Ann. Geophys., 24, 679–687, 2006
www.ann-geophys.net/24/679/2006/

Annales Geophysicae

Indirect mapping of the source of the oppositely directed fast plasma flows in the plasma sheet onto the auroral display

A. G. Yahnin[1], I. V. Despirak[1], A. A. Lubchich[1], B. V. Kozelov[1], N. P. Dmitrieva[2], M. A. Shukhtina[2], and H. K. Biernat[3]

[1]Polar Geophysical Institute, Kola Science Center of the Russian Academy of Sciences, Apatity, Russia
[2]Institute of Physics, Sankt-Petersburg State University, Sankt-Petersburg, Russia
[3]Space Research Institute, Austrian Academy of Sciences, Graz, Austria

Received: 8 October 2005 – Revised: 13 December 2005 – Accepted: 15 January 2006 – Published: 23 March 2006

Abstract. Data from Polar and Geotail spacecraft are combined to investigate the relationship between locations of active auroras and the magnetotail plasma sheet region where reversed fast plasma flows are generated during substorms. Using the magnetospheric magnetic field model, it is shown that at the beginning of the tailward fast flow the ionospheric footprint of the spacecraft measuring the flow tends to be located poleward of the auroral bulge. The spacecraft within the earthward flow is mapped equatorward of the poleward edge of the auroral bulge. We conclude that a source of the fast plasma flows is conjugated with the poleward edge of the auroral bulge. Analysis of the behavior of the plasma and the magnetic field in the vicinity of the source of the diverging flows allows us to conclude that the source region, interpreted as the magnetic reconnection site, coincides with the region of the cross-tail current reduction, and the tailward propagation of the region is associated with the tailward propagation of the current disruption front.

Keywords. Magnetospheric physics (Auroral phenomena; Plasma sheet; Storms and substorms)

1 Introduction

The auroral substorm (Akasofu, 1964) is an ionospheric manifestation of the magnetospheric substorm – an explosive process of transformation of the magnetotail magnetic energy into the kinetic energy of plasma sheet particles. Numerous studies have shown that a breakup of one of the most equatorward auroral arcs in the nightside signals the onset of the explosive process in the magnetosphere (e.g. Liou et al., 1999), and subsequent auroral activations represent a fine structure of the process (Sergeev and Yahnin, 1979; Sergeev et al., 1986a, b; Yahnin et al., 1990). The substorm mechanism is still unknown, as well as the certain magnetospheric domain and certain plasma instability responsible for discrete auroras. Some authors consider the source located inside the current sheet, on stretched field lines (e.g. Yahnin et al., 1997), while some others argue that the source of substorm auroras is situated on dipole-like magnetic field lines (e.g. Lazutin, 1986; Shiokawa et al. 1997).

Some substorm models suggest that in the magnetotail current sheet, reconnection of anti-parallel magnetic field lines and the formation of a neutral X-line can develop. As a result, the generation of fast plasma flows (both earthward and tailward from the neutral line) and plasmoids is expected and observed (e.g. McPherron et al., 1973; Hones, 1979). Some authors suggest that the X-line can be the source of active auroras (Atkinson, 1992; Pudovkin et al., 1991).

The model by Shiokawa et al. (1997; 1998) suggests that reconnection plays a significant role (as generator of fast flows), but does not directly relate to auroras. According to this model, the auroral breakup occurs in the region of the dipole-like magnetic field where the braking of the earthward fast flow is assumed. The braking produces the inertial current that closes onto the ionosphere by field-aligned currents. The breakup appears in the region of the upward current.

In the models that consider the substorm on dipole-like field lines, the source of active auroras can be instabilities of cross-tail current (e.g. Lui, 1996), different modifications of interchange instabilities (e.g. Roux et al., 1991; Golovchanskaya et al., 2004), or instabilities in the magnetosphere-ionosphere system (e.g. Kan, 1993).

To limit the variety of the substorm models it is important to establish the relationship between substorm auroras and some magnetospheric region and/or plasma process. The solution of this task is hindered by the problem of the correct mapping in the dynamic magnetosphere. Indeed, no magnetospheric magnetic field models exist for reproducing, for example, the development of the X-line configuration.

Correspondence to: A. G. Yahnin
(yahnin@pgi.kolasc.net.ru)

Published by Copernicus GmbH on behalf of the European Geosciences Union.

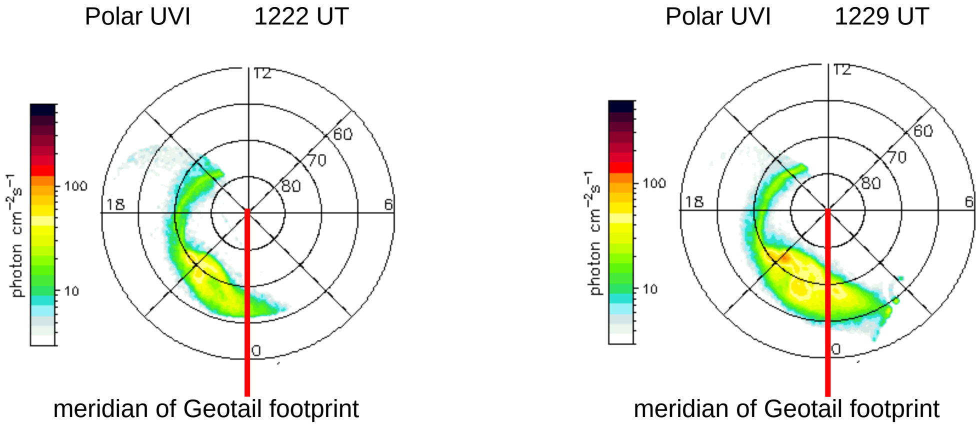

Fig. 1. Auroral displays for two moments of the auroral substorm development on 9 February 1997. The meridian of the Geotail footprint (near local midnight) is shown by the red line.

During substorms, the fast plasma flows are typically observed in the magnetotail. The earthward flows are mainly observed in the near-Earth plasma sheet at X>–15 R_E (e.g. Fairfield et al., 1999), while in the mid (–30 R_E<X<–15 R_E) and far tail the flows are often tailward, and associated with plasmoid signatures (e.g. Ieda et al., 2001). Statistically, the earthward and tailward plasma flows relate, respectively, to positive and negative excursions of the B_z-component of the magnetic field in the plasma sheet (e.g. Ohtani et al., 2004). The oppositely directed flows are assumed to be generated simultaneously by the same source as demonstrated by Petrukovich et al. (1998), on the basis of data from two radially spaced spacecraft. Observations of the oppositely directed flows expected for the magnetic configuration with the X-line can be considered as a signature of magnetic reconnection. (It is worth noting that the physical nature of magnetic reconnection is not well understood, especially the plasma process leading to the formation of the diffusion region. For example, in a recent review, Lui et al. (2005) stressed that standard 2-D and steady-state consideration of this process should be revised by taking into account the 3-D and transient character of the real process. However, comparing the competing mechanisms related to the magnetic energy release, Lui et al. (2005) have noted that perhaps only magnetic reconnection provides plasma flows ordered by the magnetic field configuration independent of the regime of the process.)

In the course of a substorm, the satellites in the mid-tail can register the reversal of the tailward plasma flow relative to the earthward plasma flow. This fact is interpreted as tailward movement (or reappearance) of the reconnection site (Hones, 1979; Forbes et al., 1981; Angelopoulos et al., 1996). Recently, Runov et al. (2003) confirmed this interpretation by multipoint observations on Cluster. They analyzed the flow reversal event at ∼17 R_E during a substorm and observed, besides the typical V_x and B_z variations, other reconnection signatures including plasma inflow into the diffusion region and inversion of the magnetic field curvature during transition from tailward to earthward flow.

In this paper, the attempt to correlate the active substorm auroras with the fast plasma flow reversal events in the plasma sheet is made on the basis of comparing observations on board the Polar and Geotail satellites. The Ultra Violet Imager on board Polar allows for the observation of the atmospheric UV luminosity which is due to the precipitation of auroral electrons (Torr et al., 1995). Due to the spatial resolution of $\sim 40 \times 40\,\mathrm{km}^2$ the individual discrete auroral arc can not be resolved from Polar. Nevertheless, the location of the sharp poleward boundary of luminosity can be considered as a proxy for the poleward boundary of discrete auroras (Baker et al., 2000) forming the substorm auroral bulge. The data from the MFI and LEP instruments on board Geotail (Kokubun et al., 1994; Mukai et al., 1994) are used for measurements of magnetic field and plasma parameters in the plasma sheet.

In Sect. 2 we present criteria used for the event selection. Section 3 is devoted to data analysis, including a description of typical examples, results of a superposed analysis of plasma sheet parameters during flow reversals, and the analysis of the relationship between auroras and plasma sheet phenomena. In Sect. 4 the results are briefly discussed, and the conclusions are formulated in Sect. 5.

2 Event selection

To select the events for our analysis we use the following criteria: 1) the auroral substorm should be observed by the UV imager on board Polar, 2) the meridian of the Geotail footprint should cross the polar edge of the auroral bulge, and 3) Geotail, in the night plasma sheet, should observe the first (after an interval of low-speed plasma fluxes) tailward-to-earthward plasma flow reversal. Plasma flows with velocities

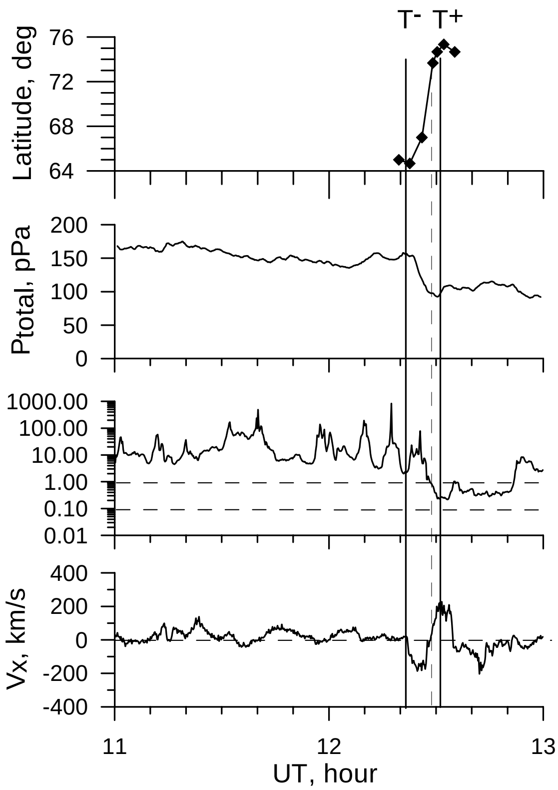

Fig. 2. The behavior of the aurora and plasma sheet parameters during the event of 9 February 1997. From top to bottom: the latitude of the poleward edge of the aurora seen by Polar UVI at the meridian of Geotail (only a fragment of the keogram around the time of the plasma flow reversal is shown); the total (magnetic plus plasma) pressure at the Geotail location; the ratio between the plasma and magnetic pressure (parameter β) at the location of Geotail; the V_x component of the plasma velocity in the plasma sheet observed by Geotail.

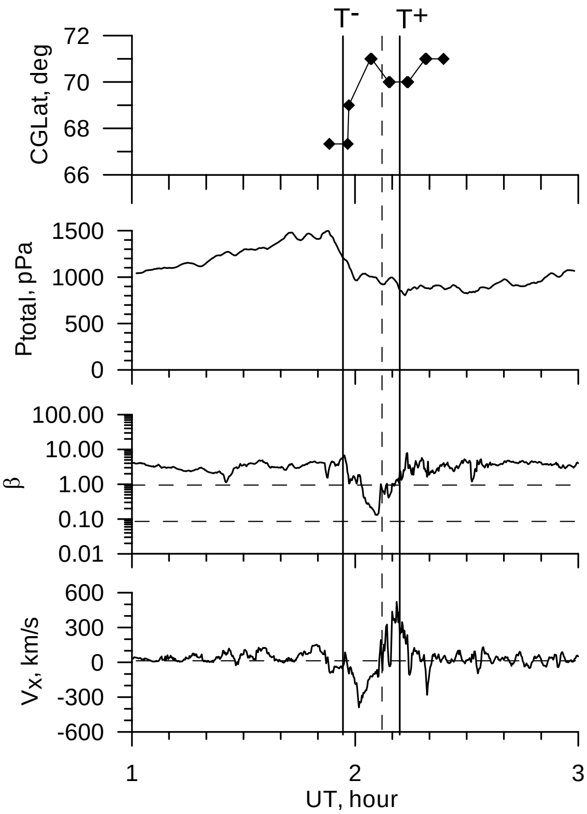

Fig. 3. The same as Fig. 2 but for event of 2 July 1996.

$V>200$ km/s are considered, and the criterion $\beta>0.1$ (β is the ratio of kinetic plasma pressure to magnetic pressure) is applied for the plasma sheet identification. The survey of the data for 1996–1997, when the apogee of Geotail was about 30 R_E, revealed 14 events which met the above criteria. For selected events the Geotail spacecraft was at distances within the range of 10–30 R_E, but most cases fall into the range of distances of 20–30 R_E. To increase the "statistics" at more close distances, one more event (~21:00 UT of 13 November 1998) was added.

3 Data analysis

3.1 Example of the considered data – event of 9 February 1997

Figure 1 presents two auroral images (in the LBH-long emission) from Polar during one of the events studied (9 February 1997). The auroral substorm began much earlier than the time of the first image, but at that time UVI was viewing the evening sector. In fact, up until 12:22 UT, the auroral activity was also concentrated in the evening (as evidenced by VIS, another imager on board the Polar spacecraft; L. Frank is the principal investigator, data not shown). The maximal poleward expansion of the bulge was at 12:35 UT, whereupon the recovery phase started. Around this time the Geotail satellite was at X=–27 R_E. The latitude of the spacecraft footprint significantly varies depending on the magnetic field model used for the mapping, but the local time stays rather stable. The local midnight meridian, where the Geotail footprint is mapped, is shown by the red bar in Fig. 1. The latitude of the poleward edge of the auroral bulge mapped on the Geotail footprint meridian is shown on the most upper panel of Fig. 2. Only data from images made in the LBHl emission with a time resolution of ~0.5–3 min are used for the construction of this meridional profile of aurora, the so-called keogram. (The poleward boundary of the bulge at the meridian of the Geotail footprint is determined, for definiteness, at the level of 20 photon/cm^{2}s). The keogram demonstrates the clear poleward expansion of the bulge, starting around 12:22 UT. Plasma and magnetic data from Geotail for the period 11:00–13:00 UT are shown in Fig. 2. After 12:22 UT, the satellite started to measure

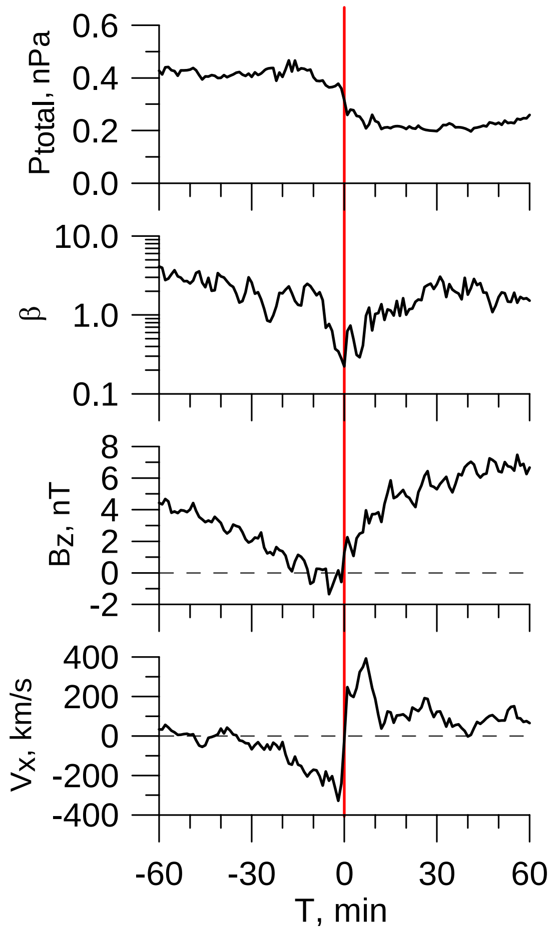

Fig. 4. The behavior of the plasma and magnetic field parameters in the plasma sheet obtained by the method of superposed epoch. The moment of the plasma flow reversal is used as a reference time.

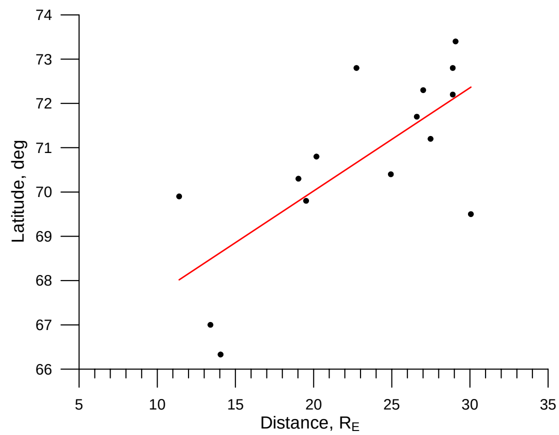

Fig. 5. The relationship between the latitude of the poleward edge of the auroral bulge at the meridian of Geotail and the distance between Geotail and the Earth at the moment of the flow reversal registration.

the fast tailward plasma flow. The flow changes its direction at about 12:29 UT, and the earthward flow was registered until 12:35 UT. During the flow direction reversal, the latitude of the poleward edge of auroras can be estimated as 73° CGMLat. The reversal is associated with the decrease in both the total (magnetic plus plasma) pressure and β.

3.2 Example of the considered data – event of 2 July 1996

The event of 2 July 1996 has been described in much detail by Frank et al. (2001), on the basis of the Polar VIS imager and Geotail data. In this case, the Geotail was at a distance of 11.5 R_E. Although in their paper Frank et al. (2001) did not pay attention to the flow direction changes, they concluded that the substorm onset was associated with the merging of the magnetic field inside the Geotail orbit.

The Polar UVI keogram and the Geotail plasma and magnetic data for this substorm are shown in Fig. 3. As in Fig. 2, the upper panel in Fig. 3 shows the latitude of the poleward border of the UV aurora at the meridian of the Geotail spacecraft. Other panels show the plasma sheet parameters obtained from the Geotail plasma and magnetic data. The event is associated with the poleward expansion of auroras. Both tailward and earthward flows are inside the plasma sheet with $\beta>1$, while the flow direction reversal is related to the decrease of β. Near the reversal, the decrease in the total (magnetic plus plasma) pressure is also seen. The latitude of the polar edge of aurora at the time of the flow reversal is about 70.5° CGMLat.

3.3 Superposed epoch analysis of the plasma sheet parameters in the vicinity of the source of the diverging fast plasma flows

The result of the superposed epoch analysis of the plasma and magnetic field behaviors for all 15 selected events is shown in Fig. 4. The moment when Geotail registers the reversal of the plasma flow direction is chosen as the reference time (bottom panel). Several features in the vicinity of the source of the diverging flows can be revealed from this analysis. The brief interval of negative B_z is associated with the tailward flow, and the sharp increase in B_z (dipolarization) is associated with the earthward flow. The reversal of the flow direction is related to an excursion of the parameter β to low values. The upper panel demonstrates a stepwise decrease in the total (kinetic plus magnetic) pressure centered at the time of the reversal.

3.4 Relationship between the location of the source of the diverging flows and the latitude of auroras

For all considered events, the latitude of the poleward edge of the auroras at the meridian of the Geotail footprint was determined at the moment of the flow reversal. The dependence of the latitude of the auroral bulge on the distance of

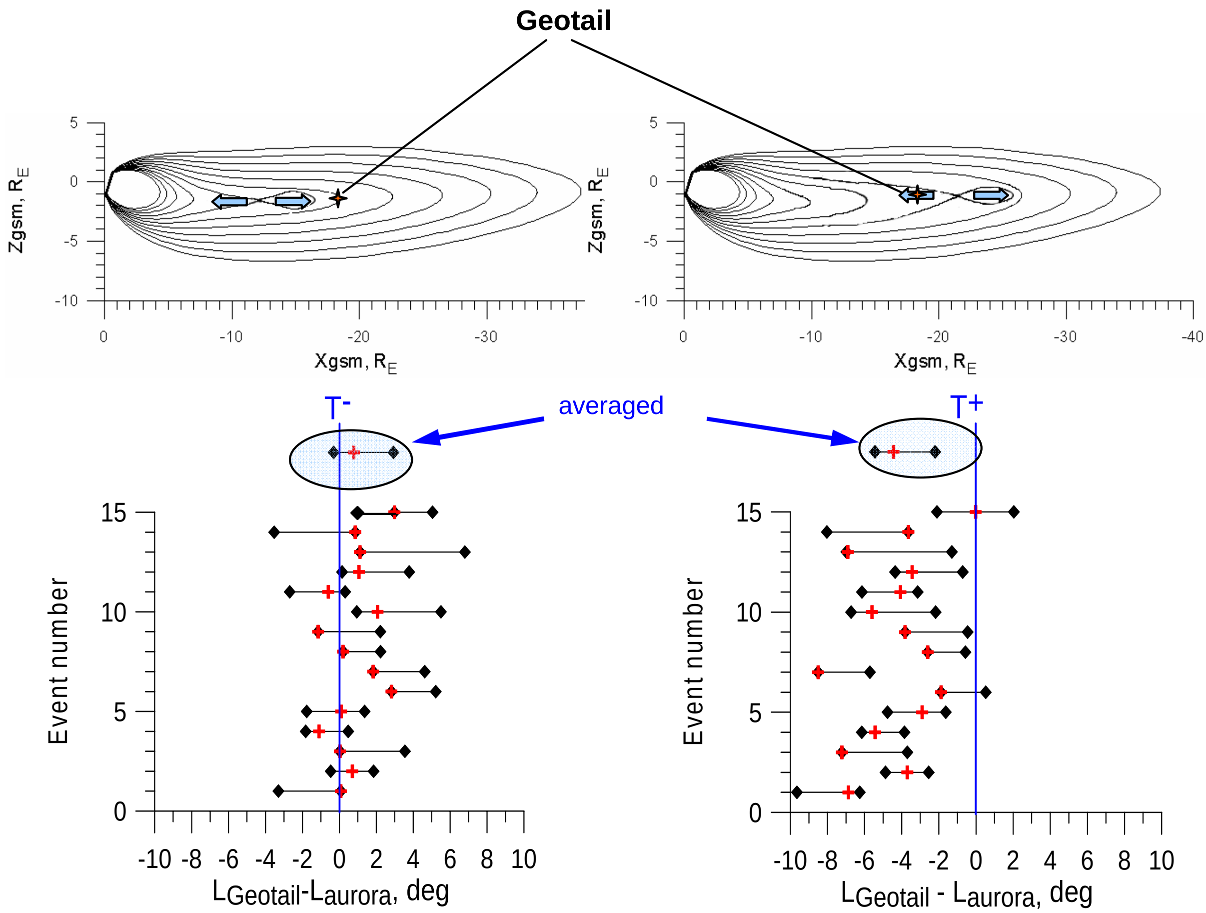

Fig. 6. Mapping of Geotail onto the ionosphere relative to the location of the poleward edge of the auroral bulge for the spacecraft situated tailward (left) and earthward (right) of the diverging flows source location. The upper panel shows these situations schematically. The horizontal bars at the bottom panel represent the results of mapping for 15 events using the T89 model for all possible input parameters (K_p=1–7). The red cross on each bar marks the mapping result for the model that better fits the observations of the total pressure at the Geotail location. The averaged relative latitudes are also shown.

the spacecraft detecting the reversal of the flow direction is shown in Fig. 5. The latitude of the auroras displays a tendency to increase with the geocentric distance of the spacecraft detecting the flow direction reversal. The linear fit for the dependence is:

$$\Phi\,[^\circ] = 64.4 + 0.23 \cdot X\,[R_E]\,, \qquad (1)$$

where Φ is the latitude of the poleward edge of the auroral bulge; X is the downtail distance; $10 < X < 30$.

3.5 Mapping of Geotail onto the ionosphere relative to the auroral bulge poleward boundary

Although Fig. 5 demonstrates a relationship between the locations of the source of the diverging flows in the magnetotail and the poleward edge of active auroras in the ionosphere, this does not imply their conjugacy.

As already mentioned, the direct mapping of the region of the oppositely directed flows' generation is impossible. Indeed, this region is associated with a magnetic field singularity (e.g. X-line) that cannot be reproduced by existing empirical models of the magnetosphere magnetic field. Here, to estimate the conjugacy of these structures (the aurora and the source of the diverging flows) and to avoid the possible singularity problem, the mapping is made for two instants, before and after the registration of the flow direction reversal. The instants are 1) the moment (T^-) just before the time when the disturbance associated with the tailward fast flow achieves the Geotail spacecraft and 2) the time (T^+) when the spacecraft registers the maximum velocity of the earthward flow (see Figs. 2 and 3). The expected configuration of the magnetosphere and relative location of Geotail for the moments T^- and T^+ are schematically shown in Fig. 6 (upper panel). The source of the diverging flows is associated with the X-line, and tailward flow is inside the plasmoid. For the moment T^- (on the left) Geotail is situated just outside of the plasmoid. For the moment T^+ (on the right) the spacecraft is within the dipolarized region with the earthward flow. Since the magnetic field at the spacecraft location has no singularities, it is assumed that at T^- and T^+ the magnetic field in the vicinity of the spacecraft can be reproduced by some standard model.

For mapping, the Tsyganenko (1989) model (T89) is used. This model is parameterized by the geomagnetic activity index K_p. It is worth noting that this empirical model (like any other empirical model) has a statistical nature; thus, it cannot guarantee against significant errors of mapping in concrete situations, especially in such dynamical ones as substorms.

To avoid this ambiguity of mapping, we applied the T89 model for two extreme parameter values (K_p=1 and K_p=7). This gives a possible range of the Geotail footprint locations relative to the latitude of the poleward edge of the bulge. The range of the distances is marked in Fig. 6 by horizontal bars for both T^+ and T^- and for every considered event.

Another way to choose the appropriate model is to take the one which gives the best coincidence with the observed total pressure $P{=}nkT+B^2/8\pi$ (the result of mapping, using the model chosen in such a way, is labeled by a red cross). One may see that the ionospheric footprint of the satellite measuring the tailward (earthward) flux tends to map poleward (equatorward) of the polar (poleward) boundary of the auroral bulge. One may also note an asymmetry in the mapping. Thus, at T^- the average location of the Geotail footprint in the adapted model (red cross) is about one degree poleward of the auroral bulge, while at T^+ it is situated as far as four degrees equatorward of the poleward edge of the bulge.

4 Discussion

During registration of the plasma flow reversal events in the plasma sheet, the poleward (equatorward) shift of the spacecraft projection with respect to the auroral bulge polar edge associated with the tailward (earthward) fast plasma flow is observed (see Fig. 6). We interpret this as evidence of the conjugacy of the source of the flow reversals in the plasma sheet and the polar boundary of the substorm auroras in the ionosphere. This conclusion is also supported by several early studies on the basis of Polar and Geotail data devoted to the correlation of fast plasma flows in the magnetotail and auroral dynamics. Fairfield et al. (1999) investigated the situations when Geotail was at X >–15 R_E during substorms and observed the earthward flows. The mapping of Geotail (using the T89 model) for cases when Polar UVI data were available showed the Geotail footprint being within the auroral bulge. Ieda et al. (2001) observed tailward flows when Geotail was in the mid-tail at X<–20 R_E. The examples shown in that paper demonstrate that the Geotail footprint was poleward of or coincided with brightening auroras. Nakamura et al. (2001) considered short-lived earthward flows at distances of 10–30 R_E and correlated the flows with auroral activations. Mapping of Geotail was done using both the standard T89 model and the modified model adapted to measurements of several available spacecraft (see Kubyshkina et al., 1999). In most cases the earthward flows were associated with auroral activations poleward of the Geotail footprint. Although the above mentioned authors did not consider the flow reversals, their results are consistent with the result shown in Fig. 6.

The relationship between the reversal of the plasma flow direction in the plasma sheet and substorm auroras has been considered on the basis of case studies by Borodkova et al. (2002) and Perraut et al. (2003), using, respectively, the Polar and Interball-1 and Polar and Geotail data. They concluded that the flow direction changes from tailward to earthward when the auroras expand to a latitude higher than that of the footprint of the spacecraft situated in the tail. Here, this conclusion is supported by larger statistics.

A clear asymmetry in the location of the Geotail footprint relative to the polar edge of the substorm aurora, for the moments T^- and T^+, is seen in Fig. 6. In our opinion, this also confirms the conjugacy of the source of the diverging flows with the auroral bulge polar edge. Indeed, since T^- is defined as the moment of the beginning of the fast tailward flow, the Geotail location at T^- is just ahead of the plasmoid, presumably resulting from reconnection on closed field lines. The ionosphere projections of the plasmoid boundary and X-line are the same, thus, there should be no large latitudinal difference between the Geotail footprint and auroras. In contrast, at T^+ the spacecraft is at the field line which has been reconnected, and there should be a latitudinal separation between its footprint and the X-line projection, proportional to the reconnected flux amount.

The presented observations do not explain how the particle fluxes needed for the aurora generation are produced. Some light on this problem is shed by recent observations by Geotail and by the Cluster constellation. Thus, Alexeev et al. (2005), analyzing the field-aligned electron currents in the vicinity of the plasma flow reversal registered by Cluster, found the net electron current consistent with the so-called Hall current system which is expected for reconnection. Earthward of the X-line the electron inflow along the magnetic field into the diffusion region was found in the plasma sheet boundary layer and the outflowing (earthward) electrons were observed inside the plasma sheet. Nakamura et al. (2004), using the Cluster and Geotail data, also observed earthward beams of >2 keV electrons within the plasma sheet at the earthward side of the ion diffusion region and the tailward beams of <1 keV electrons in the PSBL. These findings agree well with the structure of particle flows revealed from the Geotail observations by Nagai et al. (1998; 2001). It was suggested that corresponding field-aligned electric currents are closed within the diffusion region at one side of the current circuit. One can suggest (e.g. Atkinson, 1992) that the other end of the circuit is in the ionosphere. In such a scenario, the electrons flowing out of the diffusion region can produce the auroras. This suggestion needs, however, to be confirmed by conjugate observations at different altitudes.

The tailward propagation of the source of the diverging plasma flows is associated with the poleward expansion of ionospheric signatures of the substorm, that is, the auroral bulge and westward electrojet (Sergeev et al., 1982; Angelopoulos et al., 1996). The dependence shown in Fig. 5 relates the locations of substorm structures in the ionosphere and magnetosphere. The velocity of the poleward propagation of auroras is of the order of 1 km/s (Akasofu, 1964; Sergeev and Yahnin, 1979; Kornilova et al., 1990). (The average velocity of the poleward expansion of auroras in the events considered in this paper was ∼0.7 km/s). If we assume that the fit in Fig. 5 represents not only a mutual location, but also the correlated movement of the structures, the average velocity of the tailward propagation of the source of the diverging flows in the magnetosphere can be estimated as ∼280 km/s (∼200 km/s for events in this study).

Ohtani et al. (1992) and Jacquey et al. (1993) showed that during substorms the tail lobe magnetic field variations are consistent with the tailward movement of the tail current disruption region. The velocity of the tailward expansion of the current disruption is found to be 200–300 km/s. This agrees well with the above estimate made for the tailward propagation of the source of the diverging flows. Coincidence of the velocity estimates may mean that current disruption and generation of the fast plasma flow reversals are the signatures of the same process. The latter is also confirmed by Fig. 4, where averaged plasma and magnetic field parameters are plotted relative to the moment of the reversal of the plasma flow direction. In contrast to the plasmoid signature within the tailward flow (the brief interval of negative B_z just before the reference time), the B_z component demonstrates a sharp enhancement (dipolarization) within the earthward flow, immediately after the reference time, which can be interpreted as a signature of the current disruption. Also, the total pressure decrease, typically seen during the substorm-related fast flows (Miyashita et al., 2003; Ohtani et al., 2004), is associated with the time of the change in the plasma flow direction in Fig. 4. From the pressure balance the total pressure is equal to the magnetic pressure in the tail lobe and, consequently, proportional to the squared plasma sheet current density. Thus, the total pressure decrease means a decrease in the current density (that is, the current disruption). A similar conclusion on the relationship between the reconnection site and current disruption in the magnetotail has been made by Sergeev et al. (1982) on the basis of the case study using IMP-8 observations at ∼35 R_E.

Recently, Yahnin et al. (2002), analyzing the multi-instrumental ground and magnetospheric observations, concluded that at the substorm onset the magnetospheric source of the brightening auroral arc may coincide in time and space with both reconnection and current disruption signatures. They suggested that all the mentioned phenomena are manifestations of the same process. In the present paper we found such a relationship for the poleward edge of the auroral bulge during a later stage of the substorm. The auroral bulge is typically formed by the progressive appearance of new arcs poleward of the preceding ones (Sergeev and Yahnin, 1979; Kornilova et al., 1990). Morphologically, the appearance of the new arc at the poleward edge of the bulge does not differ from the first appearance/brightening at the onset, since they are associated with similar signatures observed both on the ground and in space (Sergeev and Yahnin, 1979; Sergeev et al., 1986a, b; Yahnin et al., 1983, 1990). This may mean that the same mechanism of the arc generation is active independent of the stage of the explosive phase. The results of the present paper (see also Yahnin et al., 2002) suggest that reconnection might be an appropriate candidate for such mechanism.

5 Conclusions

This study demonstrates a close relationship between locations of the substorm auroras in the ionosphere and the source of the oppositely directed fast plasma flows at 10–30 R_E from the Earth. The further downtail the flow reversal is detected, the higher the latitude is of the polar boundary of the auroral bulge. Moreover, the mapping of the satellite measuring the tailward and earthward plasma flows allows one to conclude that the source of the diverging flows is conjugated with the poleward edge of the auroral bulge. These results are consistent with the idea that reconnection is the source of the substorm auroras. We also conclude that the generation of the diverging plasma flow (presumably, due to the magnetic reconnection process) coincides with the reduction of the cross-tail current (current disruption), and that the tailward propagation (re-appearance) of the fast flow source corresponds to the tailward shift of the current disruption front.

Acknowledgements. Data from the MFI and LEP instruments onboard Geotail were revealed from the DARTS data base. We are thankful S. Kokubun, T. Nagai, and T. Mukai for providing the data. We also thank G. Parks and other members of the Polar UVI team who made the data of the UV Imager available to the community. The work of the PGI team was partly supported by the Presidium of the Russian Academy of Sciences (RAS) through the basic research program "Solar activity and physical processes in the Sun-Earth system" and by the Division of Physical Sciences of RAS through the program "Plasma processes in the solar system". The work of N. P. Dmitrieva and M. A. Shukhtina was supported by the RFBR grant #04-05-64932. The study is a part of joint Russian-Austrian project "Solar-planetary relations and Space Weather" supported by Russian Foundation for Basic Research (grant # 03-05-20003) and by the "Österreichischer Austauschdienst" under Project I.12/04. Additional support is due to the Austrian "Fonds zur Förderung der wissenschaftlichen Forschung" under Project P17099-N08.

Topical Editor I. A. Daglis thanks W. J. Heikkila and another referee for their help in evaluating this paper.

References

Akasofu, S.-I.: The development of the auroral substorm, Planet. Space Sci., 12, 273–282, 1964.

Alexeev, I. V., Owen, C. J., Fazakerley, A. N., Runov, A., Dewhurst, J. P., Balogh, A., Réme, H., Klecker, B., and Kistler, L.: Cluster observations of currents in the plasma sheet during reconnection, Geophys. Res. Lett., 32, L03101, doi:10.1029/2004GL021420, 2005.

Angelopoulos, V., Mitchell, D. G., McEntire, R. W., et al.: Tailward progression of the magnetotail acceleration center: Relationship to substorm current wedge, J. Geophys. Res., V. 101, 24 599–24 619, 1996.

Atkinson, G.: Mechanism by which merging at X lines causes discrete auroral arcs, J. Geophys. Res., Vol. 97, 1337–1344, 1992.

Baker, J. B., Clauer, C. R., Ridley, A. J., et al.: The nightside poleward boundary of the auroral oval as seen by DMSP and the Ultraviolet Imager, J. Geophys. Res., V. 105, 21 267–21 280, 2000.

Borodkova, N. L., Yahnin, A. G., Liou, K., Sauvaud, J.-A., Fedorov, A. O., Lutsenko, V. N., Nozdrachev, M. N., and Lyubchich, A. A.: Plasma sheet fast flows and auroral dynamics during substorm: A case study, Ann. Geophys., 20, 341–347, 2002.

Fairfield, D. H., Mukai, T., Brittnacher, M., et al.: Earthward flow bursts in the inner magnetosphere and their relation to auroral brightenings, AKR intensifications, geosynchronous particle injections and magnetic activity, J. Geophys. Res., 104, 355–370, 1999.

Forbes, T. G., Hones Jr., E. W., Bame, S. J., Asbridge, J. R., Paschmann, G., Sckopke, N., and Russell, C. T.: Evidence for the tailward retreat of a magnetic neutral line in the magnetotail during substorm recovery, Geophys. Res. Lett., 8, 261–263, 1981.

Frank, L. A., Sigwarth, J. B., Paterson, W. R., and Kokubun, S.: Two encounters of the substorm onset region with the Geotail spacecraft, J. Geophys. Res., 106, 5811–5831, 2001.

Golovchanskaya, I. V., Maltsev, Yu. P., and Kornilova, T. A.: Interchange Instability Related to the Azimuthal Pressure Gradient as a Possible Mechanism of Substorm Intensification, Geomagnetism and Aeronomy, Vol. 44, No. 6, 703–710, 2004.

Hones Jr., E. W.: Transient phenomena in the magnetotail and their relation to substorms, Space Sci. Rev., 16, 617–410, 1979.

Ieda, A., Fairfield, D. H., Mukai, T., Saito, Y., Kokubun, S., Liou, K., Meng, C.-I., Parks, G. K., and Brittnacher, M. J.: Plasmoid ejection and auroral brightenings, J. Geophys. Res., 106, 3845—3857, 2001.

Jacquey, C., Sauvaud, J.-A., Dandouras, J., and Korth, A.: Tailward propagating cross-tail current disruption and dynamics of near-Earth tail: Multi-point measurement analysis, Geophys. Res. Lett., 20, 983–986, 1993.

Kan, J. R.: A global magnetosphere-ionosphere coupling model of substorms, J. Geophys. Res., 98, 17 263–17 276, 1993.

Kokubun, S., Yamamoto, T., Acuña, M. H., Hayashi, K., Shiokawa, K., and Kawano, H.: The Geotail magnetic field experiment, J. Geomagn. Geoelectr., 46, 7–21, 1994.

Kornilova, T. A., Pudovkin, M. I., and Starkov, G. V.: Fine structure of aurora in the vicinity of the poleward edge of the auroral bulge during breakup, Geomagnetism and Aeronomy, Vol. 30, 250–254, 1990.

Kubyshkina, M. V., Sergeev, V. A., and Pulkkinen, T. I.: Hybrid input algorithm: An event oriented magnetospheric model, J. Geophys. Res., 104, 24 977–24 994, 1999.

Lazutin, L. L.: X-ray emission of auroral electrons and magnetospheric dynamics, Physics and Chemistry in Space, V.14, Springer-Verlag, Berlin-Heidelberg, 220 p., 1986,

Liou, K., Meng, C.-I., Lui, A. T. Y., Newell, P. T., Brittnacher, M., Parks, G., Reeves, G. D., Anderson, R. R., and Kumoto, K.: On relative timing in substorm onset signatures, J. Geophys. Res., 104, 22 807–22 818, 1999.

Lui, A. T. Y.: Current disruption in the Earth's magnetosphere: Observations and models, J. Geophys. Res., 101, 13 067–13 088, 1996.

Lui, A. T. Y., Jacquey, C., Lakhina, G. S., et al.: Critical issues on magnetic reconnection in space plasmas, Space Science Reviews, 116, 497–521, 2005.

McPherrron, R. L., Russel, C. T., Kivelson, M. G., and Coleman Jr., P. J.: Substorm in space: The correlation between ground and space satellite observations of the magnetic field, Radio Science, V.8, #11, 1059–1076, 1973.

Miyashita, Y., Machida, S., Liou, K., Mukai, T., Saito, Y., Meng, C.-I., and Parks, G. K.: Relationship between magnetotail variations and auroral activities during substorms, J. Geophys. Res., 108(A1), 1022, doi:10.1029/2001JA009175, 2003.

Mukai, T., Machida, S., Saito, Y., Hirahara, M., Terasawa, T., Kaya, N., Obara, T., Ejiri, M., and Nishida, A.: The Low Energy Particle (LEP) experiment onboard the Geotail satellite, J. Geomagn. Geoelectr., 46, 669–692, 1994.

Nagai, T., Shinohara, I., Fujimoto, M., Hoshino, M., Saito, Y., Machida, S., Mukai, T.: Structure and dynamics of magnetic reconnection for substorm onset with Geotail observations, J. Geophys. Res., V. 103, 4419–4440, 1998.

Nagai, T., Fujimoto, M., Saito, Y., Machida, S., Terasawa, T., Nakamura, R., Yamamoto, T., Mukai, T., Nishida, A., Kokubun, S.: Geotail observations of the Hall current system: Evidence of magnetic reconnection, J. Geophys. Res., V.106, 25 929–25 949, 2001.

Nakamura, R., Baumjohann, W., Brittnacher, M., Sergeev, V. A., Kubyshkina, M., Mukai, T., and Liou, K.: Flow shear near the boundary of the plasma sheet observed by Cluster and Geotail, J. Geophys. Res., 109, A05204, doi:10.1029/2003JA010174, 2004.

Nakamura, R., Baumjohann, W., Brittnacher, M., Sergeev, V. A., Kubyshkina, M., Mukai, T., and Liou, K.: Flow bursts and auroral activations: Onset timing and foot point location, J. Geophys. Res., 106, 10 777–10 789, 2001.

Ohtani, S., Shay, M. A., and Mukai, T.: Temporal structure of the fast convective flow in the plasma sheet: Comparison between observations and two-fluid simulations, J. Geophys. Res., 109, A03210, doi:10.1029/2003JA010002, 2004.

Ohtani, S., Kokubun, S., and Russell, C. T.: Radial expansion of the tail current disruption during substorms: A new approach to the substorm onset region, J. Geophys. Res., 97, 3129–3136, 1992.

Perraut, S., Le Contel, O., Roux, A., et al.: Substorm expansion phase: Observations from Geotail, Polar and IMAGE network, J. Geophys. Res., 108 (A4), doi: 10.1029/2002JA009376, 2003.

Petrukovich, A. A., Sergeev, V. A., Zeleniy, L. M., et al.: Two spacecraft observations of a reconnection pulse during an auroral breakup, J. Geophys. Res., 103, 47–60, 1998.

Pudovkin, M. I., Semenov, V. S., Starkov, G. V., and Kornilova, T. A.: On separation of the potential and vortex parts of the magnetotail electric field, Planet. Space Sci., 39, 563–568, 1991.

Roux, A., Perraut, S., Robert, P., Morane, A., Pedersen, A., Korth, A., Kremser, G., Aparicio, B., Rodgers, D., and Pellinen, R.: Plasma sheet instability related to the westward traveling surge, J. Geophys. Res., 96, 17 697–17 714, 1991.

Runov, A., Nakamura, R., Baumjohann, W., et al.: Current sheet structure near magnetic X-line observed by Cluster, Geophys. Res. Lett., 30(11), 1579, doi:10.1029/2002GL016730, 2003.

Sergeev, V. A. and Yahnin, A. G.: The features of auroral bulge expansion. Planet. Space Sci., V.27, 1429–1440, 1979.

Sergeev, V. A., Bosinger, T., and Lui, A. T. Y.: Impulsive processes in the magnetotail during substorm expansion, J. Geophys. Res., 60, 175–185, 1986a.

Sergeev, V. A., Pellinen, R. J., Bosinger, T., Baumjohann, W., Stauning, P., and Lui, A. T. Y.: Spatial and temporal characteristics of impulsive structure of magnetospheric substorm, J. Geophys. Res., 60, 186–198, 1986b.

Sergeev, V. A., Yahnin, A. G., Hones Jr., E. W.: On the plasma sheet current changes during substorm according to data from the IMP-8 satellite (in Russian), Cosmic Research, V.20, 636–639, 1982.

Shiokawa, K., Baumjohann, W., and Haerendel, G.: Braking of high speed flows in the near-Earth tail, Geophys. Res. Lett., 24, 1179–1182, 1997.

Shiokawa, K., Baumjohann, W., Haerendel, G., Paschmann, G., Fennell, J. G., Friis-Christensen, E., Lühr, H., Reeves, G. D., Russell, C. T., Sutcliffe, P. R., and Takahashi, K.: High-speed ion flow, substorm current wedge, and multiple Pi 2 pulsations, J. Geophys. Res., 103, 4491–4508, 1998.

Torr, M. R., Torr, D. G., and Zukic, M., et al.: A far ultraviolet imager for the international solar-terrestrial mission, Space Sci. Rev., 71, 329–383, 1995.

Tsyganenko, N. A.: A magnetospheric magnetic field model with a warped tail current sheet, Planet. Space Sci., 37, 5–20, 1989.

Yahnin, A. G., Bosinger, T., Kangas, J., and Belian, R. D.: Some implications on substorm dynamics inferred from correlations between multiple flux peaks of drifting proton clouds and ground observations, Ann. Geophys., 8, 327–336, 1990.

Yahnin, A. G., Sergeev, V. A., Gvozdevsky, B. B., and Vennerstrom, S.: Magnetospheric source region of discrete auroras inferred from their relationship with isotropy boundaries of energetic particles, Ann. Geophys., 15, 943–958, 1997.

Yahnin, A. G., Sergeev, V. A., Kubyshkina, M. V., Pulkkinen, T. I., Liou, K., Meng, C.-I., Angelopoulos, V., Borodkova, N. L., Mukai, T., and Kokubun, S.: Timing and Location of Phenomena During Auroral Breakup: A Case Study , Adv. Space Res., V.30, 1775–1778, 2002.

Yahnin, A. G., Sergeev, V. A., Pellinen, R. J., Baumjohann, W., Kaila, K. U., Ranta, H., Kangas, J., and Raspopov, O. M.: Substorm time sequence and microstructure on 11 November 1976. J. Geophys., V.53, 182–197, 1983.