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Observation of repeated intense near-Earth reconnection on closed field lines with Cluster, Double Star, and other spacecraft

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[1] We report strong repeated magnetic reconnection pulses that occurred deep inside closed plasma sheet flux tubes at $r \leq 14$Re. They have been observed with a fortuitous spacecraft constellation during three consecutive turbulent magnetic dipolarizations, accompanied by localized auroral brightenings near the equatorward edge of a wide auroral oval. The reconnection separatrix was mapped to ~64° CGLat in the ionosphere, where a very energetic and narrow energy-dispersed ion injection with unusually steep dispersion slope was observed. Reconstruction of the reconnection rate from magnetic waveforms at Cluster provided a reconnection pulse duration (~1 min) and peak strength ($E_R \sim 8$ mV/m) consistent with direct observations in the reconnection outflow region. The magnetic activity was rather weak, although the concurrent solar wind flow pressure was above the norm. We suggest that near-Earth reconnection events may be a phenomenon more frequent than generally thought. We also confirm that reconnection and the growth of strong turbulence in the near tail are strongly coupled together in near-Earth reconnection events. **Citation:** Sergeev, V., et al. (2007), Observation of repeated intense near-Earth reconnection on closed field lines with Cluster, Double Star, and other spacecraft, *Geophys. Res. Lett.*, *34*, L02103, doi:10.1029/2006GL028452.

1. Introduction

[2] Turbulent current disruption (CD) in the inner magnetosphere or the explosive growth of magnetic reconnection (MR) in the midtail current sheet are considered as alternative substorm onset mechanisms, whose distinction is a one of the targets in the forthcoming THEMIS mission. On the one hand there is ample but indirect evidence of a near-Earth location of the substorm onset (deep on closed field lines, near the transition between the current sheet and dipole-like region, from 6.6 Re to 10–12 Re, see, e.g. a summary by *Lui* [1996]). In contrast, the statistics of reconnection flows from Geotail observations show that the most probable location of the X-line was at 20–30 Re [*Nagai et al.*, 1998; *Baumjohann et al.*, 1999]. As a consequence, the MR and CD are often treated as spatially separated and, therefore, different processes. However their large separation may not necessarily be the case. A small number of direct observations of near-Earth ($r \leq 15$ Re) reconnection has also been published (e.g., *McPherron and Manka* [1985], *Sergeev et al.* [1995], and *Miyashita et al.* [2005], all done with a limited instrumental or spacecraft coverage which makes the interpretation non-unique); other past and recent evidence of near-Earth reconnection onsets were discussed by *Baker et al.* [1996] and *Petrukovich and Yahnin* [2006]. The scarcity of direct observations could in fact be due to (1) the infrequent chances to probe a very thin reconnection-related current sheet, (2) the difficulty in diagnosing the reconnection unambiguously with one (or few randomly located) spacecraft, (3) a number of other important factors (azimuthal and meridional separations between spacecraft and onset locations, magnetic configuration etc.) which are rarely under control. Detailed and undisputed in situ observation of near-Earth reconnection still has a great value for the understanding of the explosive dissipation processes in substorms and in space plasmas in general.

[3] Here we report a unique interval in which we look simultaneously at signatures of both MR and CD processes in a rare case of three repeated near-Earth reconnection events, during which all main variables were observed. This possibility has occurred largely due to fortuitous spacecraft configuration, with the Cluster and Double Star (TC2) spacecraft bracketing the near-Earth neutral line near the central meridian of the tail activity. (See *Annales Geophysicae 2001 (N10-12) and 2005 (N11)* for the description of the instruments at these spacecraft). We also apply a recently developed reconstruction technique [*Semenov et al.*, 2005] to recover the reconnection parameters from Cluster magnetic variations in one event. This event provides reliable observations of very intense reconnection repeatedly observed on closed field lines in the near-Earth tail region during weak magnetic activity. In addition we show (for the first time) the low-altitude ion signature of near-Earth reconnection. Finally, we briefly discuss the solar wind conditions favorable for near-Earth

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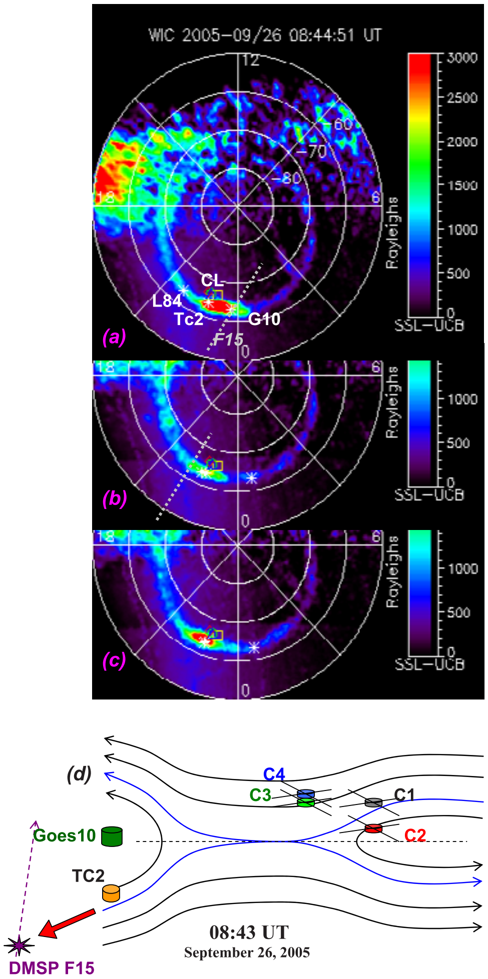

Figure 1. (a–c) IMAGE WIC auroral images of localized auroral brightenings (at 084451 UT, 093251UT and 094112UT) for three activations *a*, *b* and *c*, correspondingly, with spacecraft ionospheric footpoints computed using the T96 model. (d) Schematic of spacecraft positions mapped onto the 23 h MLT meridional plane during the event *a*.

reconnection as well as the close coupling between CD and MR processes.

2. Data Analyses

[4] Between 08 and 10 UT on September 26, 2005, when the Cluster spacecraft crossed the current sheet at 14–15 Re distance and other spacecraft (TC2, Goes10 and LANL084) probed the inner magnetosphere near the geosynchronous distance, the IMAGE WIC camera recorded three localized auroral brightenings at rather low latitudes ~64°CGLat (events *a*, *b*, *c* in Figure 1). The footpoints of Cluster and TC2 are close to each other in the ionosphere, and in all three cases they appeared near the central meridian of activation (near 23 h MLT). Other geosynchronous spacecraft (LANL084, Goes10) were within 1–2h MLT from this meridian, see their relative location in the scheme of Figure 1d. Also the DMSP F15 spacecraft crossed the auroral brightening region during the first minute of activation *a*.

[5] In the inner magnetosphere, three plasma injections and dipolarization events (*a*, *b*, *c*) were detected at 0843, 0931 and 0941 UT (Figure 2, bottom), accompanying the localized auroral brightenings displayed in Figure 1. These were the only remarkable events during these two hours. Between activations (*a*) and (*c*) the Cluster baricenter moved from $[-15.3; 3.7; -0.1]$ to $[-15.8; 3.8, -0.9]$ Re GSM, while TC2 was moving upward in Z (from -1.4 Re to -0.5 Re) in the plasma sheet at $X \approx -6.5$ Re and $Y \approx +1.9$ Re. Therefore they all stay near the 23 h MLT meridional plane, near the central longitude of the activation. At this time Cluster C1, C2 and C3 formed a triangle in the XY plane with a separation about 9000 km whereas C3 and C4 (closest to the Earth) had the same X,Y but were separated by 900 km in Zgsm allowing thin and thick current sheets to be distinguished.

[6] In this favourable configuration, Cluster provided decisive evidence of tailward reconnection-related outward flows. During activations *b*, *c* the spacecraft crossed the current sheet (Figure 2, top), detecting strong tailward ion outflows (up to 500 km/s and 1000 km/s, correspondingly) synchronized with southward Bz variation and energetic (isotropic) electron beams (during activation *b*). Of particular importance is the large difference between the Bx components at C3 and C4, suggesting proximity of a very thin current sheet (expected near the reconnection region) with current density up to 30–40 nA/m^2. A systematic large ($\sim 0.3\ B_{LOBE}$) Hall quadrupole By magnetic field [e.g., *Runov et al.*, 2003] was also observed (Figure 3), with $\delta By \bullet Bx < 0$ confirming the more Earthward position of nearby reconnection region (δBy is the deviation of average By from the dashed reference line). All main predictions of active reconnection operating at $X > -15$ Re (thin CS, quadrupole Hall By, fast tailward outflow of plasma carrying southward Bz, particle acceleration) were reliably observed in these events, clearly confirming magnetic reconnection Earthward of -15 Re.

[7] During activation *a* (Figure 4a), Cluster C2 closest to the neutral sheet observed a strong southward Bz (down to -15 nT), intense Eygse up to >10 mV/m (as recorded by the double probe, which implies transverse tailward outflows, $[\mathbf{E} \times \mathbf{B}]_x/\mathbf{B}^2 \sim -400$ km/s), and a strong energetic electron flux increase ($E_e > 50$ keV). A strong tailward field-aligned anisotropy of the energetic electrons was measured by the RAPID instrument (increase of tailward electron flux by a factor of 5–10 during ~10 spins, see Figure S1 in auxiliary material[1]) consistent with a near-Earth source. This unidirectional energetic electron beam was observed up to energies as high as ~300 keV.

[8] In contrast to the later events *b*, *c*, other Cluster spacecraft (C1, C3, C4, located further from the neutral sheet) did not register the energetic electron beams and the fast flows during the event *a*. Thus, although the spacecraft stayed inside the plasma sheet (and within 0.5 Re from each other and from the neutral sheet), they apparently did not cross the reconnection separatrix, but rather stayed in the reconnection inflow region (see the scheme in Figure 1d). The tailward progression of the magnetic perturbations is seen in Figure 4 between C4 and C1 (time delay about 10 sec over ~9000 km separation distance could be determined when matching the waveforms by a time shift),

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2006GL028452.

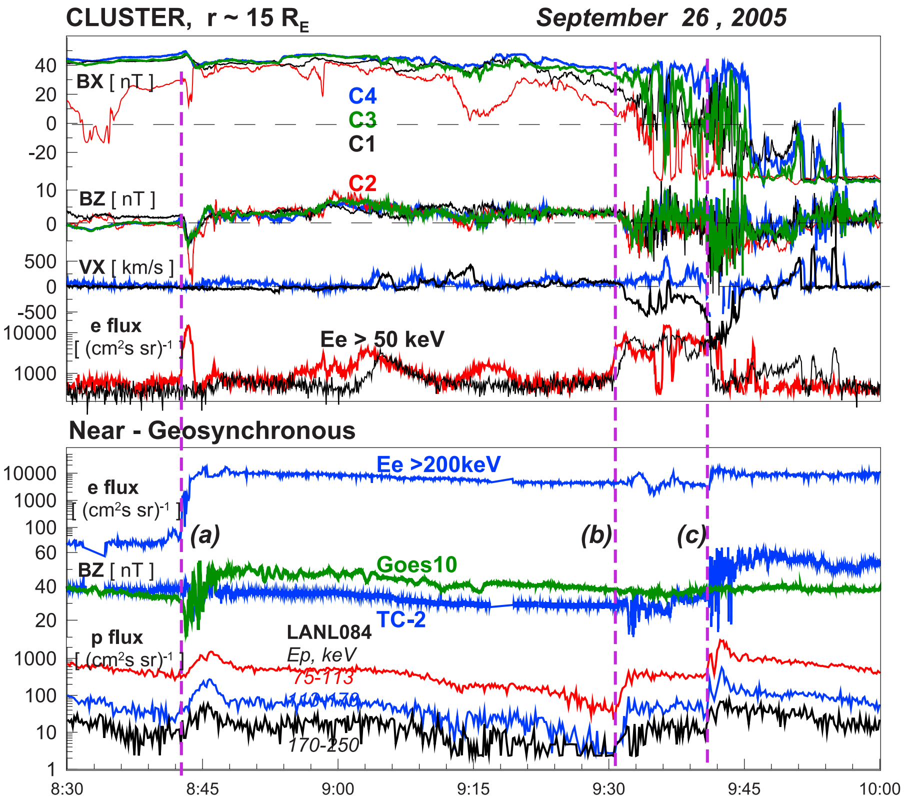

Figure 2. Survey of observations (top) at the Cluster spacecraft and (bottom) in the near-geosynchronous region (at TC2, Goes10 and LANL084).

suggesting a ~900 km/s tailward propagation velocity, also consistent with reconnection.

[9] Recently, a method was introduced, that uses the elementary magnetic field perturbations in the inflow region computed in 2D MHD theory. For an impulsive localized reconnection source it allows us to reconstruct the reconnection rate and its other parameters (e.g. the distance) based on the observed B-waveforms and on some a priori information [*Semenov et al.* 2005]. Event *a* is amenable to this method since the observations were made within a few Re distance from the reconnection source and in the central sector of the activation (to minimize 3D effects) and covered both outflow (C2) and inflow (C1,C3,C4) regions. Other observations (E-field at C2) are available to test the results. Additional a priori information were the spacecraft GSM coordinates and the Alfven velocity in the inflow region (V_A = 900 km/s) inferred from tailward propagation of magnetic perturbations. This speed corresponds to the Alfven speed of proton plasma with density 0.5 cm^{-3} and B = 30 nT observed near plasma sheet boundary. Figure 4c shows the reconstruction results for the simplest version which uses only Bz perturbations as inputs (more detailed investigation with a comparison of different models will be published elsewhere). The reconstructed X-line location was $X \approx -11 \pm 1$ Re, the duration and the peak values of the reconnection pulse were ~100 sec and E_R from 4 to 8 mV/m (using inputs from different spacecraft separately), which are consistent with the time interval of the energetic electron beam at the C2

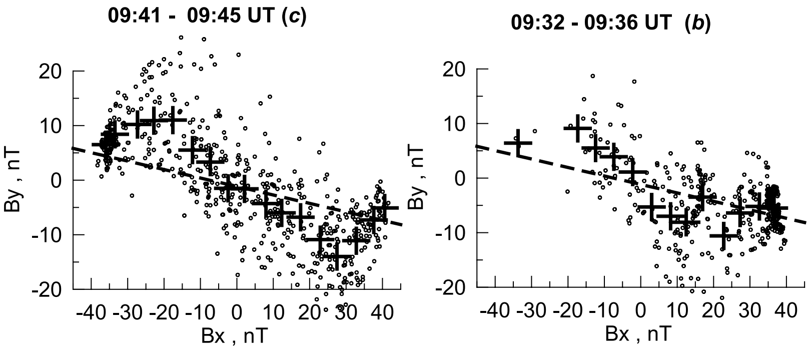

Figure 3. Distributions of By perturbations across the current sheet thickness (using Bx as a proxy of Z-coordinate) at all Cluster spacecraft during the activations *b* and *c*. The reference dashed line indicate the linear By(Bx) regression obtained by using all data between 09 and 10 UT except for the short disturbed time intervals corresponding to the events *a*, *b*, *c*.

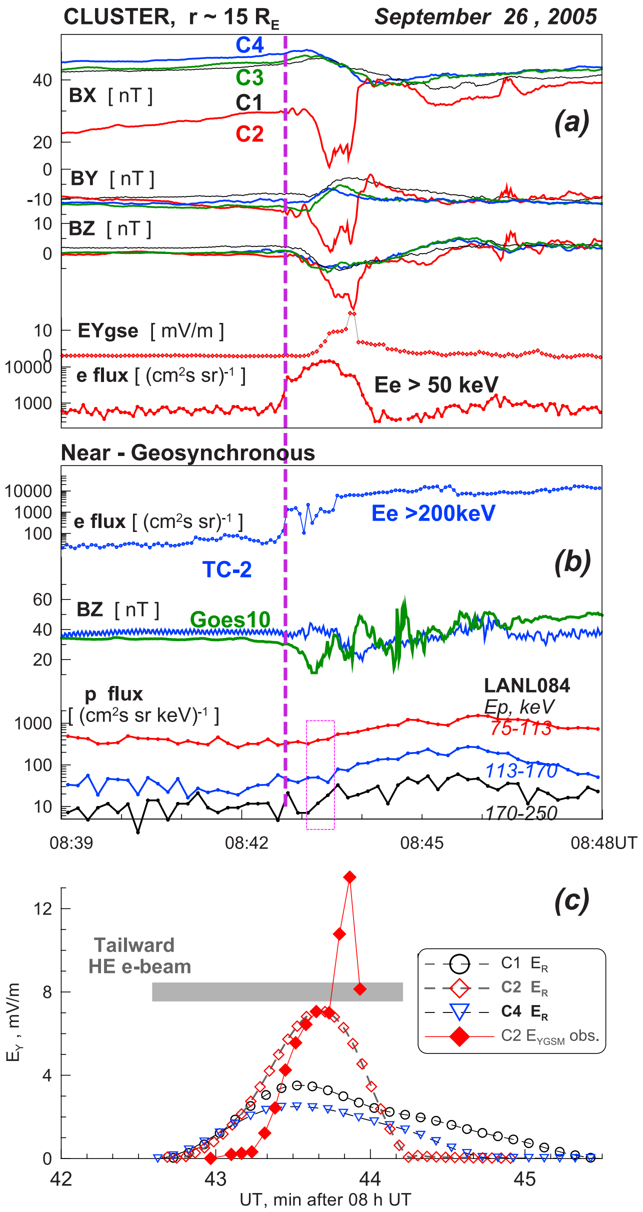

Figure 4. Observations during event *a* (a) at Cluster and (b) near the geosynchronous orbit; the vertical line marks the onset of energetic electron burst at C2 and TC2 spacecraft. (c) Comparison between reconstructed reconnection rate E_R and observed E_{YGSM} computed from the C2 double probe measurements when the magnetic field elevation angle in spacecraft coordinates was above 15°.

spacecraft and are not far from the E_{YGSM} values computed from the double probe measurements. The consistency between the amplitudes of δB, δE and tailward propagation speed V_A with those predicted by the MHD reconnection model are important evidence in favor of the reconnection-related origin of these perturbations.

[10] Shortly before the isolated onsets *a* and *b*, the C2 spacecraft was near the neutral sheet (or crossed it temporarily, see Figure 2); the neutral sheet magnetic field was weak on these occasions, $Bz \sim 1$ nT (a) or $\sim$3–4 nT (b). The magnetic field at C4 (spacecraft closest to the lobe) approached 50 nT and the Bz-component at Goes10 and TC2 were only $\sim$40 nT, both suggesting a very stretched tail configuration favorable for reconnection. The standard T96 model (based on corresponding SW parameters) gave an insufficiently stretched configuration, thus we modified the model parameters to obtain a best fit to the magnetic fields observed by Cluster, TC2, TC1 (in the lobes at 03 LT) and Goes10 spacecraft at 0842 UT, just prior to activation *a* (see *Kubyshkina et al.* [1999] for method description). Although the model was not quite able to produce sufficient amount of field stretching without introducing non-physical effects (a large southward Bz appeared at $r > 10$ Re, resulting in an unrealistic large magnetic island which severely distorts the mapping), using the best-fit model (without such island) we found that the Cluster C2 spacecraft maps to at least as low as $\leq 64°$ CGLat, and maybe even lower if a better field model was available. The TC2 footpoint location was found at 63.5°... 64°, suggesting that TC2 and Cluster field lines map close to each other and could both be in the proximity of reconnection separatrix. This explains why the energetic electron flux increases at TC2 and C2, the earliest indications of the activation *a* (Figures 4a and 4b), were simultaneous (within one 4s spin period).

[11] A low-altitude signature of intense impulsive acceleration was also observed at separatrix latitudes. This part of the auroral zone was crossed by the DMSP F15 spacecraft between 084320 and 084350 UT (see the spectrogram and the results of energy dispersion analyzes in Figures S2 and S3 in auxiliary material). The crossing took place in the middle of the energetic electron burst at C2 and TC2 (a first indication of strong reconnection-related acceleration). The most spectacular feature in this region was the very intense and energetic energy-dispersed ion beam observed between 64° and 64.5°. The dispersion fitted well to the time-of-flight (TOF) equation $t_2 - t_1 = (L/k)\,(1/v_2 - 1/v_1)$ (where indices 1, 2 correspond to different energies W_1 and W_2) confirming its TOF nature. The apparent flight distance (L/k, where L is the actual distance to the source) obtained was, however, too short, 2.4 Re, to be a pure temporal ($k = 1$) effect. (We discard the possibility of a large >30 kV field-aligned potential drop at 2.4 Re altitude as a source of the proton beam since it has no accompanying gap on the electron spectrogram).

[12] It may however be consistent with spatial dispersion created by ions produced by a moving localized source such as a magnetic separatrix. This would assume that the latitudinally limited source operated at a distance L (along the field line) in the equatorial plane, and that its ionospheric footpoint moved poleward at speed Vr due to intense magnetic reconnection. With the DMSP orbital spacecraft motion in the equatorward direction *Vsc*, the coefficient k in the TOF equation becomes $k = 1 + Vsc/Vr$ (see also *Alexeev et al.* [2006] for a similar kind of model applied to reconnection-produced electron dispersion). With $Vsc \sim 3.7$ km/s and $Vr \sim 1$ km/s (which is a standard velocity of poleward auroral expansion) we obtain $k \approx 4.7$ and $L = 2.4 * k \approx 11$ Re.

3. Discussion

[13] The data set presented here provides the most detailed and reliable evidence of impulsive near-Earth reconnection, with the location of the X-line in the range

between ∼9–10 Re (from our modelling efforts, to be consistent with the B-fields observed near the geosynchronous distance) and 13–14 Re (as follows from Cluster observations and reconstruction efforts).

[14] A novel feature is the observation of a low-altitude manifestation of the intense reconnection. The energy-dispersed proton beam was very similar to the VDIS structures at the poleward edge of the oval, which are known to be the convection-filtered mappings of distant reconnection lines [e.g., *Elphic et al.*, 1995; *Sauvaud and Kovrazhkin*, 2004]. The differences with the generic VDIS are that the proton beam (1) was located near the equatorward boundary of a very wide auroral oval (spanning 63°... > 70° CGLAT); (2) has an order of magnitude higher energy flux (10^8 eV/(cm^2 · s · sr), which is explained by more dense and energetic source population available in the near-Earth region, and (3) has an unusually steep slope, explained by the combination of fast poleward shift of the X-line footpoint (source) and of fast equatorward motion of the spacecraft across this structure. Difference with other kinds of dispersed ion structures observed in the equatorward part of the oval is that these other kinds are much less energetic (below a few keV) and usually show a localized field-aligned potential drop and upflowing ion beams as a source [e.g., *Hirahara et al.*, 1996]. The electron signatures of such structures are absent in our observations. All these facts support the conclusion that this narrow energetic ion beam maps to the active near-Earth reconnection region. We have a clear indication of the high intensity of the reconnection impulses in these events (tailward plasma outflows up to 1000 km/s, Ey exceeding 10 mV/m, electron beam energy up to 200–300 keV).

[15] The large width of the auroral oval in DMSP observations (with a poleward edge at >70° CGLat and the separatrix mapped to ∼64°) combined with the fact that none of the Cluster spacecraft left the plasma sheet during the whole time period 0830–0950 UT (see e.g. Figure S4 in auxiliary material) indicate that these intense reconnection bursts occurred deep inside the closed flux tube region. Intense reconnection repeating deep in the plasma sheet on closed field lines at $r < 14$ Re during the events with typical CD signatures in the inner magnetosphere seems to be firmly established in our case. This is at variance with the existing view that intense reconnection (peak E_R is proportional to Alfvenic electric field in the inflow region $E_A = (V_A \cdot B)_{IN}$, with $E_R \sim 0.2E_A$ [e.g., *Birn et al.*, 2001]) is associated mostly with lobe reconnection. Such a view ignores the fact that $E_A \sim B_{IN}^2$ can be large in the outer regions of near-Earth plasma sheet because of the large magnetic field magnitude in this region. Similarly to some previous observations [e.g., *Sergeev et al.*, 1995; *Miyashita et al.*, 2005], the magnetic activity during this event was rather weak: the peak magnetic perturbations observed by Canadian and Alaskan magnetometer networks beneath and around the auroral brightening region were only about 100, 50 and 350 nT.

[16] The reason for repeated appearance of X-lines at such close locations is not quite obvious to us. The tail configuration was very stretched as indicated by the lobe field values exceeding 50 nT and by the low geosynchronous H-(Bz-)component field values of 30–40 nT observed at that time. However the IMF during the period of interest has only a small Bz component which is reflected in the weak auroral zone activity. According to the WIND and ACE measurements, the SW flow pressure between 08 and 0920 UT approached $P_d \sim 8$ nPa (caused by the SW density exceeding 20 cm^{-3}, not shown). We assume that it is the enhanced flow pressure that kept the tail in a stressed state favorable for the near-Earth onset. This has some indirect support in statistical data by *Gerard et al.* [2004] who showed that a decrease of substorm onset latitude correlates best with the solar wind dynamic pressure. However, a direct study of X-line positions depending on solar wind parameters did not reveal any role of flow pressure, whereas the dependence on IMF Bz was quite obvious [*Nagai et al.*, 2005].

[17] All (three) consecutive turbulent dipolarization and HE particle injection events were observed by an excellent spacecraft configuration allowing all major activity parameters to be observed, and all major signatures of near-Earth reconnection to be identified unambiguously. First indications of reconnection and dipolarization started almost simultaneously (within 20 sec), with the high-energy electron beam at Cluster being the first signature in the isolated events *a* and *b* (Figures 2 and 4 and also *Sergeev et al.* [2006, Figure 3]). Moreover, strong turbulence, which is the core phenomenon of the current disruption, was observed not only in the geosynchronous region, but also in the tailward reconnection outflow region probed by Cluster (best seen in events *b*, *c*, Figure 2). The CD-like turbulence in the near-geosynchronous region on quasi-dipolar field lines appears simultaneously with the turbulence in the plasma sheet tailward of the X-line. Furthermore, the high-frequency turbulence in both regions had similar spectra [*Sergeev et al.*, 2006, Figure 4]. This confirms that both reconnection and current disruption are essential elements in the initiation of the localized explosive reconfiguration [*Angelopoulos et al.*, 1999]). It may be realized if either (a) the reconnection-produced fast outflows generate and transport intense turbulence, or (b), the turbulence created by some current instability (CFCI or others [*Lui*, 1996]) plays an important role in the initiation of reconnection. We hope these questions will soon also be at the focus of studies in the THEMIS project.

[18] **Acknowledgments.** The data of CARISMA and GIMA magnetometer networks, the solar wind observations from ACE and WIND (from CDAWeb website), DMSP particle spectrograms (from JHU/APL website) and geosynchronous energetic particle data (from LANL website) were used in this study. We thank all these data providers for making available these observations and C. Carr for the FGM data from TC1. We thank both referees for their constructive comments. VAS thanks Austrian Academy of Science for the financial support during his stays in Graz. This work was supported by INTAS grant 03-51-3738, by RFBR grant 04-05-64932 and Russian Ministry of Science grant 15392, by Austrian Science Fund project P17099-N08 and by International Space Science Institute. The work by VA was supported by NASA grant RTOP 370.16.40.04/102230.

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