Formation of the thin current sheets in substorms and its relation to the magnetic reconnection

Y. Asano, R. Nakamura, A. Runov, W. Baumjohann, T. Takada, I. Shinohara, A. Balogh, B. Klecker, and H. Rème

Abstract: The dynamical structure of current sheets during the growth phase of substorms is examined using Cluster multi-satellite observations. We present an event in which the current sheet temporarily becomes a non-Harris current sheet, namely, a bifurcated current sheet, and then a sheet with an over-intense current in the center in the last stage of the growth phase. Temporal variation of the current sheet thickness caused by a compressional wave with a time period of several minutes is also observed. It seems associated with the local activity in a different local time sector. Sausage-mode oscillation of the current sheet which is observed in the expansion phase or associated with fast plasma flows, is not found during the growth phase.

Key words: substorm, magnetotail, current sheet.

1. Introduction

Formation of thin current sheets with a vertical scale of an ion inertial length is considered to be one of the most important processes in substorm onset mechanisms. In particular, it is believed to be closely related to the occurrence of the magnetic reconnection in the magnetotail. Gradual thinning of the current sheet in the growth phase has been reported repeatedly [10, 11, 18, 17]. However, these previous observations of the thin current sheet before the substorm onset was limitted in the region $X_{gsm} > -15R_E$.

On the other hand, the initial location of the X line formation is revealed to be in the region $-30\ R_E < X_{gsm} < -20\ R_E$ from the past observations [12, 13, 6]. Only a part of the near-Earth current sheet becomes thin comparable to the ion inertial length [1]. On average it is only down to several thousands km. This is usually interpreted as the spatial localization of the "real" thin current sheet formation.

However, recent observations have revealed that the current sheet structures frequently deviate from the normal Harris-type current sheet, namely, over-intense current in the center or bifurcated current sheets [2]. An embedded thin intense current in the center is found to be extended to the tail region $X_{gsm} = -30\ R_E$ [14]. Such a type of current sheet may be important in the evolution of instabilities which lead to the X line formation, yet the direct observation of such type of the thin current sheet by the single satellite was difficult.

Furthermore, the current sheet in the growth phase frequently shows flapping motions [24] or kink-like-mode oscillation [19, 16]. Temporal variation of the current sheet structure might be also important in triggering magnetic reconnection. Especially, since the existence of the sausage-mode oscillation temporarily creates a intense current in the center or bifurcated structure. Although such type of the variation has been reported only in the substorm expansion phase or associated with fast flows [9], this may be another important mechanism if it exists in the growth phase.

In this paper, we report two examples of the current sheet dynamical structure in the substorm growth phase, with a temporal oscillation of the current sheet and with a current sheet structure different from the Harris-type structure. We also discuss the possibility of these structure relating to the formation of the magnetic neutral line.

Received 31 May 2006.

Y. Asano. Tokyo Institute of Technology (JSPS Research Fellow), Meguro, Japan.
R. Nakamura, A. Runov, W. Baumjohann, and T. Takada. Space Research Institute, Austrian Academy of Sciences, Graz, Austria.
I. Shinohara. Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Sagamihara, Japan.
A. Balogh. Imperial College, London, UK.
B. Klecker. Max-Planck-Institut für extraterrestrische Physik, Garching, Germany.
H. Rème. CNSR/CERS, Toulouse, France.

2. Observation

We use magnetic field data obtained by the fluxgate magnetometer (FGM) experiment [3] with the time resolution of 4 seconds, and proton moments obtained by the Composition and Distribution Function Analyser (CODIF) or ion bulk velocity by the Hot Ion Analyzer (HIA) of the Cluster Ion Spectrometry (CIS) instrument [15] with the time resolution of 4 - 12 seconds (depends on the interval and the instrument). Presented current density is calculated using curlometer-technique with the magnetic field obtained from four satellites with the time resolution of 4 seconds.

2.1. Oscillation

The first example is observed in September 3, 2004 slightly on the dawn side of the magnetotail. Fig.1(a) shows the summary plot of the Cluster observation from 0200 to 0240 UT. From top to bottom, three components of the magnetic field, proton density and temperature, current density, and x-component of the ion velocity are plotted, respectively. Panel (b) shows the relative location of the satellites in the xz-, yz-, and xy-planes. Separation among the satellites is about 1500 km, CL3 (dotted line) is in the southern-most location, while the CL1 (solid line) is in the northern-most location. Substorm onsets are identified from the ground magnetograms at 0212

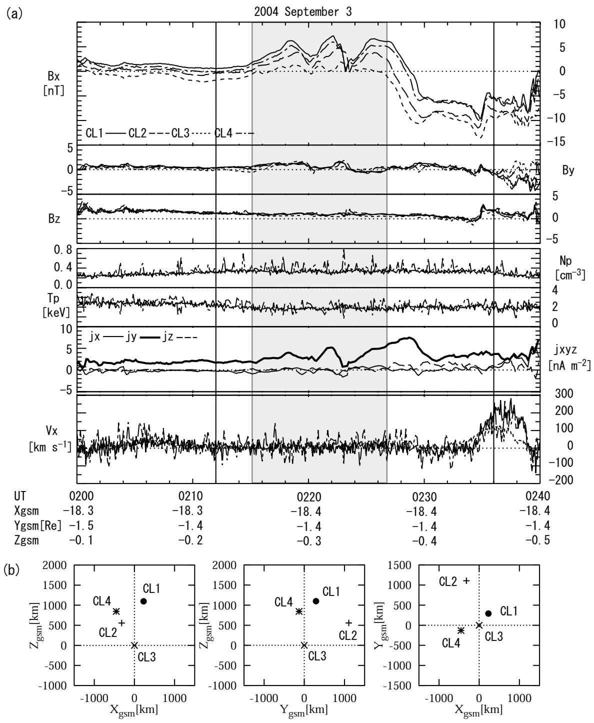

Fig. 1. (a) Summary plot of September 03, 2004 event. (b) Relative location of the four satellites at 0230 UT. See detail in the text.

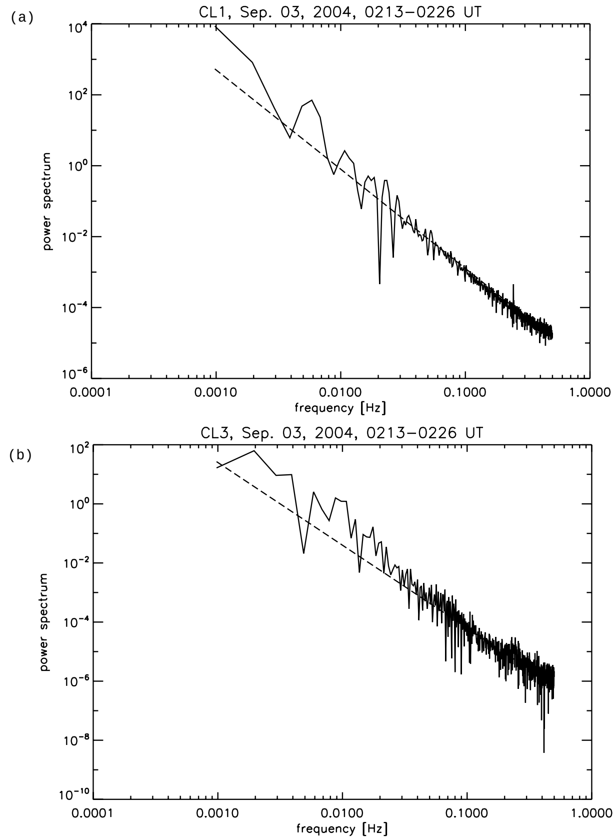

Fig. 2. Wave power spectra between 0213 UT and 0226 UT obtained by CL1 (a) and CL3 (b).

UT and 0236 UT (not shown), indicated by vertical lines in the panel (a). Evolution of the negative / positive bays in the ground magnetograms and auroral breakup (not shown) at 0212 UT onset shows that substorm activities are observed only on the pre-midnight sector, there was no activity on the dawn side. Associated with the next onset at 0236 UT, the evolution of the negative and positive bays as well as auroral expansion extends to the post-midnight region, where the satellites are located and the Earthward fast flow is observed.

Before the first onset at 0212 UT, Cluster observes almost constant cross-tail current density $j_y \sim 3\ \mathrm{nA\,m^{-2}}$ without any distinct variation or disturbance of the magnetic field or any fast plasm flow. B_z shows slight decrease, indicating the formation of the stretched magnetic field configuration in the magnetotail. B_y remains $\sim$ zero, namely, j_y remains to be a cross-tail perpendicular current in the neutral sheet. Associated with the first onset, periodic variation of the current sheet (B_x) initiates. While the southern-most spacecraft CL3 stays in the neutral sheet, B_x from other satellites changes between 0 and several nT. It can be seen that associated with the peak of B_x at CL1 (0218 UT and 0222 UT), B_x at CL3 has the smallest value, indicating the existence of the out-of-phase oscillation in the neutral sheet. Hence, the calculated cross-tail current density j_y in the neutral sheet changes temporarily from 0 to 8 $\mathrm{nA\,m^{-2}}$. This variation does not accompany any B_y or B_z variation, which suggests that the oscillation is purely compressional.

Fig.2 (a,b) shows the Fourier power spectra of the oscillation by CL1 (northern hemisphere) and CL3 (neutral sheet). While both satellites show the oscillation with the time period of 2-4 min (f = 0.004 - 0.008 Hz) which comes from the in-phase (kink-mode) oscillation, CL3 in the neutral sheet also shows the oscillation of up to 0.02 Hz (T = 50 sec) in the compressional variation. Note that the kink-like mode oscillation is found to propagate toward the dusk side of the magnetotail with the velocity of about 50 $\mathrm{km\,s^{-1}}$, namely, toward the local onset active region, with the timing analysis of B_x during the interval. Thus, the current sheet can temporarily change its thickness before the local onset of the substorm activities at 0236 UT.

2.2. Temporal atypical structure

Here, we show another example of the current sheet in the growth phase. This event is observed in August 24, 2003. At 1830 UT, the satellites are located slightly on the dawn side of the magnetotail. Fig.3 (a) shows the summary plot of the Cluster observation at 1820-1845 UT in the same format as the Fig.1(a). Fig.3(b) shows the relative location of the four satellites in the xz-, yz-, and xy- planes. The separation among the satellites is about 200 km, which is smaller than the ion inertial scale ($\sim$ 350 km with $n_i = 0.4\ \mathrm{cm^{-3}}$). The CL4 satellite is located at the southern-most position. Pi2 onset of the substorm is identified from Yinchuan magnetogram at 1836 UT, indicated by a vertical line in the panel (a), which is followed by a clear positive bay (not shown). Proton velocity V_x shows a weak tailward flow with negative B_z just before (1834 UT) and after (1837 UT) the onset, then the clear fast tailward flow is observed at 1840 UT. Before the onset until 1835 UT, all satel-

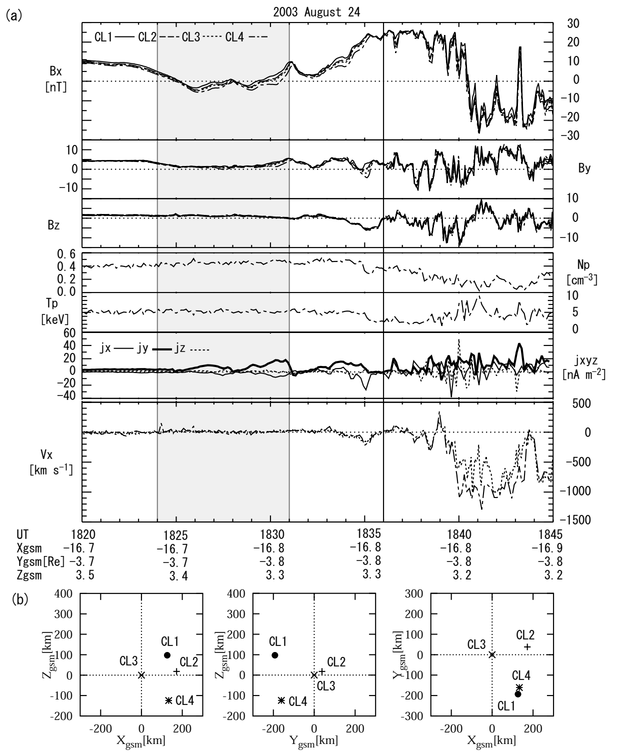

Fig. 3. (a) Summary plot of August 24, 2003 event and (b) the relative locations of the satellites at 1830 UT.

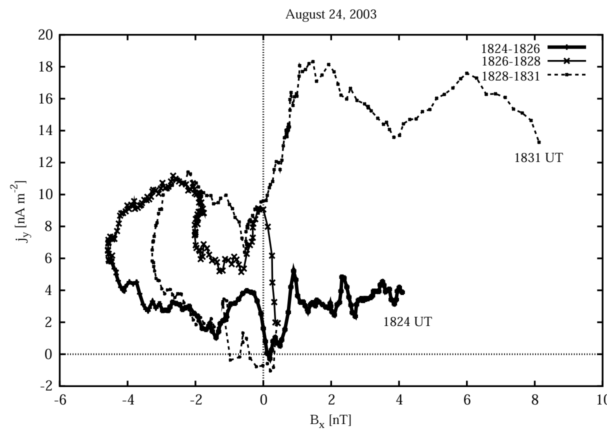

Fig. 4. j_y is plotted against B_x of the barycentric magnetic field.

lites are located inside the plasma sheet, and repeatedly cross the neutral sheet ($B_x = 0$) during the interval in a gray-hatched area. This vertical motion of the current sheet is with the time period of about 1-2 min (f = 0.008 Hz) as is also obtained by the power spectrum obtained from the satellite observation (not shown). Other components of the magnetic field are generally small, B_y is about 1.5 nT, B_z decreases from 1 nT to zero.

During the first crossing at 1825 UT from the northern hemisphere to the southern hemisphere, we can easily find that the cross-tail current density j_y is the smallest ($\sim\ 0\ \mathrm{nA\,m^{-2}}$) when the satellites are at the neutral sheet. This means that the structure of the current sheet is bifurcated during the interval. During the second crossing of the neutral sheet (1827-1828 UT), j_y changes from $6\ \mathrm{nA\,m^{-2}}$ to $9\ \mathrm{nA\,m^{-2}}$, then quickly reduces to $-1\ \mathrm{nA\,m^{-2}}$, inside the region where $|B_x|$ of the barycentric magnetic field is smaller than 2 nT. In the third interval from the southern hemisphere to the northern hemisphere, CL4 stays just on the south side of the plasma sheet from 1829 to 1830 UT ($B_x = -2$ nT), B_x of CL1 in the northern-most location becomes larger in the northern hemisphere, indicating the increase of the current density in the neutral sheet. j_y changes from $6\ \mathrm{nA\,m^{-2}}$ up to $19\ \mathrm{nA\,m^{-2}}$ at the end of the interval. The half thickness of the Harris-type current sheet with its peak value $19\ \mathrm{nA\,m^{-2}}$ and lobe magnetic field $B_L = 25$ nT, is about 1000 km. The result suggests that the current is concentrated in the center of the plasma sheet in this interval. Fig.4 shows the variation of j_y against B_x of barycentric magnetic field among the satellites. A thick solid line shows the time sequence of the observation from 1824 UT to 1826 UT, a thin solid line is from 1826 UT to 1828 UT, and a thin dashed line is the evolution from 1828 UT to 1831 UT. We can see that the first crossing shows the minimum current density in the center, during the second crossing, current density quickly decreases from $9\ \mathrm{nA\,m^{-2}}$ to $-1\ \mathrm{nA\,m^{-2}}$, and the third crossing shows the intense current in the center.

From the result of these three crossings, we find that the structure of the current sheet changes from the bifurcated to the over-intense structure within a few minutes just before the onset of a substorm onset.

3. Discussion

In the above section, we showed that the current sheet can be dynamically changed in the growth phase of substorms. Fig.5

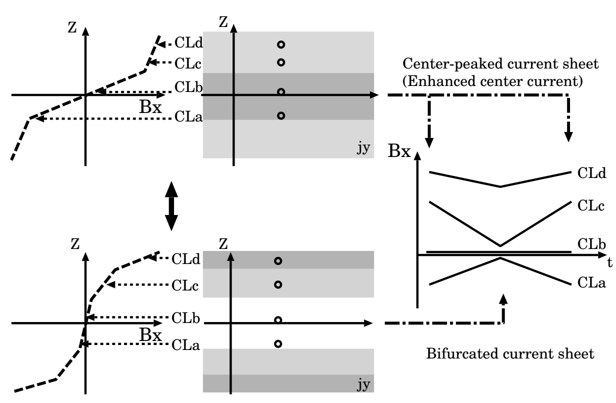

Fig. 5. Schematic picture of the variation of the current sheet structure from center-peaked current sheet and bifurcated current sheet, and associated observations by four satellites.

is the schematic picture of the variation of the current sheet structure between center-peaked current sheet and the bifurcated current sheets, and associated observations of the magnetic field (B_x) by four satellites is shown in the right panel. There is a report of the sausage-mode oscillation of the current sheet in the substorm expansion phase [9] in which they discussed that the oscillation can be described in the frame of the magnetotail eigen-mode oscillation with the time frequency of

0.03-0.06 Hz and 0.15 Hz. There also exists a compressional wave in the neutral sheet [4, 5, 25]. These studies revealed that the wave is closely related to the existence of fast plasma flows. Note that such kind of oscillation in the growth phase without any fast flow has not been reported. We surveyed from the four-years' Cluster observations of the neutral sheet associated with the substorm growth phase, but the presented 2004 September 3 event is an only clear event which shows the oscillation in the growth phase. Although formation of the thin current sheet frequently prevents us from observing the neutral sheet in the growth phase, and not so many events are suitable for the analysis of the current sheet, the result indicates that the sausage-mode oscillation or the compressional wave is rare in the growth phase.

Theoretically, while the possibility of evolution of the sausage-mode instability is discussed [7], however, the sausage-mode instability is found to be not favorable in the substorm growth phase [26]. Considering their conclusion and our observational result, it seems difficult that the sausage-mode oscillation enhances in the substorm growth phase, although our result cannot fully deny the possibility. Furthermore, our example is associated with the breakup at different local time, and there is the possibility that the oscillation is caused by this remote activity, propagating to the satellite location associated with the local disturbances such as fast plasma flows. The possibility that the perturbation generated at the other area can also be the source of another onset of the reconnection is discussed in the solar flare [20].

The other possibility that the variation of the current sheet structure changed from the Harris-type current sheet to the bifurcated or the over-intense current in the center and its relation to the formation of an X line is, on the other hand, suggested in several theoretical studies. Formation of the current sheet different from the Harris-type structure is classically discussed [8] considering the pressure anisotropy, which has been further generalized [21]. It is also discussed that the instabilities in the non-Harris current sheet leads to the substorm onset mechanisms, considering drift-kink instability and lower-hybrid drift instability [22]. Using three-dimensional full particle simulation, the quick triggering of the magnetic reconnection in the ion-scale thin current sheet from the intense current in the center [23]. Considering these results, our result that the current sheet temporarily becomes thin in the center and forms the intense current in the late stage of the growth phase, can satisfy the condition which enhanced some kinds of instabilities leading to the magnetic reconnection, and seems to be one of the candidate which is related to the trigger process of the magnetic reconnection. Further analysis of the temporal variation of the current sheet structure is expected in the future study.

4. Summary

Cluster observations of the magnetotail current sheet in the substorm growth phase show that in the course of the gradual current sheet thinning, the current sheet temporarily changes its structure to the bifurcated structure and the structure with the over-intense current in the center. The current sheet also shows temporal variation of current sheet thickness in the center, with the time frequency of $\sim$ 0.01-0.02 Hz. The compressional-mode oscillation is possibly associated with the local substorm activity at different local time. Such compressional variation are observed associated with the kink-like-mode variation of the current sheet.

Acknowledgements

This work is supported by the INTAS 03-51-3738 grant. We thank H. U. Eichelberger for the help with the FGM data. Data from ground magnetograms are provided by WDC for Geomagnetism, Kyoto.

References

1. Asano Y., T. Mukai, M. Hoshino, Y. Saito, H. Hayakawa, and T. Nagai, Statistical study of thin current sheet evolution around substorm onset, *J. Geophys. Res.*, *109*, A05213, doi:10.1029/2004JA010413, 2004.
2. Asano Y., R. Nakamura, W. Baumjohann, A. Runov, Z. Vörös, M. Volwerk, T. L. Zhang, A. Balogh, B. Klecker, and H. Rème, How typical are atypical current sheets?, *Geopys. Res. Lett.*, *32*, L03108l, doi:10.1029/2004GL021834, 2005.
3. Balogh A., C. M. Carr, M. H. Acuña, M. W. Dunlop, T. J. Beek, P. Brown, K.-H. Fornacon, E. Georgescu, K.-H. Glassmeier, J. Harris, G. Musmann, T. Oddy, and K. Schwingenschuh, The Cluster magnetic field investigation: Overview of inflight performance and initial results, *Ann. Geophys.*, *19*, 1207-1217, 2001.
4. Bauer T. M., W. Baumjohann, R. A. Treumann, N. Sckopke, and H. Lühr, Low-frequency waves in the near-Earth plasma sheet, *J. Geophys. Res.*, *100*, 9605-9617, 1995a.
5. Bauer T. M., W. Baumjohann, and R. A. Treumann, Neutral sheet oscillations at substorm onset, *J. Geophys. Res.*, *100*, 23,737-23,743, 1995b.
6. Baumjohann W., M. Hesse, S. Kokubun, T. Mukai, T. Nagai, and A. A. Petrukovich, Substorm dipolarization and recovery, *J. Geophys. Res.*, *104*, 24,995-25,000, 1999.
7. Büchner J. and J.-P. Kuska, Sausage mode instability of thin current sheets as a cause of magnetospheric substorms, *Ann. Geophys.*, *17*, 604-612, 1999.
8. Cowley S. W. H., The effect of pressure anisotropy on the equilibrium structure of magnetic current sheets, *Planet. Space Sci.*, *26*, 1037, 1978.
9. Fruit G., P. Louarn, E. Budnik, J. A. Sauvaud, C. Jacquey, D. Le Quéau, H. Rème, E. Lucek, A. Balogh, and N. Cornilleau-Wehrlin, On the propagation of low-frequency fluctuations in the plasma sheet: 2. Characterization of the MHD eigenmodes and physical implications, *J. Geophys. Res.*, *109*, A03217, doi:10.1029/2003JA010229, 2004.
10. Kaufmann R. L., Substorm currents - Growth phase and onset, *J. Geophys. Res.*, *92*, 7471-7486, 1987.
11. Mitchell D. G., D. J. Williams, C. Y. Huang, L. A. Frank, and C. T. Russell, Current carriers in the near-Earth cross-tail current sheet during substorm growth phase, *Geophys. Res. Lett.*, *17*, 583, 1990.
12. Nagai T., M. Fujimoto, Y. Saito, S. Machida, T. Terasawa, R. Nakamura, T. Yamamoto, T. Mukai, A. Nishida, and S. Kokubun, Structure and dynamics of magnetic reconnection for substorm onsets with Geotail observations, *J. Geophys. Res.*, *103*, 4419, 1998.

13. Nagai T., M. Fujimoto, R. Nakamura, W. Baumjohann, A. Ieda, I. Shinohara, S. Machida, Y. Saito, and T. Mukai, Solar wind control of the radial distance of the magnetic reconnection site in the magnetotail, *J. Geophys. Res.*, *110*, A09208, doi:10.1029/2005JA011207, 2005.
14. Pulkkinen T. I., D. N. Baker, L. L. Cogger, L. A. Frank, J. B. Sigwarth, S. Kokubun, T. Mukai, H. J. Singer, J. A. Slavin, and L. Zelenyi, Spatial extent and dynamics of a thin current sheet during the substorm growth phase on December 10, 1996, *J. Geophys. Res.*, *104*, 28475, 1999.
15. Rème H., C. Aostin, J. M. Bosqued, I. Danduras, B. Lavraud, J.-A. Sauvaud, A. Barthe, J. Bouyssou, Th. Camus, O. Coeur-Joly and others, First multispacecraft ion measurements in and near the Earth's magnetosphere with the identical Cluster ion spectrometry CIS experiment, *Ann. Geophys.*, *19*, 1303-1354, 2001.
16. Runov A., V. A. Sergeev, W. Baumjohann, R. Nakamura, S. Apatenkov, Y. Asano, M. Volwerk, Z. Vörös, T. L. Zhang, A. Petrukovich, A. Balogh, J.-A. Sauvaud, B. Klecker, and H. Rème. Electric current and magnetic field geometry in flapping magnetotail current sheets, *Ann. Geophys.*, *23*, 1391-1403, 2005.
17. Sanny J., R. L. McPherron, C. T. Russell, D. N. Baker, T. I. Pulkkinen, and A. Nishida, Growth-phase thinning of the near-Earth current sheet during the CDAW 6 substorm, *J. Geophys. Res.*, *99*, 5805, 1994.
18. Sergeev V. A., D. G. Mitchell, C. T. Russell, and D. J. Williams, Structure of the tail plasma/current sheet at $\sim 11 R_E$ and its changes in the course of a substorm, *J. Geophys. Res.*, *98*, 17345, 1993.
19. Sergeev V. A., A. Runov, W. Baumjohann, R. Nakamura, T. L. Zhang, A. Balogh, P. Louarn, J. -A. Sauvaud, and H. Rème, Orientation and propagation of current sheet oscillations, *Geophys. Res. Lett.*, *31*, L05807, doi:10.1029/2003GL019346, 2004.
20. Shibata K., and S. Tanuma, Plasmoid-induced-reconnection and fractal reconnection, *Earth Planets Space*, *53*, 473-482, 2001.
21. Sitnov, M. I., P. N. Guzdar, and M. Swisdak, A model of the bifurcated current sheet, *Geophys. Res., Lett.*, *30*(13), 1712, doi:10.1029/2003GL017218, 2003.
22. Sitnov, M. I., A. T. Y. Lui, P. N. Guzdar, and P. H. Yoon, Current-driven instabilities in forced current sheets, *J. Geophys. Res.*, *109*(A3), A03205, doi:10.1029/2003JA010123, 2004.
23. Tanaka K. G., I. Shinohara, and M. Fujimoto, Quick magnetic reconnection triggering in an ion-scale current sheet: Transition from Type-I to Type-II, *Geophys. Res. Lett.*, *32*, L17106, doi:10.1029/2005GL023718, 2005.
24. Toichi T., and T. Miyazaki, Flapping motions of the tail plasma sheet induced by the interplanetary magnetic field variations, *Planet. Space Sci.*, *24*, 147, 1976.
25. Volwerk M., W. Baumjohann, K.-H. Glassmeier, R. Nakamura, T. L. Zhang, A. Runov, Z. Vörös, B. Klecker, R. A. Treumann, Y. Bogdanova, H.-U. Eichelberger, A. Balogh, and H. Rème, Compressional waves in the Earth's neutral sheet, *Ann. Geophys.*, *22*, 303-315, 2004.
26. Yoon P. H. and A. T. Y. Lui, On the drift-sausage mode in one-dimensional current sheet, *J. Geophys. Res.*, *106*, 1939-1947, 2001.