Magnetic reconnection and current disruption in the inner magnetosphere — a case study

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Abstract: Three consecutive turbulent magnetic dipolarizations accompanied by auroral brightenings near the equatorward boundary of wide auroral oval were observed with fortuitous spacecraft constellation on September 26, 2005. All were associated with strong near-Earth reconnection pulses (at $r \leq 14$Re with Cluster probed the tailward reconnection outflow region) with separatrix mapped to $\sim 64^{\circ}$CGLat in the ionosphere where a narrow energy-dispersed ion injection was observed. Onset of magnetic reconnection was nearly simultaneous or lead as compared to the turbulent dipolarization and energetic particle injection onsets. The reconnection tailward outflow contained intense turbulence with the properties similar to that in the turbulent dipolarization regions and with intensity correlating with the outflow amplitude. We conclude that the reconnection process and the growth of strong turbulence in the near tail are strongly coupled together, at least in near-Earth reconnection events, and that near-Earth location of the reconnection site may be more frequent phenomenon than typically thought. In that case it assumed to be possible due to enhanced SW flow pressure which kept the magnetic configuration very stretched in the absence of strong energy loading into the magnetosphere; the ground magnetic perturbations ranged between 50 and 300nT in these intense reconnection events.

Key words: Substorms, reconnection, current disruption.

1. Introduction

Turbulent current disruption (CD) in the inner magnetosphere or the explosive growth of magnetic reconnection (MR) in the midtail current sheet were considered as alternative substorm onset mechanisms, whose distinction is a one of main targets of the forthcoming THEMIS project. Most controversy comes from ample but indirect evidence of near-Earth location of the substorm onset (deep on closed field lines, around 10 Re, near the transition between the current sheet and dipole-like region, see e.g. a summary by [5, 11], as contrasted to the statistics of reconnection flows from Geotail observations showing that most probable location of the X-line was at 20-30Re [7]. Because of that MR and CD are often treated as spatially far separated and, therefore, different processes. However a large separation may not necessarily be the case: recent indirect evidence of near-Earth onsets were emphasized by [11], a small number of direct observations of near-Earth ($r \leq 15$Re) reconnection events have also been published [1, 12, 6]. The scarcity of direct observations could in fact be due to the little chance to observe in the very thin reconnection-related current sheet, due to difficulty to diagnose the reconnection with one (or few occasionally located) spacecraft, and due to a number of other important variables (azimuthal and meridional separations between spacecraft and onset locations, magnetic configuration etc) which are rarely under the control.

Here we show a unique event in which we look simultaneously at signatures of both (MR and CD) processes in the rare case of near-Earth reconnection where all main variables were under the control. This possibility have occurred largely due to fortuitous spacecraft configuration, with the Cluster and Double Star (Tc2) spacecraft bracketed the near-Earth neutral line near the central meridian of tail activity in the course of 3 subsequent events. (See Annales Geophysicae 2001 (N10-12) and 2005 (N11) for the description of instruments). This provides us with reliable observations of very intense reconnection reappearing on closed field lines in the near-Earth tail region.

2. Observations

Between 08 and 10 UT on September 26, 2005 (when Cluster spacecraft approached and crossed the current sheet at 14–15 Re distance) 3 plasma injections and dipolarization events (a, b, c) were detected in the inner magnetosphere at 0843, 0931 and 0941 UT - Figure 1(bottom), accompanied by corresponding localized auroral brightenings centered at the 23 h MLT meridian and at $\sim 64^{\circ}$ CGLat (from IMAGE WIC observations, not shown here). Between the activations (a) and (c) the Cluster baricenter moved from [-15.3; 3.7; -0.1]Re to [-15.8; 3.8, -0.9]Re GSM, and TC2 was moving upward in Z (from -1.4Re to -0.5Re) in the plasma sheet with X=-6.5Re and Y=+1.9Re, therefore they all stay near 23 h MLT meridional plane, near the central longitide of activation. Other spacecraft (LANL084, Goes10) were within 1-2h MLT from this meridian. At this time Cluster C1,C2 and C3 formed a triangle in XY plane with separations about 9000km whereas C3/C4 (closest to the Earth) had the same X,Y but were separated by 900km in Zgsm allowing to distinguish the thin and thick current sheets.

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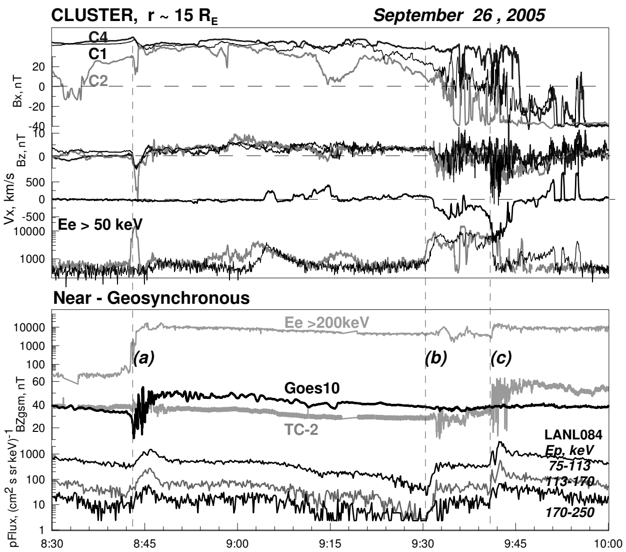

Fig. 1. Survey of observations at Cluster spacecraft (top) and in the geosynchronous region (at TC2, Goes10 and LANL084, bottom).

In this favourable configuration Cluster provided decisive evidence of tailward reconnection-related outflow, as specified below. During activations b, c the spacecraft crossed the current sheet (Figure 1, top), detecting strong ion and convection tailward outflows (up to 500km/s and 1000km/s, correspondingly) synchronous with southward Bz variation and energetic (isotropic) electron beam (during the activation b). Of particular notice is the large difference between Bx components at C3,C4, suggesting a proximity of very thin current sheet (expected near the reconnection region) with current density up to 30-40 nA/m^2. Systematic large ($\sim\ 0.5B_{LOBE}$, sign (By*Bx)$<\ 0$, not shown here) Hall quadrupole By magnetic field was also observed suggesting the more Earthward position of nearby reconnection region. All main predictions of active reconnection operated 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, rejecting any doubts in near-Earth location of magnetic reconnection.

During the activation a strong southward Bz (down to -15nT), intense Eygse up to > 10 mV/m (resulting in tailward outflows ($[\mathbf{E}\times\mathbf{B}]_\mathbf{x}/\mathbf{B^2}\sim$ -400km/s in cross-B flow component), and strong energetic electron beam were observed but only by one spacecraft C2, closest to the neutral sheet. A strong evidence in favor of near-Earth reconnection source was also a strong tailward field-aligned anisotropy of electron beam measured by RAPID instrument (by a factor of 5-10 flux increase of electrons in tailward direction during ~ 10 spins, not shown here), this energetic electron beam was observed up to the energy as high as ~ 300 keV.

In contrast to the later events, here other Cluster spacecraft (at larger Z coordinates) did not register neither the energetic electron beam nor the fast flows, so although they stayed in-

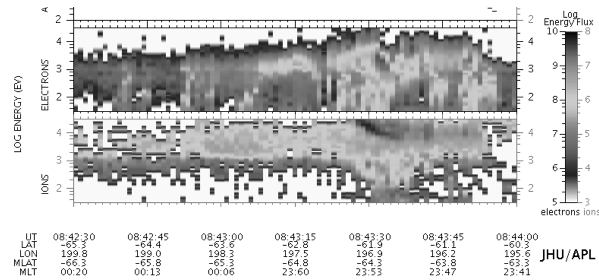

Fig. 2. Spectrograms of precipitated auroral electrons and proton fluxes measured by DMSP F15.

side the plasma sheet (and within 0.5Re from both each other and from the neutral sheet), they apparently did not cross the reconnection separatrix staying in the reconnection inflow region. However the obvious tailward progression of magnetic perturbations was observed between C3/C4 and C1 (time delay about 10 sec over ~ 9000km separation distance), suggesting their ~ 900km/s tailward propagation velocity, also consistent with reconnection.

A new observation is of low-altitude particle signatures of the near-Earth reconnection region. Tuning the T96 magnetospheric model to fit the magnetic fields observed by Cluster, Tc2 and Goes10 spacecraft at 0842 UT, just prior to the activation a (see [4] for the method description), indicated that Cluster C2 spacecraft should map to very low latitude, $\leq 64°$ CGLat. (With this best possible model the model field at Cluster was still less than observed, the full agreement could not be obtained since further intensification of the tail current quickly brought to the growth of unphysical structure, a large magnetic island). This equatorial part of the auroral zone was crossed by DMSP F15 spacecraft between 084320 and 084350 UT, i.e. just 1 min after the onset of energetic electron burst at C2 and Tc2 (a first indication of strong reconnection-related acceleration). Most spectacular feature in this region is the very intense and energetic energy-dispersed ion beam observed between $64°$ and $64.5°$. The dispersion was very well fitted by the time-of-flight 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 distance was however too short,(L/k)= 2.4 Re, to be a pure TOF (k=1) effect. (It may be consistent with the reconnection at 12 Re taking into account the fast poleward progression of the ionospheric footpoints of magnetic separatrix which increases k; not shown here). The facts (narrow source of very energetic ions with unusual steep slope near the expected separatrix footpoint when the reconnection is going on) support that this narrow energetic ion beam provides the mapping of near-Earth reconnection region, similarly to the well-known VDIS structures existing at the poleward edge of the auroral oval which are the mappings of distant reconnection lines, e.g. [2]. But here the energetic energy-dispersed ion beam is located near the equatorward boundary of otherwise very wide auroral oval (from $63°$ to $70°$ CGLAT according to the measurements at DMSP F15).

3. Discussion

3.1. Occurrence of near-Earth reconnection

All (three) consecutive turbulent dipolarization and HE particle injection events in our case were observed with excellent spacecraft coverage allowing all major activity parameters to be controlled. Cluster-TC2 constellation bracketed the near-Earth reconnection region, being at the central meridian of corresponding auroral activation. Presence of near-Earth reconnection was established undoubtedly by registering all major reconnection signatures, such as (1) tailward fast flows and southward Bs on the tailward side of reconnection line, (2) Hall By perturbations in this region, (3) acceleration of energetic electrons with occasional tailward beam feature (in the event a), (4) thin current sheet signature. In addition, narrow energy-dispersed intense beam of energetic ions was observed in the ionosphere in the expected ionospheric projection of the reconnection separatrix (event a), this time near the equatorward edge of the wide auroral oval. The fact, that neither of Cluster spacecraft left the plasma sheet during the whole period 0830-1000 UT, together with a large width of auroral oval in DMSP observations indicate that these intense reconnection pulses occurred deep in the closed flux tubes. The fact of intense reconnection going on on closed field lines at $r < 14$ Re during events with typical CD signatures in the inner magnetosphere seems to be firmly established in our case.

Generally the probability of such near-Earth location of reconnection is considered as very small one (e.g. recent work [8]). However this also could partly be explained by very small probability to encounter very thin reconnection region, as argued in [11, 12]. Our direct observation of the reconnection systematically reappearing at so small distance require to re-evaluate this possibility. One should not also ignore a possibility of another X-line forming further downtail with a possibility of nearly-simultaneous multiple active reconnection sites, as suggested by some observations (e.g. [10]). These (why/when near-Earth events occur? and, could there be multiple active centers?) could be the interesting questions to address in the forthcoming THEMIS project.

The reason of repeating X-lines appearance at so close location 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 existing at that time. However the IMF during the period of interest was slightly northward which is reflected in weak auroral zone currents. The SW flow pressure during that time approached $P_d \sim 8$ nPa (due to the SW density exceeding $20cm^{-3}$) according to WIND and ACE measurements, so we may assume that it is enhanced flow pressure which kept the tail in a stressed state favored the near-Earth onset. This has some indirect support in statistical data [3]] which showed that a decrease of substorm onset latitude correlates best with the P_d parameter. 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 [8]. So the question is open, it should be addressed again, possibly with trying different criteria to define the crossing of reconnection region (high electron temperature criterion used in [8] seems too restrictive, at least it rejects our events if applied).

3.2. Reconnection versus current disruption?

Figure 3 shows our attempt to compare the onset times of different activity characteristics during three activations (a, b, c). These characteristics include the energetic electron bursts, southward Bz, tailward flows and turbulence in the tail, energetic electron flux increase, particle injection and turbulent dipolarization in near-Earth region, as well as auroral brightening (from IMAGE WIC camera, at 2 min time resolution) and ground magnetic bay (at 1min resolution) in the ionosphere. Although onset determination could be questioned in some cases (e.g. onset of plasma sheet turbulence in non-isolated event c), the earliest onsets in both regions (near-geosynchronous and plasma sheet on the tailward side of the X-line) are nearly simultaneous (to within 10-20s). During isolated onsets a, b the earliest signature was that of energetic electron beam at Cluster location. The durations of activations in both regions are also comparable.

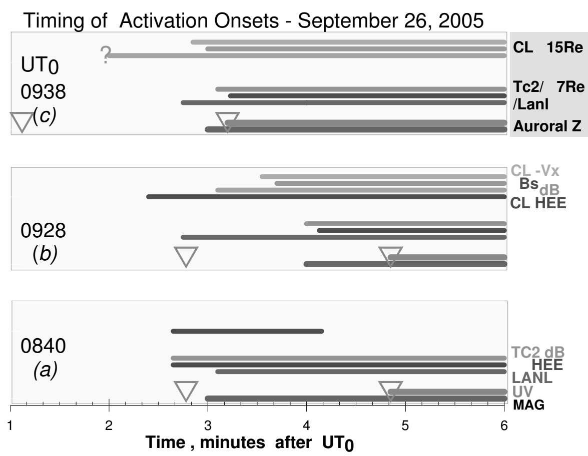

Fig. 3. Timing of different signatures in the ionospheric , geosynchronous and current sheet regions during three activations.

One weak point in the discussion of the reconnection (MR) and current disruption (CD) as the alternative mechanisms of substorm onsets seems to be the observational characterization of the current disruption, that is a number of signatures allowing to establish its presence and distinguish from another disruptive process, like the reconnection. In fact, the list of predictions provided by CD proponents (e.g. [5]) mostly include those related to the localized nature and near-Earth appearance of the activation in the intense current sheet region (which are suitable for near-Earth reconnection as well), rather than the properties intimately related to the basic physics of current disruption. Its main physical distinction is the high-amplitude turbulence which is able to destruct temporarily the frozen-in plasma behavior. However the strong turbulence is also a feature of the plasma sheet, particularly during high-speed flows (e.g. [13]). Strong turbulence was also observed by Cluster in the tailward reconnection outflows in our events b, c, see e.g. Fig.1, at the same time when it was probed on

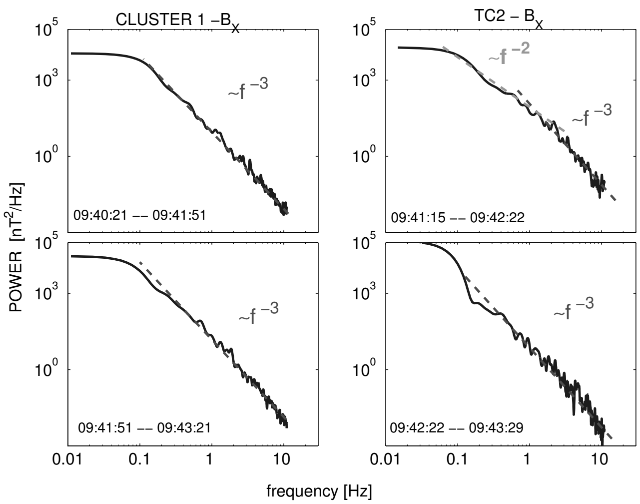

Fig. 4. Power spectra of Bx magnetic component at Cluster1 and TC2 spacecraft for two brief episodes of the event c.

the Earthward side by Tc2 spacecraft. Detailed comparison of turbulence properties observed with similar instruments operating on both sides from the reconnection is possible in this event (here we show the first results, more detailed investigation will be published elsewhere).

Figure 4 illustrates an interesting detail: Whereas the peak low-frequency wave activity seem to be stronger in the Earthward region that is in stronger mean magnetic field (e.g. at 094222UT), the power spectra of magnetic field variations during this most powerful turbulence event have similar power law in the high-frequency part (above 0.2-0.3 Hz, that is above the proton gyrofrequency) at both Cluster1 and Tc2. Its slope $\alpha \approx 3$ is not far from those previously reported either in the plasma sheet BBFs ($\alpha \approx 2.6$ [13]) or in the near-Earth current disruption events ($\alpha \approx 2.4$ [9]).

Whereas the more detailed intercomparisons and a study of the turbulence character are the subjects of special study which will be published elsewhere, these initial comparisons show, that not only the CD-like turbulence in near-geosynchronous region on dipole-like field lines appears simultaneously with the turbulence in the plasma sheet tailward of the X-line, the high-frequency turbulence in both regions may be of the same character and origin. This suggests another view of MR/CD, being the close partners (rather than opponents) in the initiation of the localized explosive reconfiguration. This may be realized either if (a) the MR-produced fast outflows generate and transport intense turbulence, or (b), the turbulence created by some current instability (CFCI or others, [5]) plays an important role in the initiation of reconnection.

As the concluding remark we may point out three questions which would be important to address in the THEMIS project. (1) We need to develop the better operational criteria to identify/distinguish the CD process from magnetic reconnection; (2) To study the turbulence in strong Bz-field as compared to the turbulence in BBFs and near the X-line; (3) A comparative study of dynamics in the plasma sheet and near-Earth region for the events with mid-tail reconnection onset as compared to the near-Earth MR events.

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