CLUSTER OBSERVATIONS AND GLOBAL SIMULATION OF THE COLD DENSE PLASMA SHEET DURING NORTHWARD IMF

J. Raeder[1], W. Li[1], J. Dorelli[1], M. Øieroset[2], and T. Phan[2]

[1]*Space Science Center, University of New Hampshire, Durham, New Hampshire, USA*
[2]*Space Science Laboratory, University of California, Berkeley, California, USA*

ABSTRACT

We present Cluster data and results from an OpenGGCM simulation study for an interval of more than 30 hours of nearly due northward IMF. Cluster, which is located in the near-Earth plasma sheet, observes a 3 hour long gradual transition from a hot tenuous plasma sheet (HTPS) to a cold dense plasma sheet (CDPS). The simulation shows a very good agreement with the Cluster data. Analysis of the simulation shows that the cold dense plasma is of magnetosheath origin. It first enters the magnetosphere by dual lobe reconnection. Subsequently the plasma convects around the flanks into the plasma sheet. The time scale of this process is of the order of 2 hours. After the plasma reaches the plasma sheet it remains essentially stagnant.

Key words: Plasma sheet, geotail, simulation.

1. INTRODUCTION

The plasma sheet in Earth's magnetotail is usually filled with tenuous ($\ll$ 1 cm^{-3}) and hot ($\gg$1 keV) plasma. The plasma is believed to enter the tail either from the solar wind through reconnection at the dayside and subsequent convection over the cusps and through the mantle into the plasma sheet, or from the ionosphere as a result of direct outflow. Both processes are modulated by the solar wind and the interplanetary magnetic field (IMF) [1, 2, 3]. Specifically, during geomagnetic quiet times, when the IMF is northward these processes should minimize, i.e., dayside reconnection ceases and ionospheric outflow minimizes because of the reduced energy input into the magnetosphere and ionosphere.

However, it is often observed that during quiet times the plasma density in the tail plasma sheet significantly increases, to more than 1 cm^{-3}, and the plasma significantly cools, to less than 1 keV [4, 2, 5]. This appears at first glance counter-intuitive, because the processes that provide plasma to the plasma sheet become less efficient. It is thus important to study cases where a CDPS forms, even though they appear to be relatively rare.

CDPS formation has been attributed to a variety of process, in particular to particle diffusion [2], to Kelvin-Helmholtz waves [6, 4, 7, 8, 9], and to reconnection at the tail lobes of both hemispheres [10, 11, 12]. In this paper we will present evidence from Cluster observations and from global magnetosphere simulations that dual-lobe reconnection is sufficient to produce the CDPS.

2. THE OCTOBER 22/23 EVENT

A remarkable CDPS event occurred on October 22/23 2003, during the so-called Halloween storms. The IMF turned northward around 1600 UT on October 22 and stayed very strongly northward for more than 30 hours. The Cluster II spacecraft were at the same time located in the near-Earth plasma sheet, around (-15,10,0) RE in GSE coordinates. Time-lagged solar wind and IMF data from ACE along with the relevant Cluster data are shown in Figure 1 with black lines. The Figure shows, from bottom to top the solar wind velocity, the solar wind density, the solar wind dynamic pressure, the IMF clock angle, the plasma velocity at Cluster, the plasma temperature at Cluster, and the plasma density at Cluster. The values of the solar wind parameters are about average and do not show much variation. On the other hand, the IMF clock angle is remarkable. After 1800 UT it is near 90 degrees (due north) and remains near 90 degrees for more than 30 hours, although only the first 12 h are shown here. More details of this event may be found in [13, 14].

We ran a simulation of this event using the OpenGGCM [15] global model of the magnetosphere ionosphere thermosphere system. Time series from the simulation were taken at the Cluster location. The results are shown in Figure 1 with red lines. There is a remarkable agreement between the data and the simulation results. The cold dense plasma sheet in the simulation nearly perfectly

Proceedings Cluster and Double Star Symposium – 5th Anniversary of Cluster in Space, Noordwijk, The Netherlands, 19 - 23 September 2005 (ESA SP-598, January 2006)

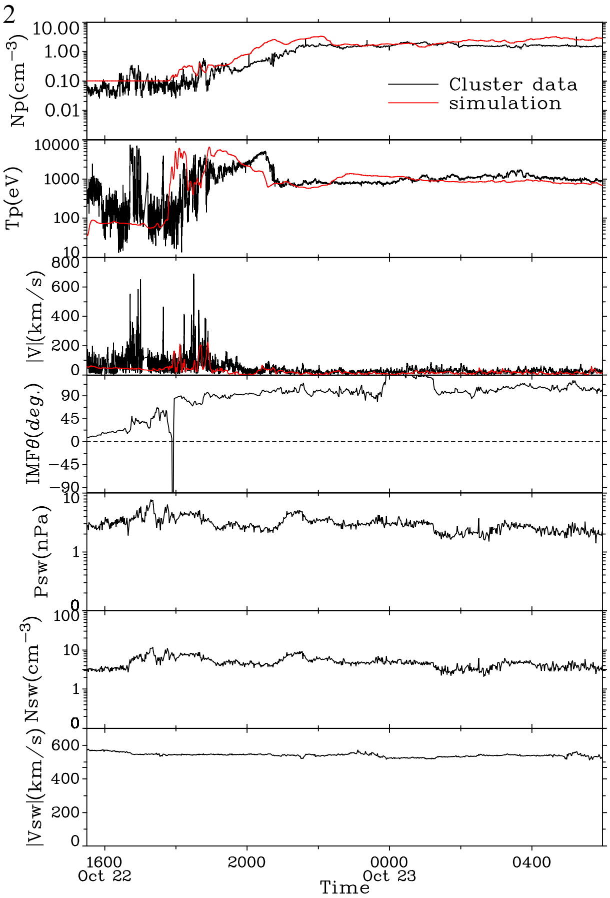

Figure 1. Time series, showing from top to bottom with black lines: The plasma density at Cluster, the plasma temperature at Cluster, the plasma velocity at Cluster, the IMF clock angle at ACE, the dynamic pressure at ACE, the plasma density at ACE, and the plasma velocity at ACE. The red lines show the corresponding modeling result.

matches the measured density and temperature values. Furthermore, the simulation also reproduces the 3 hour rise time between the HTPS to the CDPS.

Based on the good match between the simulation results and the data we further investigate the simulation results to uncover the physical process that leads to the CDPS formation.

Figure 2 shows the trajectory of a plasma parcel traced backwards from the Cluster location. Starting from the solar wind, the plasma parcel first encounters the bow shock. At the bow shock it is deflected southward and duskward. Between 1042 UT and 1047 UT the parcel encounters the magnetopause and enters the magnetosphere. During this encounter the parcel is accelerated back northward and sunward. Subsequently, the parcel convects into the dusk sector of the near-Earth tail.

Figure 3 shows the variation of the relevant physical parameters of the plasma parcel as it convects through the magnetosphere. The panels show, from top to bottom, the

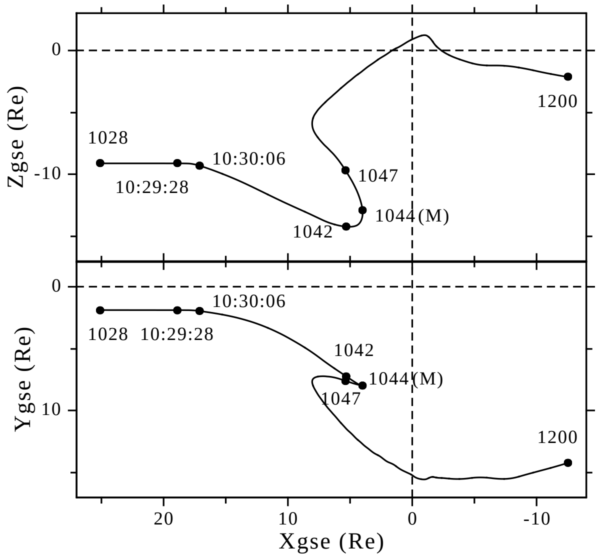

Figure 2. Trajectory of a fluid element that was traced backwards from the Cluster location to the solar wind. The markers correspond to the markers in Figure 3 and also indicate the time. Note that the total convection time of this fluid element is 1.5 hours.

plasma temperature and density, the magnetic field magnitude, the velocity magnitude, and the z component of the plasma velocity. There are also markers in this figure that correspond to markers in Figure 2 to establish the relation.

As the plasma parcel encounters the bow shock it becomes heated and its temperature rises. A second temperature rise occurs later, 1045 UT. At that time, the parcel also encounters a distinct minimum in the magnetic field, and it is slightly accelerated. Moreover, its flow direction changes from southward to northward. As we show below, the plasma parcel at this time encounters the magnetopause current sheet very close to the southern lobe reconnection site, but northward of the reconnection site. The parameters shown in Figure 3 are consistent with this interpretation. After the encounter with the reconnection site the plasma parcel slows down and slowly convects into the tail plasma sheet. While it convects, its temperature and density slowly decrease, consistent with adiabatic expansion.

3. THE THREE-DIMENSIONAL PICTURE

Figure 4 shows a three-dimensional rendering of the trajectory of the fluid parcel shown in Figure 2. In addition to the path of the fluid element the figure shows field lines through the fluid element as it convects along. These field lines clearly show how the field topology changes and how the plasma gets captured from the magnetosheath into the magnetosphere and ultimately into the tail plasma sheet. The field lines a labeled sequentially with numbers

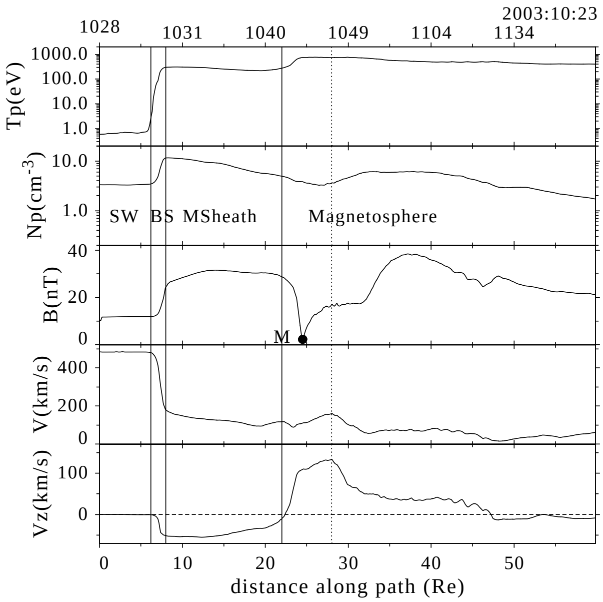

Figure 3. Plasma and field values associated with the fluid element in Figure 2. The vertical lines mark, from right to left, the entry and exit of the bow shock, respectively, and the crossing of the magnetopause. The dot marks the encounter of the magnetic field minimum. From top to bottom, the panels show: The plasma temperature, the plasma density, the magnetic field magnitude, the magnitude of the plasma velocity, and the z component of the plasma velocity.

to make it easier to follow them through the figure.

When the plasma element traverses the bow shock the field line starts draping around the magnetosphere in the magnetosheath (lines 1-6). The following line (7) is no longer a solar wind field line. It has reconnected with lobe field lines both in the northern and in the southern hemisphere, and is now part of a closed magnetosphere field line. The sharply kinked northern and southern tips of the field line clearly show that it has just undergone reconnection. Subsequently, the now closed field line contracts rapidly (lines 8-15) due to the jxB force associated with the field line kinks. As a result the plasma is accelerated (compare Figure 3), the sharp kinks are straightened out, and the field line shortens. This constitutes the capturing process of the plasma that is contained in the flux tube. This process is essentially the same as the one that was proposed by Song and Russell (1992) [10] to explain the formation of the Low Latitude Boundary Layer (LLBL) during northward IMF. Following the capturing process the plasma convects into the nightside plasma sheet (lines 16-25). While convecting tailward the field lines become longer and the flux tube volume likely increases. As a consequence the plasma adiabatically expands. Such expansion is also indicated in Figure 3 which shows dilution and cooling of the plasma during the convection into the plasma sheet. The plasma is thus hotter than the magnetosheath plasma due to the heating from the reconnection process, yet less dense than the magnetosheath plasma due to the expansion.

4. SUMMARY, DISCUSSION, AND CONCLUSIONS

We have successfully modeled the October 22/23 CDPS event and shown that the simulation results match the observed formation of the CDPS remarkably well. Further analysis of the simulation shows that the cold dense plasma enters the magnetosphere by double lobe reconnection and subsequently convects into the tail.

Besides double lobe reconnection other mechanisms have been proposed to explain the formation of the CDPS. Particle diffusion can potentially transport mass across a boundary such as the magnetopause. However, if anything, the numerical model used here for the simulation is more diffusive (mass, momentum, or heat) than nature. There is nothing in the model results that indicate that particle diffusion plays a significant role bringing the cold dense plasma into the plasma sheet. In particular, it would be difficult to explain the entry of the plasma deep into the plasma sheet where the mass density gradients are small.

Kelvin-Helmholtz (KH) waves, which have been observed near the flank magnetopause, particularly during northward IMF periods, can potentially enhance the diffusion process and facilitate the plasma entry [8, 9]. The Cluster observations of this event do not show any indication of KH waves present at the spacecraft. This does not necessarily mean that they play no role. They could be present at the magnetopause allowing the plasma to enter the plasmasheath, which could the be further brought inward by convection. We have inspected our simulation results to see if there are any KH waves present. We see that there are surface waves present at the magnetopause, however, they appear to be entirely driven by solar wind fluctuations. Thus, in the simulation KH waves play no role.

We therefore conclude that dual lobe reconnection is sufficient to produce the cold dense plasma sheet. However, more case studies are needed to confirm this result.

ACKNOWLEDGEMENTS

We thank the ACE MAG and SWE teams for making their data available. The research was funded by NASA grant NAG5-12768 at UC Berkeley and by NSF grants ATM-036211 and ATM-0441046 and the University of New Hampshire. Computations were performed at the National Center for Supercomputer Applications (NCSA) and at the San Diego Supercomputer Center (SDSC).

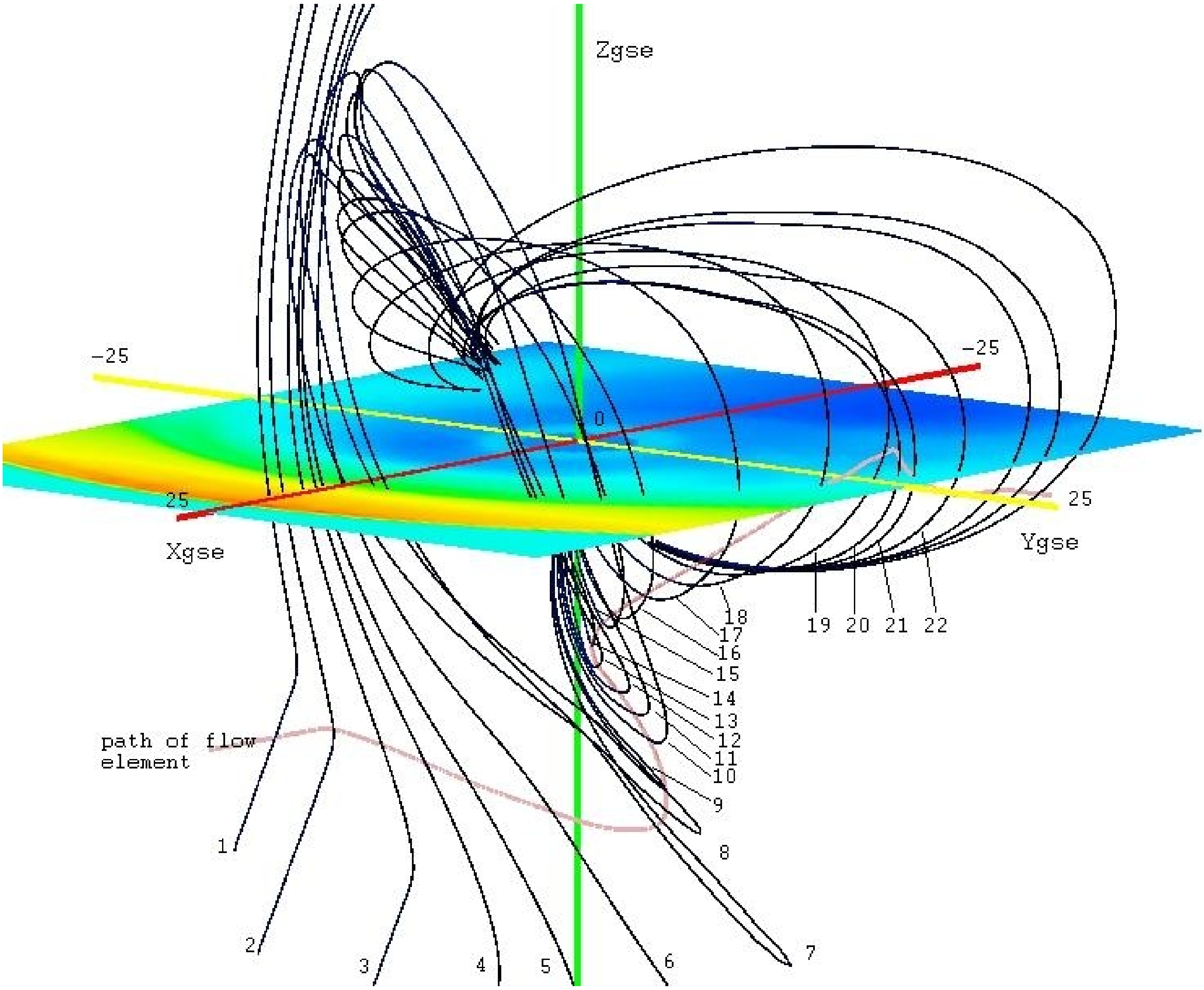

Figure 4. Three-dimensional rendering of the motion of the fluid element and of the convection of the flux tubes along with the fluid element. The equatorial plane shows color-coded the plasma pressure for better orientation. The field lines are sequentially numbered to make it possible to follow their motion in time. The magnetic flux tube from the solar wind first drapes around the magnetosphere and then reconnects behind the cusps with lobe field lines to become a closed magnetosphere flux tube. The sharp kinks in flux tube 7 are testament to that process. The flux tube the shrinks and sinks into the magnetosphere. It subsequently convects around the flanks into the tail and becomes part of the plasma sheet.

REFERENCES

1. Wing, S. and Newell, P. 2d plasma sheet ion density and temperature profiles for northward and southward IMF. *Geophysical Research Letters*, 29:21, 2002.

2. Terasawa, T., Fujimoto, M., Mukai, T., Shinohara, I., Saito, Y., Yamamoto, T., Machida, S., Kokubun, S., Lazarus, A. J., Steinberg, J. T., and Lepping, R. P. Solar wind control of density and temperature in the near-Earth plasma sheet: WIND/GEOTAIL collaboration. *Geophys. Res. Lett.*, 24:935, 1997.

3. Baumjohann, W., Paschmann, G., Sckopke, N., Cattell, C. A., and Carlson, C. W. Average plasma properties in the central plasma sheet. *J. Geophys. Res.*, 94:6597, 1989.

4. Fujimoto, M., Nishida, A., Mukai, T., Saito, Y., Yamamoto, T., and Kokubun, S. Plasma entry from the flanks of the near-Earth magnetotail: Geotail observations in the dawnside LLBL and the plasma sheet. *J. Geomag. Geoelec.*, 48:711, 1996.

5. Øieroset, M., Phan, T. D., Fujimoto, M., Chan, L., Lin, R. P., and Skoug, R. Spatial and temporal variations of the cold dense plasma sheet: Evidence for a low-latitude boundary layer source? volume 133, page 253. AGU Monogr. Ser., American Geophysical Union, 2001.

6. Fujimoto, M. and Terasawa, T. Anomalous ion mixing within an MHD scale Kelvin-Helmholtz vortex. *J. Geophys. Res.*, 99:8601, 1994.

7. Fujimoto, M., Terasawa, T., Mukai, T., Saito, Y., Yamamoto, T., and Kokubun, S. Plasma entry from the flanks of the near-Earth magnetotail: Geotail observations. *J. Geophys. Res.*, 103:4391, 1998.

8. Fairfield, D. H. Geotail observations of the Kelvin-Helmholtz instability at the equatorial magnetotail boundary for parallel northward fields. *J. Geophys. Res.*, 105:21159, 2000.

9. Hasegawa, H., Fujimoto, M., Phan, T., Rème, H., Balogh, A., Dunlop, M. W., Hashimoto, C., and Tan-Dokoro, R. Rolled-up Kelvin-Helmholtz vortices and associated solar wind entry at earth's magnetopauses. *Nature*, 430:755, 2004.

10. Song, P. and Russell, C. T. Model of the formation of the low-latitude boundary layer for strongly northward interplanetary magnetic field. *J. Geophys. Res.*, 97:1411, 1992.

11. Raeder, J., Walker, R. J., and Ashour-Abdalla, M. The structure of the distant geomagnetic tail during long periods of northward IMF. *Geophys. Res. Lett.*, 22:349, 1995.

12. Raeder, J., Berchem, J., Ashour-Abdalla, M., Frank, L. A., Paterson, W. R., Ackerson, K. L., Lepping, R. P., Kokubun, S., Yamamoto, T., and Slavin, S. A. Boundary layer formation in the magnetotail: Geotail observations and comparisons with a global MHD model. *Geophys. Res. Lett.*, 24:951, 1997.

13. Li, W., Raeder, J., Dorelli, J., Oieroset, M., and Phan, T. D. Plasma sheet formation during long period of northward IMF. *Geophys. Res. Lett.*, 32:L12S08, doi: 10.1029/2004GL021524, 2005.

14. Øieroset, M., Raeder, J., Phan, T. D., Wing, S., McFadden, J. P., Li, W., Fujimoto, M., Rème, H., and Balogh, A. Global cooling and densification of the plasma sheet during an extended period of purely northward IMF on October 22-24, 2003. *Geophys. Res. Lett.*, page submitted, 2004.

15. Raeder, J. Global Magnetohydrodynamics – A Tutorial. In J. Büchner, Dum, C. T., and Scholer, M., editors, *Space Plasma Simulation*. Springer Verlag, Berlin Heidelberg New York, 2003.