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Multiple-spacecraft observation of a narrow transient plasma jet in the Earth's plasma sheet

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Abstract. We use observations from five magnetospheric spacecraft in a fortuitous constellation to show that narrow transient plasma flow jets of considerable length formed in the tail can intrude into the inner magnetosphere and provide considerable contribution to the total plasma transport. A specific auroral structure, the auroral streamer, accompanied the development of this narrow plasma jet. These observations support the 'boiling' plasma sheet model consisting of localized underpopulated plasma tubes (bubbles) moving Earthward at high speeds as a realistic way to resolve the 'convection crisis' and to close the global magnetospheric circulation pattern.

1. Introduction

The global magnetospheric circulation is powered by the solar wind which drags tailward the magnetospheric plasma tubes recently opened at the dayside magnetopause by the magnetic reconnection process (*Cowley* [1982]). To close the circulation pattern one also has to reconnect the open flux tubes and to return the newly formed closed plasma tubes back to the dayside magnetopause. The latter processes are not under the direct control of the solar wind as they are on the dayside so the balance can not be adjusted automatically. Usually the transport is unbalanced on these two segments of the circulation pattern which results in the loading or unloading of the magnetic energy stored in the magnetotail and produces an explosive phenomenon in the magnetosphere, namely substorms (*Cowley* [1982]; *Baker et al.* [1996]). However sometimes a balance is achieved, with these rare cases known as steady convection events or convection bays (*Sergeev et al.* [1996a]). The reasons for such variant behavior of the magnetotail are not understood but are of fundamental interest.

In fact, there exists a serious constraint on the laminar Earthward flow imposed by the strong plasma heating and compression in the contracting closed plasma tubes. In realistic tail-like configurations, if plasma behaves nearly adiabatically (as follows from observations (*Borovsky et al.* [1997]), this quickly creates strong plasma pressure gradients which brake the Earthward convection (*Erickson and Wolf* [1980]). Various explanations have been suggested to resolve this 'convection crisis' but none of them has been shown to give a global-scale solution to this long-standing controversy.

Another constraint comes from observations showing that statistically about 80% of all plasma sheet transport in the midtail (15–30 R_e) is realized in the form of short-duration (a few minutes) flow pulses called Bursty Bulk Flows (BBFs) (*Angelopoulos et al.* [1992]). This agrees best the expectations of the bubble model (*Chen and Wolf* [1993]), which predicts sporadic narrow jets consisting of underpopulated plasma tubes. However whether the bubbles can penetrate to the inner magnetosphere to close the circulation pattern was doubted even by the authors of the bubble hypothesis (*Chen and Wolf* [1993]). The basic problem is that the parameters of the individual BBFs which are critical for the bubble model of plasma sheet transport (their cross-tail size, and, especially, their lifetime and extent along the tail) are very difficult to measure with a single (or a few randomly distributed) magnetospheric spacecraft. A difficult task is also to prove that the signatures observed at different locations in the magnetosphere belong to the same transient localized structure. This accomplishment is only possible if the latter structure has a distinct auroral fingerprint whose position can be compared with the ionospheric footpoints of magnetospheric spacecraft. Here we report the observations from a unique conjunction of four magnetospheric spacecraft supported by global auroral imaging which allowed us to monitor the development of an intense flow burst during most of its lifetime, to identify the auroral streamer as the ionospheric fingerprint of the flow burst, and to evaluate the importance of narrow plasma jets in the global transport.

2. Observations

An interesting conjunction of satellites occurred at about 2030 UT on December 10, 1996, near the peak of convection bay which started after 1920 UT in response to the southward interplanetary magnetic field measured by the Wind spacecraft (not shown here). NASA spacecraft Polar, near its apogee, provided the global auroral images in two (alternating) UV LBH luminosity bands at 36 s time resolution (*Liou et al.* [1997]). The auroral distribution and spacecraft positions are illustrated in the Figure 1. A magnetic field model for that particular epoch was constructed using the hybrid algorithm (*Kubyshkina et al.* [1999]) to fit the magnetic field observations at Geotail and Interball/Tail

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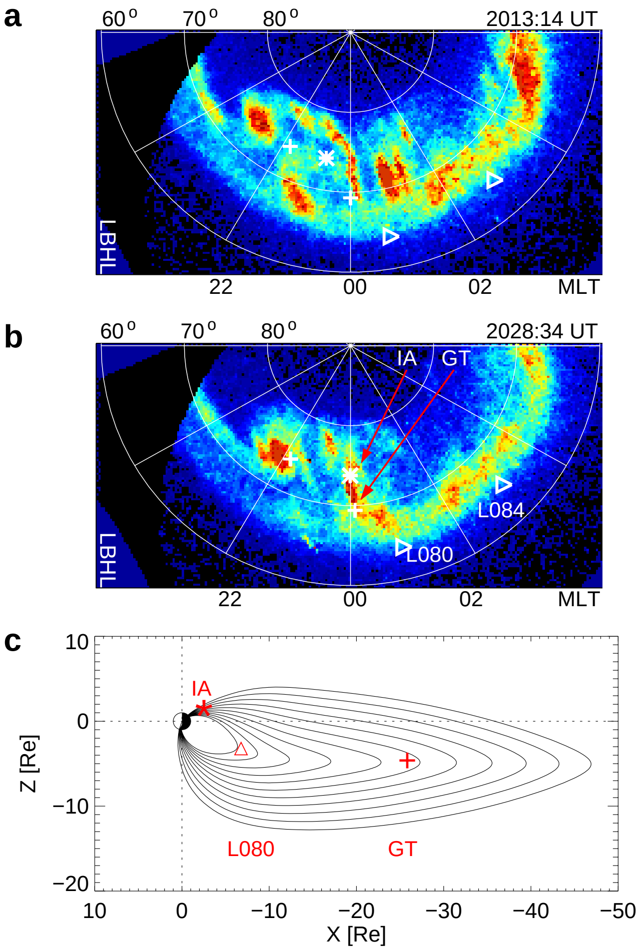

Figure 1. Auroral structures and spacecraft configuration on December 10, 1996: a,b, UVI images from Polar spacecraft in coordinates Corr. Geomagn. Latitude and Magnetic Local Time with superimposed footpoints of magnetospheric spacecraft (mapped along the magnetic field lines to the ionosphere) for 2013 UT (a) and 2028 UT (b); c, configuration of modeled magnetic field lines in the midnight meridional plane and positions of three key spacecraft.

spacecraft (at 22h MLT in the tail), as well as the isotropic boundary position (b2i) measured by the DMSP-F12 satellite. The Russian spacecraft Interball-Auroral (IA) at ∼3 R_e altitude monitored at 6 s time resolution the ion precipitation coming from the distant tail. The Japanese–US spacecraft Geotail (GT) measured both magnetic field and plasma distribution functions (12 s resolution) at 26 R_e distance in the plasma sheet center (the plasma beta parameter was > 1 during the time period studied). The Los Alamos National Laboratory spacecraft 1991–080 (L80) monitored the fluxes of energetic electrons (10 s resolution) at geostationary orbit (6.6 R_e). These three spacecraft were at that time close to the magnetic midnight being mapped close to the bright auroral form, the auroral streamer, aligned approx. from north-to-south (Figure 1b). In addition another geostationary spacecraft (L84) monitored the particle fluxes at ∼03 h MLT meridian.

Many transient structures were seen in each data set. The most intense transient was observed during a conjunction of spacecraft ionospheric footpoints with the auroral streamer (Figure 1b). In the Figure 2 the energy dispersion in the ion beam seen at the Interball spacecraft between 2025 and 2031 UT should be interpreted as the time-of-flight effect of particles impulsively accelerated in the equatorial current sheet (*Sauvaud et al.* [1999]). Backward tracing of particle trajectories (which depends mostly on the particle travel length rather than on the magnetic field model used) gives for this structure an ion flight distance of 40±4 R_e and the ion injection time as 2022:00 UT (±25s). The transient structure at Geotail (26 R_e) which started at 2023:14 UT as a fast Earthward flow burst and sharp compression of the magnetic field (B_z component), is a typical BBF signature in the observations made near the plasma sheet center. Its delay with respect to the ion injection inferred from Interball data implies an average propagation velocity of ∼1200 km/s. This is about twice as large as compared to the peak velocity measured at Geotail (∼700 km/s) and is about the Alfven velocity in the outer plasma sheet (under B∼20 nT and n∼ 0.1 cm^{-3}).

Approaching the Earth along the tail axis, the flux increase of energetic electrons was observed at 6.6 R_e at 2031:00 UT (L80) implying ∼8 min delay with respect to the Geotail flow burst and the average propagation velocity ∼250 km/s which is about 1/3 of the peak flow measured at Geotail. Three minutes later this injection was also detected at the L84 spacecraft (∼2 hours MLT to the east) with a clear energy dispersion, which implies that these electrons were not injected here but experienced azimuthal magnetic drift from the injection point. Backward tracing of particle trajectories showed that they were injected to geostationary distance near the meridian of the L80 spacecraft and within 1 min from the injection time at that spacecraft. The small duration of the the injection (burst halfwidth < 4 min at L84 at the energy 50 keV) implies a very narrow cross-tail scale for this injection, about 1 h MLT (see *Sergeev et al.* [1999] for the details of the backward tracing procedure).

The UV auroral streamer observed by the Polar UVI instrument near the footpoint of Interball, Geotail and L80 spacecraft actually started to develop at 2010 UT from a localized activation in the near-midnight portion of the polewardmost auroras (at ∼ 77° latitude). According to the high time resolution data (not shown here) by 2012 UT it extended below 70° latitude (Fig 1a) and by 2016–2018 UT it penetrated down to the equatorward oval boundary (∼ 65°). This early development of the auroral streamer was associated with another distinct but less intense transient activation seen at all three spacecraft (Figure 2). The dispersed ion beam seen at the Interball between 2014 and 2018 UT could be traced back to the injection time ∼2012 UT and to distances about 30 R_e (the dispersion slope determination is less accurate in this case). At Geotail the sharp B_z- and $[V \times B]_y$-component increases started at 2011:20 UT although the peak flow velocity in V_x was only 200 km/s. At 2020 UT the sharp flux increase started at the L80 spacecraft and 2 min earlier the non-dispersed injection was detected at the L84 spacecraft. For this transient we again see a similar sequence of events and roughly the same time delays. The corresponding auroral streamer was very narrow and the spacecraft conjunction with the streamer was not so perfect as in the previous case, with spacecraft footpoints being displaced westward of the streamer. This makes the interpretation of details and of timing results for this second structure less certain.

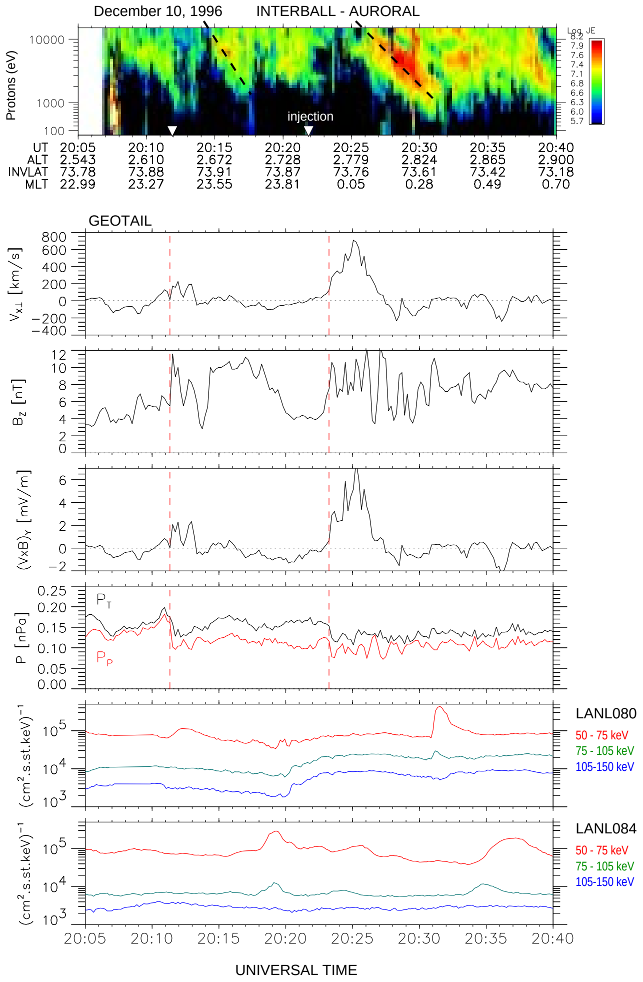

Figure 2. Summary of space- craft observations: a, energy-time spec- trogram of ion energy flux at Interball-Auroral spacecraft (inferred injection times are shown by the triangles); b, plasma sheet parameters measured at Geotail spacecraft; energetic electron flux variations at L80 (c) and L84 (d) geostationary spacecraft.

The onset of auroral development in the second (basic) event was not as distinct as for the first stage of streamer development because it occurred at the same place as the previous streamer. That narrow streamer started to disintegrate in its poleward half at ∼2022 UT. Signatures of activation in the poleward oval could be discerned at ∼2025 after which a wider streamer structure reappeared. The streamer ended with the bright activation in the equatorward oval. It is seen at 2028 UT frame (Figure 1b) and was fully developed by 2031 UT, by the time of particle injection to the geostationary orbit.

3. Discussion

In this case study, we were happy to assemble into one picture (see a scheme in Figure 3) and interpret together a number of observations. Each observation taken separately can not be interpreted unambiguously, but taken together in a single event they leave little ambiguity. The dispersed ion beams observed at Interball are typical transient structures in the poleward oval. According to *Sauvaud et al.* [1999], they are associated with auroral activations and show some correlation with fast flows in the plasma sheet (although in these earlier comparisons the conjugacy was not as good as in our case). Our results strongly confirm a close relationship between these two phenomena. On the other hand, the narrow plasma injections to 6.6 R_e which follow after the development of an auroral streamer, have been recently interpreted as a manifestation of transient jets in the plasma sheet (*Henderson et al.* [1998]; *Sergeev et al.* [1999]). Our observation proves this statement in the most direct way. A general (without details) association of fast plasma sheet flow bursts with auroral activations in the poleward oval was also recently shown (*Nakamura et al.* [1998]; *Lyons et al.* [1999]). Our estimate of azimuthal extent of the narrow injections (∼1 h MLT, or 2–4 R_e in the tail) is close to the previous estimates of the cross-tail size of bursty flows obtained with a pair of closely-spaced magnetospheric spacecraft (*Sergeev et al.* [1996b]; *Angelopoulos et al.* [1997]). On all these points our results agree with the previous work so the individual structure studied here may be quite representative for that class of phenomena.

In the best conjugacy condition the events observed at three points, the ion injection at ∼40 R_e (sensed remotely by the time-of-flight dispersed ion beam at the Interball), strong plasma flow burst at 26 R_e (Geotail) and plasma injection at 6.6 R_e (L80, also confirmed by L84 observation), are nicely ordered in time suggesting the transient plasma jet propagating from at least 40 R_e to 6.6 R_e in 10 minutes. Durations of ion beam and of flow burst were similar, about 4 minutes. The braking of the flow speed along its path also follows from the observed time delays. However in a difference with some flow braking models predicting the sudden stop of Earthward flow at the distances ≤ 10 R_e (*Shiokawa et al.* [1997]), here the plasma jet could penetrated down to 6.6 R_e. The structure is narrow in cross-tail extent, about 2-4 R_e. Schematically these results are shown in the Figure 3.

The geometry of this transient plasma stream is just what was predicted by the bubble model (*Chen and Wolf* [1993]). Two more essential predictions of this model are also confirmed. One is that the jet is a plasma tube with increased equatorial magnetic field and depressed plasma pressure (this has been shown previously by *Sergeev et al.* [1996b] and agrees with the behavior of B_z and plasma pressure, see Fig. 2, when spacecraft stayed all the time in the central

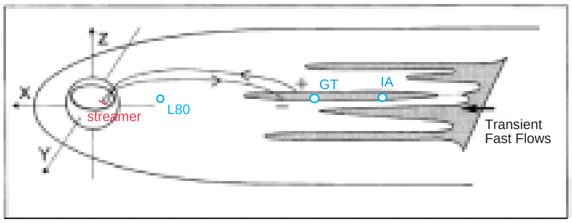

Figure 3. Schematic picture of transient plasma jets (updated from *Sergeev et al.*, [1996a]). Equatorial mapping of basic spacecraft is also shown. Strong plasma jet is just passing in the equatorial plane past the equatorial footpoint of Interball-Auroral and Geotail spacecraft and is approaching the inner magnetosphere, as occurred at ∼2025 UT on December 10, 1996. Precipitation of electrons accelerated in the jet-associated upward field-aligned current forms the auroral streamer seen on the Polar UVI images.

plasma sheet). Another prediction is that the underpopulated jet is polarized (as schematically shown in the Figure 3) so the upward field aligned current is expected on the duskward side of the jet. Due to the field-aligned electron acceleration into the ionosphere, it could be seen as a bright north-south structure, the auroral streamer. The predicted polarization of the jet is supported by *de la Beaujardiere et al.* [1994] who observed the aurora at the duskward edge of a plasma flow jet measured in the ionosphere. Recently *Amm et al.* [1999] inferred a field-aligned current pattern similar to that drawn in the Figure 3 as well as the north-south aligned upward FAC sheet near the conductivity enhancement associated with the north-south auroral form.

During the 4 min long flow burst the average flux transport ($[V \times B]_y = 3.1$ mV/m in our case) multiplied by $\sim$3 R_e cross-tail size gives about a 60 kV transport rate in the plasma jet, which is about the average transport rate in the magnetospheric circulation during the disturbed periods (60–100 kV (*Cowley* [1982]). We counted a dozen of similar auroral streamers seen by the UVI imager during one hour between 1935 and 2035 UT on that day (some of them or their remnants can be discerned in Figs. 1a,b). These streamers were randomly distributed in different local time zones between 20 and 03 h MLT, and they had associated fast flows at Geotail only for the auroral activations which occurred close in MLT to the Geotail footprint (*Nakamura et al.* [1998]). If all these streamers had associated narrow jets with the same transport efficiency as in the studied jet structure, their integrated effect will give about 3/4 of the required average flux transport. This agrees with previous statistics about the BBFs role in the transport obtained from the analysis of plasma sheet observations (*Angelopoulos et al.* [1992]).

In conclusion, due to fortuitous constellation of five spacecraft and the opportunity of global imaging of the aurora we were able to assemble observations from different parts of magnetotail to show their consistence with the picture of a narrow transient flow jet. For the first time we show that the $\sim$3 R_e wide fast plasma jet propagates over considerable distance, from $\geq$40 R_e in the midtail, and is able to reach the inner magnetosphere at 6.6 R_e in about 10 minutes. We also confirmed that narrow flow jet has an associated auroral streamer as its ionospheric projection and that it represents the underpopulated plasma tube (plasma bubble). Our results shows that the plasma bubbles are real and capable of transporting plasma into the inner magnetosphere. The bubble mechanism is thus a viable candidate to resolve the long-standing 'convection crisis' controversy and to realize the return plasma transport in the magnetospheric circulation pattern.

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