Global cooling and densification of the plasma sheet during an extended period of purely northward IMF on October 22–24, 2003

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Received 15 September 2004; revised 27 October 2004; accepted 24 January 2005; published 28 April 2005.

[1] The October 22–24, 2003 interplanetary magnetic cloud was characterized by an exceptionally long interval (∼32 hours) of nearly purely northward interplanetary magnetic field (IMF). Following the northward IMF turning Cluster observed a gradual transition to a cold (<1 keV) and dense (∼1–2 cm^{-3}) plasma sheet (CDPS). Cluster observed CDPS continuously for the following ∼30 hours while passing through the neutral sheet from the northern to the southern hemisphere. DMSP observations mapped to the equatorial plasma sheet reveal that the CDPS extended to all nightside local times. The FAST satellite observed reversed ion dispersion signatures in the cusp indicative of poleward-of-cusp reconnection, and nearly no polar cap. The CDPS observations show good agreement with a global MHD simulation where the CDPS is formed by poleward-of-cusp reconnection capturing magnetosheath plasma and convecting it to the tail. The process shrinks the size of the lobes (and therefore the polar cap) significantly, as observed. **Citation:** Øieroset, M., J. Raeder, T. D. Phan, S. Wing, J. P. McFadden, W. Li, M. Fujimoto, H. Rème, and A. Balogh (2005), Global cooling and densification of the plasma sheet during an extended period of purely northward IMF on October 22–24, 2003, *Geophys. Res. Lett.*, *32*, L12S07, doi:10.1029/2004GL021523.

1. Introduction

[2] When the interplanetary magnetic field (IMF) turns from southward to northward the plasma properties of the plasma sheet changes distinctively [e.g., *Fujimoto et al.*, 1996; *Terasawa et al.*, 1997; *Øieroset et al.*, 2002]. The usual near Earth plasma sheet density of ∼0.3 cm^{-3} typically increases by a factor of 3 and the ion temperature decreases from a few keV to 1 keV or less [*Terasawa et al.*, 1997]. This regime of the plasma sheet has been termed the cold dense plasma sheet (CDPS). It has been detected deep inside the magnetosphere, and often consists of a mixture of magnetosheath and magnetospheric plasma [*Fujimoto et al.*, 1996, 1998, 2002; *Fuselier et al.*, 1999; *Phan et al.*, 2000]. The CDPS is dominated by H^+, usually with an absence of low-energy O^+ [*Fuselier et al.*, 1999; *Rème et al.*, 2001].

[3] Several solar wind transfer processes have been suggested as being responsible for the formation of the CDPS. The candidate processes include (1) slow diffusion of solar wind plasma across the flank low-latitude boundary layer (LLBL) [*Terasawa et al.*, 1997], (2) capture of solar wind plasma by non-linear Kelvin-Helmholtz instabilities on the flank magnetopause [*Fujimoto and Terasawa*, 1994; *Fairfield et al.*, 2000; *Hasegawa et al.*, 2004], and (3) capture of magnetosheath plasma by poleward-of-cusp reconnection in both hemispheres [*Song and Russell*, 1992; *Raeder et al.*, 1995, 1997]. The relative importance of these processes in terms of CDPS formation is presently not known. This is largely due to the fact that CDPS formation is a process which takes several hours [*Terasawa et al.*, 1997; *Øieroset et al.*, 2002], during which the solar wind and IMF parameters typically vary substantially, making model-data comparison difficult.

[4] Here we report a case study where an exceptional interplanetary magnetic cloud event provided stable solar wind conditions with a nearly purely northward IMF for more than 32 hours. During the strongly northward IMF interval the plasma sheet observed by Cluster and DMSP was cold and dense for more than 30 hours. We compare the Cluster observations with a MHD simulation using the observed solar wind parameters as input. The good agreement between observations and simulation suggests that the CDPS could be formed by poleward-of-cusp reconnection in this case.

2. Observations

2.1. ACE Solar Wind Observations

[5] The unshifted ACE solar wind ram pressure, density, speed, and the IMF $\theta = \arctan(B_z/|B_y|)$ angle from 15:00 UT on October 22 to 09:00 UT on October 24, 2003 are shown in Figures 1a–1d. At 17:50 UT the leading edge of an interval of almost purely northward IMF ($\theta \sim 90°$) was observed by ACE 235 R_E upstream of the Earth. During the purely northward IMF interval the magnitude of the IMF B_x component was small (2–4 nT compared to 6–12 nT for IMF B_z). An increase in the solar wind ram pressure from 1 to ∼4 nPa at 16:39 UT on October 22, 2003 preceded the purely northward IMF interval. The solar wind speed was decreasing steadily from ∼550 km s^{-1} to ∼400 km s^{-1}) during the purely northward IMF interval. With a solar wind speed of 550 km s^{-1} the strongly northward IMF front would reach the frontside magnetopause at ∼18:35 UT, ∼45 min after being observed by ACE (at 17:50 UT). At 02:30 UT on October 24 ACE observed a turn of the theta

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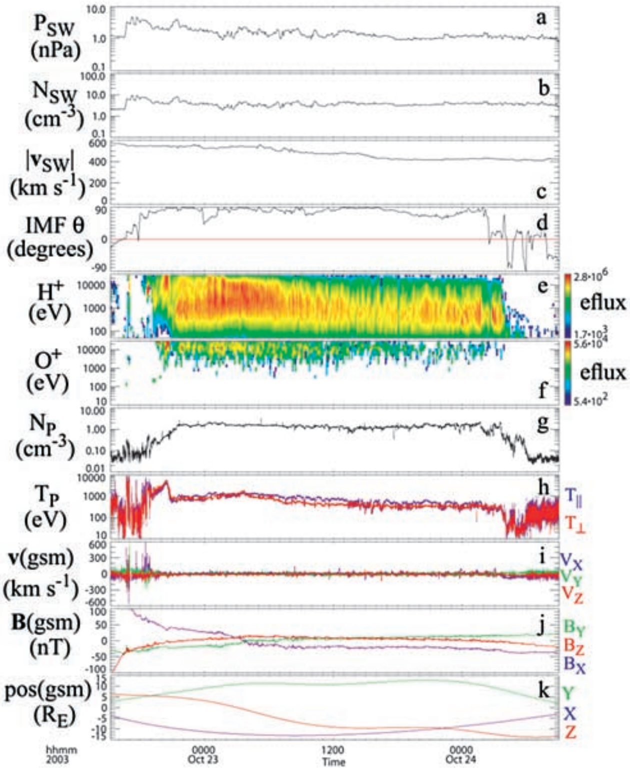

Figure 1. Unshifted ACE and Cluster 1 plasma and magnetic field observations from October 22, 2003, 15:00 UT to October 24, 2003, 09:00 UT. (a) ACE solar wind ram pressure; (b) ACE solar wind density; (c) ACE solar wind speed; (d) ACE IMF $\theta = \arctan(B_z/|B_y|)$ angle; (e) H^+ spectrogram from Cluster CODIF; (f) O^+ spectrogram from Cluster CODIF; (g) Cluster HIA density; (h) Cluster HIA temperature; (i) Cluster HIA velocity (GSM); (j) Cluster magnetic field (GSM); (k) Cluster spacecraft position (GSM). The strongly northward IMF interval lasts more than 32 hours, from October 22, 2003, 17:50 UT to October 24, 2003, 02:25 UT. Cluster observed more than 30 hours of CDPS, from October 22, 2003, 21:00 UT to October 24, 2003, 03:30 UT. During the northward IMF cloud Cluster traversed the nightside dusk magnetosphere from north to south and remained inside the plasma sheet for 32 hours. The CDPS observed by Cluster covered a region of at least 6 R_E in X_{GSM}, 4 R_E in Y_{GSM}, and 18 R_E in Z_{GSM}, including the neutral sheet.

angle to below 45°, marking the end of the purely northward IMF interval which had lasted more than 32 hours. The AE, AL, and AU indices (not shown) displayed very low auroral geomagnetic activity levels during the entire northward IMF interval, with AE being well below 100.

2.2. Cluster in Situ Observations of the Plasma Sheet

[6] Figures 1e–1k shows Cluster spacecraft 1 plasma [*Rème et al.*, 2001] and magnetic field [*Balogh et al.*, 2001] observations before and after the strongly northward IMF front observed by ACE at 17:50 UT. During the 32 hours of strongly northward IMF, Cluster sampled the near-Earth plasma sheet ($X_{GSM} = -6\ R_E$ to $-13\ R_E$) on the duskside ($Y_{GSM} = 5\ R_E$ to 13 R_E) and traversed from the northern to the southern hemisphere ($Z_{GSM} = 6\ R_E$ to $-13\ R_E$). At 20:00 UT Cluster entered the hot (~5 keV) and tenuous (0.4 cm^{-3}) plasma sheet from the northern lobe. At 20:32 UT, two hours after the strongly northward IMF front reached the Earth's dayside magnetosphere, the plasma sheet density started to increase and the temperature began to drop as a cold (1 keV) component appeared in the ion distribution (Figures 1g and 1h). At 20:47 UT the temperature had gone down to 1 keV and at 21:28 UT, almost three hours after the strongly northward IMF front reached the Earth, the density reached 1.5 cm^{-3}. The plasma sheet density remained at this level the following 30 hours, while the temperature continued to decrease slowly as the hot plasma sheet ion component faded (Figure 1e). The CDPS was nearly stagnant, with flow speeds generally below 50 km s^{-1} throughout the ~30 hours interval.

[7] At the beginning of the CDPS interval the CDPS consisted of two distinct populations of H^+, one at low energies (~1 keV) and one at high energies (~10 keV) (Figure 1e). The high energy population gradually disappeared and the cooling and densification of the plasma sheet was due to the presence of the low energy component. High energy (>10 keV) O^+ was present throughout the CDPS interval, with a gradually decreasing flux (Figure 1f). No low-energy (~1 keV) O^+ was present during the CDPS interval.

[8] The end of the strongly northward IMF interval observed by ACE at 02:30 UT reached the front side magnetopause at ~03:30 UT on October 24, 2003. Cluster observed a drop in both density and temperature at 03:43 UT, indicating the exit of the spacecraft into the southern lobe after almost 32 hours of continuous plasma sheet observations.

2.3. DMSP Observations of the Plasma Sheet

[9] While the detailed high-resolution Cluster measurements are restricted to the duskside, low-altitude polar-orbiting DMSP satellites provide the average plasma sheet conditions over longer time intervals and over a wide local time region [*Wing and Newell*, 1998]. Figures 2a and 2b show the DMSP average temperature and density mapped to the equatorial plasma sheet for the 30 hours of Cluster CDPS observations. The DMSP plots show that the entire nightside plasma sheet from dawn to dusk is cold (1–2 keV)

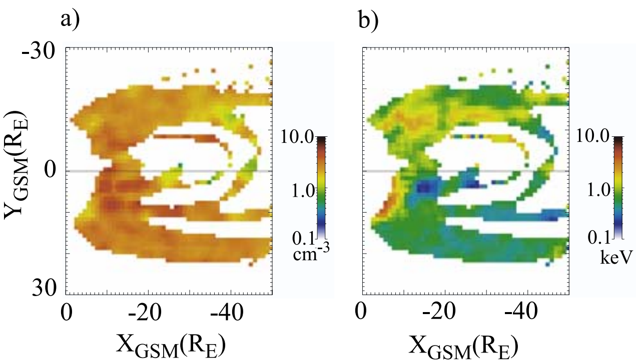

Figure 2. DMSP average (a) density and (b) temperature for the 30 hours of CDPS observed by Cluster. The entire nightside plasma sheet at all local times became cold and dense.

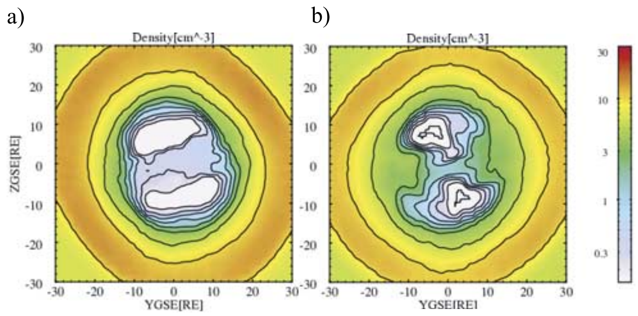

Figure 3. 2D cuts of the density at $X_{GSE} = -10\ R_E$ in the MHD simulation of the observed event (a) before the CDPS interval; (b) after onset of the CDPS interval. Cold dense plasma of magnetosheath origin enters from the flanks due to poleward-of-cusp reconnection in both hemispheres and gradually fills the magnetotail.

and dense (2–3 cm^{-3}) during this time, with the dusk flank being colder than the dawn flank.

3. Comparison With Global MHD Simulations

[10] We have compared the CDPS observations presented above with a global MHD simulation using the ACE solar wind data as input. The model takes into account the IMF B_x component as well as the dipole tilt. For a detailed description of the simulation and the deduced mechanism of solar wind entry and transport into the tail see the accompanying paper [*Li et al.*, 2005]. *Li et al.* [2005] show that the CDPS in this simulation is formed by poleward-of-cusp reconnection in both hemispheres capturing magnetosheath plasma and convecting it into the tail. The simulation produces a CDPS with gross features remarkably similar to what was observed. Figures 3a and 3b show Y-Z (GSE) cuts of the density in the global MHD simulation at $X_{GSE} = -10\ R_E$, near the Cluster X_{GSE} location. Figure 3a displays the plasma density distribution at 17:50 UT, before the purely northward IMF front reached the Earth (at 18:35 UT), and Figure 3b shows the density distribution at 23:02 UT, after more than 4 hours of strongly northward IMF. In Figure 3a the tail consists of two large and nearly empty lobes surrounding a tenuous plasma sheet. In Figure 3b the CDPS fills almost the entire tail volume as it penetrates from the flanks and the lobes have become much smaller compared to the lobes prior to the strongly northward IMF.

[11] A more quantitative comparison between the Cluster observations and the simulated data at the Cluster location is shown in Figure 4. The agreement between the simulation and the observations is good. Not only does the simulation reproduce the CDPS ($N \sim 2\ cm^{-3}$, $T_p \sim 1$ keV) in its final state (after 21:28 UT on October 22) to high accuracy, but the gradual transition from HTPS to CDPS that took ~3 hours was also reproduced (although the absolute density levels do not match perfectly). Thus poleward-of-cusp reconnection naturally produces the gradual transition from hot and tenuous to cold and dense plasma sheet. Also, both the simulated and observed CDPS are nearly stagnant ($|\mathbf{v}| < 50$ km s^{-1}) (Figure 4c).

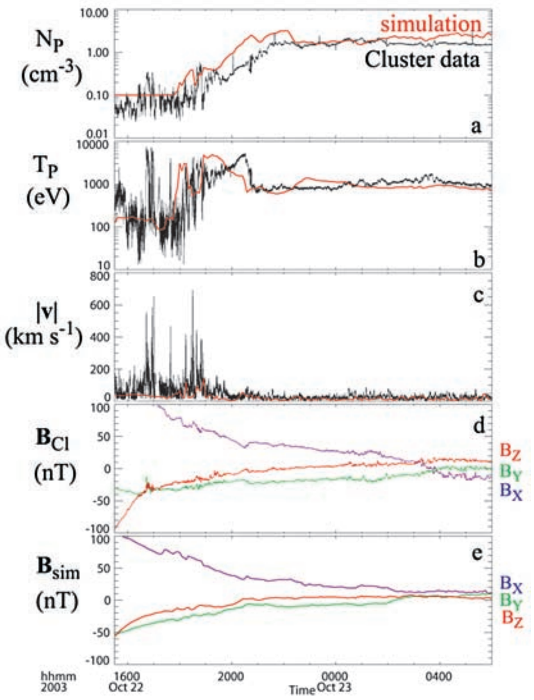

Figure 4. Comparison between Cluster observations (black) and simulated data along the Cluster path (red) (a) density; (b) temperature; (c) flow speed; (d) magnetic field components observed by Cluster (GSM); (e) simulated magnetic field components (GSM).

4. Evidence for Poleward-of-Cusp Reconnection

[12] Reversed cusp ion dispersion (ion energy increasing with latitude) observed by polar-orbiting satellites is a well-known indicator of poleward-of-cusp reconnection [*Bosqued et al.*, 1985]. During the CDPS interval the FAST satellite observed clear signatures of reversed ion dispersion. Figure 5 shows an ion spectrogram from a noon-midnight pass at

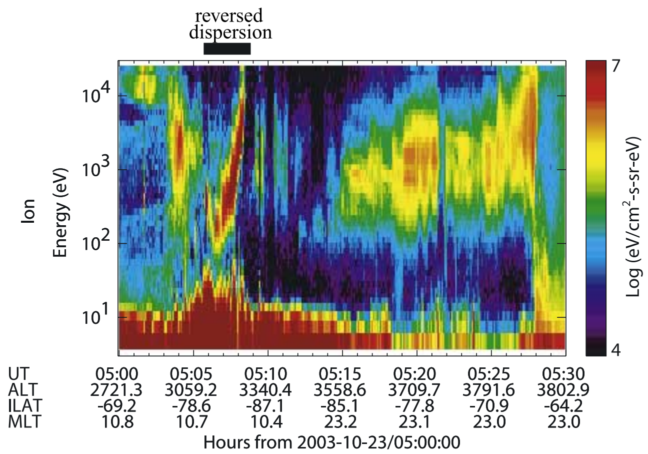

Figure 5. FAST noon-midnight pass in the southern hemisphere on October 23, 2003, 05:00–05:30 UT, during the interval of CDPS. Reversed ion dispersion is seen in the cusp, indicating poleward-of-cusp reconnection.

05:00–05:30 UT on October 23, 2003, after more than 10 hours of northward IMF. The reversed cusp ion dispersion was observed at ~05:08 UT. The empty polar cap occupied an unusually small volume on this day and the CDPS filled almost the entire polar cap, indicating small lobes in the magnetotail, similar to the simulation results.

5. Summary and Discussion

[13] We have reported continuous observations of the Earth's plasma sheet during an interval where the IMF was nearly purely northward for more than 32 hours. These exceptional IMF conditions allow us to study the full evolution of the plasma sheet from a hot and tenuous to a cold and dense state. This extended stable IMF condition is also ideal for comparison with global simulations.

[14] As the IMF became strongly northward, Cluster observed a gradual transition from hot and tenuous to cold and dense plasma sheet on the duskside. It took three hours for the plasma sheet to reach a stable cold and dense state after the northward turning of the IMF reached the front side magnetopause. This slow, gradual onset supports the findings of previous statistical studies which found the plasma sheet to be colder and denser only after the IMF has been northward (on average) for several hours prior to the plasma sheet observation [*Terasawa et al.*, 1997; *Øieroset et al.*, 2002]. This delay led *Terasawa et al.* [1997] to suggest that the CDPS is formed by a slow diffusive process along the flank magnetopause. Here we have shown that poleward-of-cusp reconnection naturally produces this delay.

[15] A global simulation was performed [*Li et al.*, 2005] which was able to reproduce not only the final cold and dense state of the plasma sheet, but also the gradual transition from hot and tenuous to CDPS. The CDPS in this simulation is produced by poleward-of-cusp reconnection capturing magnetosheath plasma and convecting it to the tail.

[16] The good agreement between the Cluster observations and the simulation (Figure 4) suggests that poleward-of-cusp reconnection in both cusps involving the same flux tubes could produce the CDPS in this case of nearly purely northward IMF. The FAST observations of reversed ion dispersion in the cusp supports the poleward-of-cusp reconnection scenario (Figure 5). To further verify the validity of the reconnection scenario, comparisons against models need to be made at various locations along the path of the solar wind plasma as it enters the magnetosphere and convects into the tail. It also remains to be seen whether the CDPS can be formed by cusp reconnection under B_y-dominated northward IMF conditions, and whether other processes such as diffusive entry [*Terasawa et al.*, 1997] and Kelvin-Helmholtz instability [*Fujimoto and Terasawa*, 1994; *Fairfield et al.*, 2000; *Hasegawa et al.*, 2004] may contribute to the formation of the CDPS.

[17] **Acknowledgments.** We thank the ACE MAG and SWE experiment teams for making their data available. This research was funded by NASA grant NAG5-12768 at U. C. Berkeley and NASA grants NAG5-10971 and NNG04GN14G at Johns Hopkins University.

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