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How typical are atypical current sheets?

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[1] Using multi-satellite Cluster magnetic field data, we statistically examined how often an atypical, i.e., non-Harris type, current sheet is formed. We found that a cross-tail current sheet with an off-equatorial current density maximum, indicating bifurcation, is frequently formed in thin current sheets with a half thickness of ~ 1500 km. The occurrence of off-equatorial current density maxima is correlated with the occurrence of fast plasma flows, namely if fast plasma flows occur nearby, one is more likely to observe off-equatorial current density maxima. We also found that many of the center-peaked current sheets exhibit a feature different from a normal Harris sheet: namely a very intense current concentrated near the equatorial plane, embedded in a broader current sheet with lower current density. **Citation:** Asano, Y., R. Nakamura, W. Baumjohann, A. Runov, Z. Vörös, M. Volwerk, T. L. Zhang, A. Balogh, B. Klecker, and H. Rème (2005), How typical are atypical current sheets?, *Geophys. Res. Lett.*, 32, L03108, doi:10.1029/2004GL021834.

1. Introduction

[2] Recent satellite observations have shown that the cross-tail current sheet sometimes becomes different from the normal Harris-type current sheet, namely bifurcated. Such an atypical current sheet has been originally observed around the magnetic neutral line [Hoshino *et al.*, 1996; Asano *et al.*, 2004a], probably associated with ion demagnetization in the vicinity of the X line, and also in association with slow mode shock-like structures. However, the current sheet becomes bifurcated not only in the vicinity of the X line, but also at other places in various phases of substorms [Nakamura *et al.*, 2002; Asano *et al.*, 2003; Runov *et al.*, 2003a, 2003b] and even in the absence of any fast plasma flow [Sergeev *et al.*, 2003].

[3] A theoretical mechanism for atypical current sheet formation, which takes into account the pressure anisotropy, has been proposed by Cowley [1978] and generalized by Sitnov *et al.* [2003] in which non-gyrotropic plasmas are involved. Recently, several other models have also been proposed, either considering ion particle dynamics [Zelenyi *et al.*, 2003], magnetic turbulence [Greco *et al.*, 2002], ion-ion kink instability [Karimabadi *et al.*, 2003a, 2003b], or coupling of the lower-hybrid drift instability with the

Kelvin-Helmholtz instability [Ricci *et al.*, 2004]. Moreover, Birn *et al.* [2004] used steady-state Vlasov-theory and showed the formation of such atypical current sheets with an electric potential structure in a current sheet with a thickness less than an ion inertial length.

[4] However, the mechanism of current sheet bifurcation is still unclear, because there are still few observations of bifurcated current sheets. For which conditions and how often bifurcated current sheets are formed has not been revealed yet. It is also unclear whether the current density can be concentrated in the center embedded by a weaker thick current sheet as has been pointed out by McComas *et al.* [1986] and Pulkkinen *et al.* [1999]. As a next step of the investigation of atypical current sheets, in this paper we study the occurrence frequency of bifurcated current sheets using multi-satellite Cluster magnetic field data. We compare the simultaneous current density j_y occurrence in the neutral sheet and in the off-equatorial region, and examine whether they follow the Harris-type current density profile or not. Evaluation of j_y in the off-equatorial region only in one hemisphere does not directly show the occurrence of current sheet bifurcation. However, it is considered to be difficult to make an asymmetric current sheet which has only one current density maximum in the off-equatorial region. Hence it would be convincing to consider the current sheet observation whose maximum is shifted from the center as a bifurcated current sheet. We also take into account the occurrence of fast plasma flows.

2. Data

[5] We use the magnetic field data obtained by the fluxgate magnetometer (FGM) experiment [Balogh *et al.*, 2001] and ion moments obtained from the Composition and Distribution Function Analyser (CODIF) of the Cluster Ion Spectrometry (CIS) instrument [Rème *et al.*, 2001], obtained from July to October 2001 when the satellites were located in the magnetotail ($X_{gsm} < -15R_E$, $|Y_{gsm}| < 10R_E$), with the time resolution of 8 seconds. Based on the order of the Z_{gsm} position, data from 2 pairs of satellites from Cluster 1, 3 and 4 which are almost on the same XZ_{gsm} -plane are used to calculate $j_y = \Delta B_x / (\mu_0 \Delta z)$. In order to compare the current density in the neutral sheet and in the off-equatorial region at the same instance, following conditions must be satisfied:

[6] 1. The innermost satellite is near the neutral sheet ($|B_{x,i}| < 0.3B_L$), i, j , and k label the spacecraft.

[7] 2. The outermost satellite is in the off-equatorial plasma sheet ($0.3B_L < |B_{x,k}| < 0.6B_L$).

[8] 3. The middle satellite is in the plasma sheet in the same hemisphere as the outer most satellite ($|B_{x,j}| < 0.6B_L$, $B_{x,j}B_{x,k} > 0$).

[9] 4. The inner two satellites observe the neutral sheet ($|B_{x,i} + B_{x,j}|/2 < 0.15B_L$ or $B_{x,i}B_{x,j} < 0$), and the outer two

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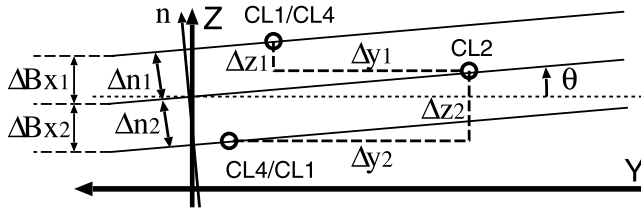


Figure 1. Calculation method of YZ_{gsm} -plane inclination angle.

satellites observe the off-equatorial region ($0.3B_L < |B_{xj} + B_{x,k}|/2 < 0.6B_L$).

[10] B_L is the estimated lobe magnetic field intensity calculated with the assumption of pressure balance between the plasma sheet and the lobe, $B_L = (B^2 + 2\mu_0 n_i k_B T_i)^{1/2}$, where B , n_i , and T_i are local values of magnetic field intensity, plasma density, and plasma temperature obtained by CL1. Note that a region with less than 60% intensity of the lobe magnetic field corresponds to $\beta \geq 1.78$, which is well inside the plasma sheet, and we automatically excluded all the lobe data with these criteria. The location of the off-equatorial region $0.3B_L < |B_x| < 0.6B_L$ is based on previous observations which showed that bifurcated current sheet maxima are located at $0.3B_L < |B_x| < 0.6B_L$ [Asano *et al.*, 2003] and $|B_x| \sim 0.5B_L$ [Sergeev *et al.*, 2003]. With these criteria, we have two pairs of the satellites, one in the neutral sheet and one in the off-equatorial region, at the same instance.

[11] In our study the inclination of the current sheet must be also considered. In the XZ_{gsm} -plane, it is not likely that because of the influence of the solar wind the tilt angle becomes large in the mid-magnetotail. However, we checked the XZ_{gsm} -plane tilt angle by comparing the magnetic B_x and B_z components in the different B_x regions observed by 3 satellites, since B_x is supposed to be converted to B_z if the tilt exists. Twenty samples (corresponding to 8% of the original data) are tilted by more than 5 degrees, and have been excluded. In the YZ_{gsm} -plane, the current sheet is sometimes inclined [Zhang *et al.*, 2002] because of the flapping-like motions propagating in the Y_{gsm} -direction [Sergeev *et al.*, 2004]. In order to exclude the effect of these phenomena, we do not use data for which the Y_{gsm} separation of the 2 satellite pairs is larger than that in the Z_{gsm} direction. Note that CL2 is separated mainly in the Y_{gsm} direction from the other satellites, and does not satisfy this criterion. Then, as is shown in Figure 1, using CL1, 2, and 4 data, a planar and constant current sheet structure is assumed, and the degree of inclination is calculated using the relation $\Delta B_{x,1}/\Delta B_{x,2} = \Delta n_{cs,1}/\Delta n_{cs,2}$, where Δn_{cs} is the separation in the direction normal to the current sheet. The current density is calculated in the rotated YZ' coordinate system. Previous observations [Zhang *et al.*, 2002; Sergeev *et al.*, 2004] have shown that a planar current sheet assumption is considered to be valid for the given separation of ~ 1500 km. In our data set, it is found that in most cases the current sheet is inclined less than 15 degrees. However, in some cases, mainly associated with magnetic disturbances, flapping motions, and with fast flows, the current sheet is inclined more than 30 degrees. These further 27 intervals are also excluded from our study.

[12] We should mention that the spacecraft separation in the Z_{gsm} direction in 2001 is about 1500 km. Hence our

study reveals bifurcation characteristics only in thin current sheets corresponding to the satellite separation, which is a few times of the ion inertial length 415 km for $n_i = 0.3 \text{ cm}^{-3}$ or the ion Larmor radius (409 km for $T_i = 5 \text{ keV}$ with $B_L = 25 \text{ nT}$).

[13] Altogether, we obtained 180 samples from 16 magnetotail crossings which satisfy the above criteria, predominantly quiet intervals.

3. Observations

[14] Figure 2 shows a summary plot of Cluster observations on August 22, 2001, 0840–0855 UT, as an example of the data sets we are using. Three components of the magnetic field (all satellites), proton density, temperature, and x -component of the bulk velocity (CL1 and CL4) are plotted. Relative positions of the 4 satellites are also shown in the bottom panels in the XZ_{gsm} plane and YZ_{gsm} plane. We see that all spacecraft were in the plasma sheet (high temperature and density), and the plasma sheet was quiet without any fast flows. The satellites stayed slightly on the dawn side of the magnetotail at $X_{gsm} = -19.0R_E$. At this time, CL2 was 1623 km on the dusk side of CL1 and showed almost the same B_x value. This shows there is a small inclination of the current sheet in the YZ -plane, only 4–7 degrees. CL3 was located southward of these two satellites, and stayed mostly near the neutral sheet, and CL4 was north of them, away from the neutral sheet. At 0845:01 UT (highlighted interval (a)), the difference in B_x between CL3 and CL1 ($\Delta z = 1367 \text{ km}$) was much larger than that between CL1 and CL4 ($\Delta z = 431 \text{ km}$). j_y in the neutral sheet (NS) and j_y in the off-equatorial region (OE) are derived as 4.2 nA m^{-2} and 2.0 nA m^{-2} , respectively. This is identified as a center-peaked current sheet. After

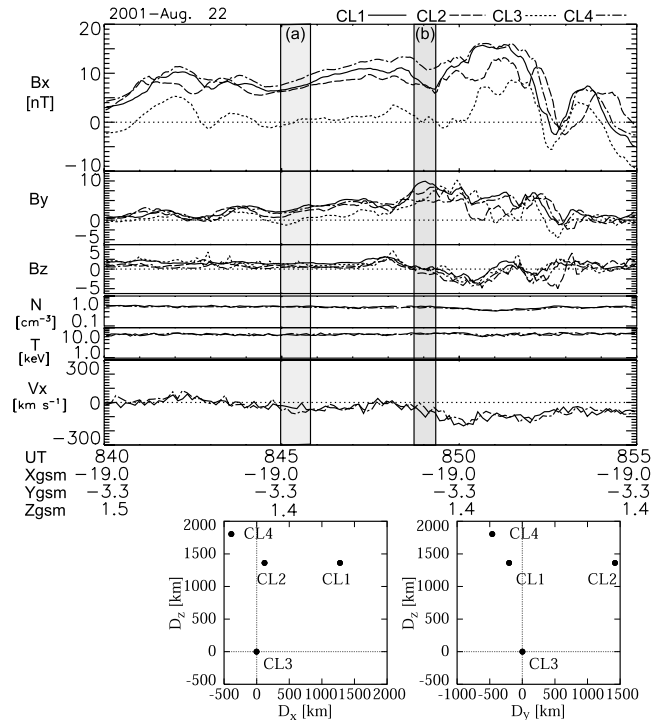


Figure 2. Cluster observation and position on August 22, 2001. See text for details.

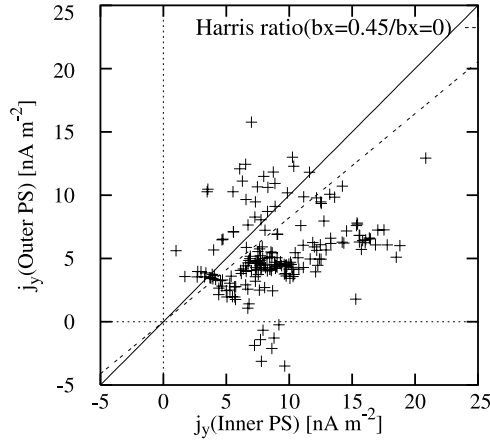


Figure 3. Distribution of j_y in the neutral sheet and in the off-equatorial plasma sheet. Theoretical ratio in the Harris-type current sheet is shown by a dashed line.

that, while CL3 stayed in the neutral sheet, indicating that the position of the neutral sheet did not change, B_x at the position of CL4 changed. At 0848:38–0848:46 UT (interval (b)), while the B_x difference between CL1 and CL3 was almost the same as during the interval (a), $j_y(\text{NS}) = 4.6 \text{ nA m}^{-2}$, B_x in CL4 was larger than before. Here, $j_y(\text{OE})$ becomes 6.5 nA m^{-2} , larger than that in the neutral sheet and hence, this case is identified as bifurcated current sheet. This signature lasts only less than one minute, and returns to a center-peaked current sheet again.

[15] Figure 3 shows the distribution of the statistical result of the current density. $j_y(\text{NS})$ is plotted against $j_y(\text{OE})$. The solid line shows $j_y(\text{NS}) = j_y(\text{OE})$, and the dashed line shows the theoretical ratio of $j_y(\text{OE})/j_y(\text{NS})$ in a Harris-type current sheet $j_y(z) = j_y(\text{NS})/\cosh^2(z/L)$, where L is the current sheet thickness. Using $j_y(\text{OE})$ at $|B_x/B_L| = 0.45 = (0.3 + 0.6)/2$ from our criteria, this can be described as $1/\cosh^2(\text{atanh}(0.45))$. As mentioned previously, we selected the data from relatively thin current sheets whose thickness is a few times of the ion inertial length, and the peak current density is usually more than 5 nA m^{-2} . This is larger than typical in the normal Harris current sheet at $X_{\text{gsm}} = -20R_E$ ($\sim 2\text{--}3 \text{ nA m}^{-2}$). With $\Delta Z_{\text{gsm}} \sim 1500 \text{ km}$, we get 5 nA m^{-2} from the magnetic field difference $\Delta B_x \sim 9 \text{ nT}$ ($=0.3B_L$ for $B_L = 30 \text{ nT}$).

[16] We can see that the main part of the data exists in the region $j_y(\text{NS}) > j_y(\text{OE})$, which indicates that a center-peaked current sheet is more frequently observed than a bifurcated current sheet. On the other hand, we do find that a bifurcated current sheet is frequently formed. The overall occurrence frequency of bifurcated current sheets is 17%. As is also shown in the event of a center-peaked current sheet (Figure 2), $j_y(\text{OE})$ frequently becomes smaller than that expected from the theoretical ratio derived from the Harris-model. This result indicates the formation of a very concentrated current in the center, embedded in a larger current sheet whose current density is small.

[17] It is noted that the difference of the spatial scale between 2 pairs of satellites (one for 1000–1500 km, the other for 200–700 km) does not change the results. Occurrence frequency of the bifurcated current sheet is almost the same (15% and 17%) for the cases when the smaller

separation is located in the neutral sheet or in the off-equatorial region, respectively.

[18] In bifurcated current sheets, $j_y(\text{NS}) < j_y(\text{OE})$, we do not see any typical current density in the center and in the off-equatorial region. We do not see any typical current density ratio, either. There are some data with the center current density almost comparable to the off-equatorial region, and some of the others show a steep decrease in the center. The local minimum current density in the center does not always become significantly smaller than the off-equatorial current density.

[19] In order to examine the relation of current sheet bifurcation to fast plasma flow activity, we examine a $\pm 15 \text{ min}$ interval around each sample of the current sheet used in this study. We take the largest $|V_x|$ data from the 3 satellites in the examined interval. The occurrence frequency of a bifurcated current sheet is plotted against the largest $|V_x|$ in Figure 4. It shows the occurrence frequency of center-peaked (dashed line) and bifurcated current sheets (solid line). We can see that a bifurcated current sheet appears in only 6% of the samples without any fast flows within the $\pm 15\text{-min}$ interval, but the occurrence frequency associated with fast flows increases up to 48%.

4. Discussion

[20] Our results show that bifurcated current sheets are not rare phenomena and can be formed repeatedly. Bifurcated current sheets appear more frequently when fast plasma flow activity is observed. However, our results show that bifurcation can occur without any fast plasma flows [Hoshino *et al.*, 1996; Asano *et al.*, 2004a] and without significant flapping motion [Asano *et al.*, 2003; Sergeev *et al.*, 2004].

[21] Our data set consists of thin current sheet cases, mainly without fast flows. Such a current sheet is found to be mainly formed in the substorm growth phase and the early expansion phase [Mitchell *et al.*, 1990; Sergeev *et al.*, 1993; Sanny *et al.*, 1994] with a small $|B_z|$ caused by a stretched magnetic field. It is also consistent with our data in which large $|B_z|$ cases ($>4 \text{ nT}$) are rare. Formation of bifurcated current sheets in the growth phase and the early expansion phase was previously reported by Asano *et al.* [2003]. It is likely that bifurcated current sheets appear frequently in thin and stretched current sheets in the substorm growth and early expansion phases. Further, it may be important to consider the mechanism of the formation of bifurcated current sheets in the course of current sheet thinning.

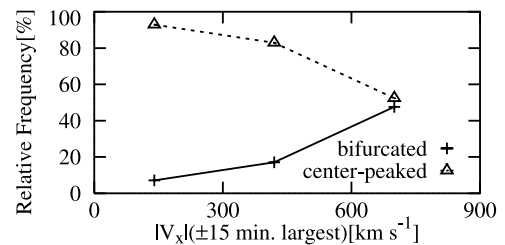


Figure 4. Relative occurrence frequency of bifurcated current sheets (solid line) and center-peaked current sheets (dashed line) plotted against $|V_x|$.

[22] We also found another interesting feature: in most cases of the center-peaked current sheet the current density is significantly intensified around the neutral sheet region, and the current density in the off-equatorial region becomes lower than that expected from the Harris-type model. Such cases were reported by *McComas et al.* [1986] and *Pulkkinen et al.* [1999]. What distinguishes the formation of bifurcated current sheets from thin intense current sheet in the center embedded in a weaker thick current sheet has been discussed with respect to pressure anisotropy (non-gyrotropy) [Cowley, 1978; Schindler and Birn, 2002; Sitnov et al., 2003]. *Asano et al.* [2004b] reported the existence of pressure anisotropy in a thin current sheet. However, any clear observation of a current sheet structure associated with the ion plasma distribution has not been achieved yet. Further study is clearly needed.

5. Conclusion

[23] We have studied the relative occurrence frequency of bifurcated current sheets, using data obtained from the Cluster satellites in 2001. In a thin current sheet (thickness is ~ 1500 km) without any fast flows or significant turbulence, the current sheet becomes bifurcated for 17% of the total time. In cases of bifurcation, however, fast plasma flows are observed within ± 15 min of the formation of the bifurcated current sheet. For center-peaked current sheets, intense current frequently appears in the center, embedded in broad lower current density region, which is also different from the theoretical Harris-type current sheet.

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References

- Asano, Y., T. Mukai, M. Hoshino, Y. Saito, H. Hayakawa, and T. Nagai (2003), Evolution of the thin current sheet in a substorm observed by Geotail, *J. Geophys. Res.*, **108**(A5), 1189, doi:10.1029/2002JA009785.
- Asano, Y., T. Mukai, M. Hoshino, Y. Saito, H. Hayakawa, and T. Nagai (2004a), Current sheet structure around the near-Earth neutral line observed by Geotail, *J. Geophys. Res.*, **109**, A02212, doi:10.1029/2003JA010114.
- Asano, Y., T. Mukai, M. Hoshino, Y. Saito, H. Hayakawa, and T. Nagai (2004b), Statistical study of thin current sheet evolution around substorm onset, *J. Geophys. Res.*, **109**, A05213, doi:10.1029/2004JA010413.
- Balogh, A., et al. (2001), The Cluster magnetic field investigation: Overview of in-flight performance and initial results, *Ann. Geophys.*, **19**, 1207.
- Birn, J., K. Schindler, and M. Hesse (2004), Thin electron current sheets and their relation to auroral potentials, *J. Geophys. Res.*, **109**, A02217, doi:10.1029/2003JA010303.
- Cowley, S. W. H. (1978), The effect of pressure anisotropy on the equilibrium structure of magnetic current sheets, *Planet. Space Sci.*, **26**, 1037.
- Greco, A., A. L. Taktakishvili, G. Zimbardo, P. Veltri, and L. M. Zelenyi (2002), Ion dynamics in the near-Earth magnetotail: Magnetic turbulence versus normal component of the average magnetic field, *J. Geophys. Res.*, **107**(A10), 1267, doi:10.1029/2002JA009270.
- Hoshino, M., A. Nishida, T. Mukai, Y. Saito, T. Yamamoto, and S. Kokubun (1996), Structure of plasma sheet in magnetotail: Double-peaked electric current sheet, *J. Geophys. Res.*, **101**, 24,775.
- Karimabadi, H., W. Daughton, P. L. Pritchett, and D. Krauss-Varban (2003a), Ion-ion kink instability in the magnetotail: 1. Linear theory, *J. Geophys. Res.*, **108**(A11), 1400, doi:10.1029/2003JA010026.
- Karimabadi, H., P. L. Pritchett, W. Daughton, and D. Krauss-Varban (2003b), Ion-ion kink instability in the magnetotail: 2. Three-dimensional full particle and hybrid simulations and comparison with observations, *J. Geophys. Res.*, **108**(A11), 1401, doi:10.1029/2003JA010109.
- McComas, D. J., C. T. Russell, R. C. Elphic, and S. J. Bame (1986), The near-Earth cross-tail current sheet: Detailed ISEE 1 and 2 case studies, *J. Geophys. Res.*, **91**, 4287.
- Mitchell, D. G., D. J. Williams, C. Y. Huang, L. A. Frank, and C. T. Russell (1990), Current carriers in the near-Earth cross-tail current sheet during substorm growth phase, *Geophys. Res. Lett.*, **17**, 583.
- Nakamura, R., et al. (2002), Fast flow during current sheet thinning, *Geophys. Res. Lett.*, **29**(23), 2140, doi:10.1029/2002GL016200.
- 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 (1999), Spatial extent and dynamics of a thin current sheet during the substorm growth phase on December 10, 1996, *J. Geophys. Res.*, **104**, 28,475.
- Rème, H., et al. (2001), First multispacecraft ion measurements in and near the Earth's magnetosphere with the identical Cluster Ion Spectrometry (CIS) experiment, *Ann. Geophys.*, **19**, 1303.
- Ricci, P., G. Lapenta, and J. U. Brackbill (2004), Structure of the magnetotail current: Kinetic simulation and comparison with satellite observations, *Geophys. Res. Lett.*, **31**, L06801, doi:10.1029/2003GL019207.
- Runov, A., R. Nakamura, W. Baumjohann, T. L. Zhang, M. Volwerk, H.-U. Eichelberger, and A. Balogh (2003a), Cluster observation of a bifurcated current sheet, *Geophys. Res. Lett.*, **30**(2), 1036, doi:10.1029/2002GL016136.
- Runov, A., et al. (2003b), Current sheet structure near magnetic X-line observed by Cluster, *Geophys. Res. Lett.*, **30**(11), 1579, doi:10.1029/2002GL016730.
- Sanny, J., R. L. McPherron, C. T. Russell, D. N. Baker, T. I. Pulkkinen, and A. Nishida (1994), Growth-phase thinning of the near-Earth current sheet during the CDAW 6 substorm, *J. Geophys. Res.*, **99**, 5805.
- Schindler, K., and J. Birn (2002), Models of two-dimensional embedded thin current sheets from Vlasov theory, *J. Geophys. Res.*, **107**(A8), 1193, doi:10.1029/2001JA000304.
- Sergeev, V. A., D. G. Mitchell, C. T. Russell, and D. J. Williams (1993), Structure of the tail plasma/current sheet at $\sim 11R_E$ and its changes in the course of a substorm, *J. Geophys. Res.*, **98**, 17,345.
- Sergeev, V., et al. (2003), Current sheet flapping motion and structure observed by Cluster, *Geophys. Res. Lett.*, **30**(6), 1327, doi:10.1029/2002GL016500.
- Sergeev, V., A. Runov, W. Baumjohann, R. Nakamura, T. L. Zhang, A. Balogh, P. Louard, J.-A. Sauvaud, and H. Rème (2004), Orientation and propagation of current sheet oscillations, *Geophys. Res. Lett.*, **31**, L05807, doi:10.1029/2003GL019346.
- Sitnov, M. I., P. N. Guzdar, and M. Swisdak (2003), A model of the bifurcated current sheet, *Geophys. Res. Lett.*, **30**(13), 1712, doi:10.1029/2003GL017218.
- Zelenyi, L. M., et al. (2003), Splitting of thin current sheets in the Earth's magnetosphere, *JETP Lett.*, **78**, 296–299, doi:10.1113/1.1625729.
- Zhang, T. L., W. Baumjohann, R. Nakamura, A. Balogh, and K.-H. Glassmeier (2002), A wavy twisted neutral sheet observed by CLUSTER, *Geophys. Res. Lett.*, **29**(19), 1899, doi:10.1029/2002GL015544.
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