of the depletion layer, which could explain the observed changes between 08:50 UT and 08:55 UT in Figs. 4 and 5 (the ratios all getting close to 1). The subsequent density decrease then would overshoot the magnetopause back out past Rumba, causing the spacecraft to pass through first the depletion layer and then the magnetopause itself, which could match the observed changes between 08:55 UT and 09:02 UT. Finally, the magnetopause would retract slightly, leaving Rumba, again, in a strongly compressed and depleted region just outside the magnetopause, matching the observations between 09:03 UT and 09:10 UT. We note, however, that the density pulse is brief (duration less than 3 min) and not very large (approximate increase of 45% and subsequent decrease of 55%, respectively). It is not clear that this is consistent with the timing of the magnetopause response as described above (duration of more than 15 min). Consequently, while this interpretation explains the sequence of features quite well, the problem with the timing makes it highly questionable.

An alternative explanation is that the transient magnetopause encounter by Rumba is caused by a structure resulting from reconnection dynamics at a lower latitude merging site and moving tailward along the magnetopause. The features of the transients may be consistent with the signature of a so called Flux Transfer Event (FTE) close to the magnetopause (Elphic, 1995), but the exact classification is not important for the discussion and has not been pursued here. Essentially, the structure would appear as a bulge on the magnetopause and its motion tailward could cause the

transient magnetopause entry of Rumba. It is not unreasonable to assume that the magnetosheath plasma immediately adjacent to the magnetopause would also be affected by the structure as it moves through. For example, the advancing magnetopause bulge could create a region of increased density ahead of it which might cause a decrease in the expected depletion at Rumba. Very recently, global magneto-hydrodynamic simulations of the solar wind magnetosphere interaction applying unprecedented high spatial resolution at the magnetopause have provided results for the reconnection dynamics at the dayside magnetopause and corresponding FTE occurrence that seems to be compatible with the observations shown here (M. Kunetzova, private communication, 2004). A detailed comparison has not yet been done.

#### 4 Summary and outlook

We have analyzed a magnetosheath traversal by the Cluster suite of spacecraft during a period of strongly southward IMF and above average solar wind density conditions. The event study provides clear evidence for intense magnetic flux pile-up and plasma depletion adjacent to the southern, high-latitude magnetopause during these conditions. The strength of the flux pile-up and depletion measured for this event is comparable to, if not stronger than, those recently reported for high-latitude northward IMF cases. Using Cluster multi-spacecraft measurements, our analysis provides not only the first direct measurement of the magnitude of the flux pile-up and depletion in the PDL but also the first direct estimate of the width of the layer. Analyzing all of the high latitude magnetosheath crossings by Cluster during the large separation cusp phase in this way would provide important observational constraints on the parameters that govern PDL formation. We propose this for a future investigation.

Changes to the flux pile-up and depletion are observed in relation with a transient encounter of the magnetopause. Two possible scenarios for the transient that might explain this were discussed. A brief density increase propagating through the magnetosheath may set the magnetopause and the adjacent plasma depletion layer in motion, causing the transient magnetopause encounter as well as the variations in the depletion parameters observed by the spacecraft. Alternatively, the observed features may be the effect of a FTE originating at a merging site at lower latitudes and moving tailward along the magnetopause and over the spacecraft.

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