Planetary and Space Science 101 (2014) 135–148

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

An influence of long-lasting and gradual magnetic flux transport on fate of magnetotail fast plasma flows: An energetic particle injection substorm event study

Motoharu Nowada [a,*], Suiyan Fu [a], George K. Parks [b], Tuija I. Pulkkinen [c], Zuyin Pu [a]

[a] Institute of Space Physics and Applied Technology, School of Earth and Space Sciences, Peking University, Beijing, People's Republic of China
[b] Space Science Laboratory, University of California Berkeley, California, United States of America
[c] School of Electrical Engineering, Aalto University, PO Box 13000, 00076 AALTO, Finland

ARTICLE INFO

Article history:
Received 14 March 2014
Received in revised form
24 June 2014
Accepted 26 June 2014
Available online 10 July 2014

Keywords:
Magnetic flux and plasma particle/energy transports
Fast plasma flows
High-speed flow braking
Substorm
Steady magnetospheric convection
Magnetotail plasma sheet

ABSTRACT

Based on multi-satellite and ground observations, we investigated an influence of long-lasting and gradual enhancements of magnetic flux transport rate on the magnetotail fast flow duration. On March 10th, 2009, THEMIS-B, which was located in the central plasma sheet of middle distant magnetotail ($X_{GSM} \sim -25.8$ R_E), observed the fast flows with the velocity exceeding 300 km/s, lasting over 3 h for intense southward Interplanetary Magnetic Field (IMF) period. During long-lasting fast flows, *AL* index variations were very extensive and their recovery was much slow. Pi 2 waves were observed at the ground observatories around the THEMIS's footpoints and at low-/mid-latitudes. The aspect for these *AL* variations suggests Steady Magnetospheric Convection (SMC), but clear substorm signatures were also observed. Further magnetic dipolarization was detected by THEMIS-A at $X_{GSM} \sim -8.2$ R_E and its nearby THEMIS-E. Only THEMIS-A observed the associated energetic electron flux enhancements. Therefore, the fast flows occurred during substorm with energetic particle injections at "imitative" SMC, which would be driven by prolonged intense southward IMF. The cumulative transport rates of magnetic and Poynting fluxes consecutively and gradually enhanced. On the other hand, THEMIS-C detected much shorter fast flows with the duration of 37 min at $X_{GSM} \sim -18.1$ R_E and weak/gradual substorm-associated dipolarization. However, the cumulative magnetic flux transport rate was enhanced only during the fast flow interval and was saturated after the fast flows. From different magnetic transport rate profiles at THEMIS-B and THEMIS-C, the realms of dipolar-configured field lines expanded to near THEMIS-C's position responsible for long-lasting fast flow-associated consecutive and gradual magnetic flux pileup. Because the resultant "high-speed flow braking" region was retreated into a few R_E tailward direction, long-lasting fast flows were almost stemmed. These results suggest that the cumulative magnetic flux transport rate is one of the important factors to determine "fate" (duration) of the magnetotail fast flows.

1. Introduction

The plasma flow velocity in/around the magnetotail plasma sheet is usually slow, and its range is lower than 100 km/s (e.g., Baumjohann et al., 1988, 1989). However, these plasma flows sometimes become high-speed whose velocity is about 400 km/s, and their durations are short-lived (Baumjohann et al., 1990; Angelopoulos et al., 1992). Angelopoulos et al. (1992) found that high-speed plasma flows occur within 10-min timescale plasma flow enhancements termed as "Bursty Bulk Flow" (BBF) events, and are associated with the velocity peaks with the rise-and-fall timescale of the order of a minute, that is, plasma flow bursts.

The magnetic flux and energy transports in the magnetotail plasma sheet are frequently raised and discussed as one of the most important physical roles of these fast flows (Angelopoulos et al., 1992, 1994, 1999; Miyashita et al., 2003). Schödel et al. (2001a, 2001b) found that the fast flows in the central plasma sheet were associated with a large convection electric field (larger than 2 mV/m), suggesting that the flow bursts play a crucial role in the transport of the magnetic flux and energy. This is because the electric field is identified as a proxy of the magnetic flux transport rate, which is described by a formula of $V_X B_Z - V_Z B_X$.

Recently, Liu et al. (2011, 2014) introduced "Dipolarizing Flux Bundle (DFB)" whose concept is based on "plasma bubble" theoretically proposed by Pontius and Wolf (1990) and Chen and Wolf (1993). DFBs are identified as small flux tubes with a more dipolar (stronger) field than the background plasma sheet magnetic field

---

[*] Corresponding author. Tel.: +86 1062751133x803; fax: +86 1062761896.
E-mail address: nowada@pku.edu.cn (M. Nowada).

http://dx.doi.org/10.1016/j.pss.2014.06.012
0032-0633/

and scales less than 3 R_E in X_{GSM} and Y_{GSM}, and their durations are only ~30% within the fast plasma flows. They postulate that DFBs play a major role in the magnetic flux transport in the plasma sheet; 65% of fast plasma flow-associated flux transport is occupied. This flux transport rate due to DFBs is about 15–35% as high as that of "Rapid Flux Transport Events (RFTs)" based on a large convection electric field, investigated by Schödel et al. (2001a, 2001b). However, detailed relationship and correlation in the magnetic flux transport between DFBs and RFTs are still open question at present.

Ohtani et al. (2005) found that the most of tail fast plasma flows at $X_{GSM} \sim -30\ R_E$ do not reach geosynchronous altitudes and are not sufficient for causing the geosynchronous dipolarization with the GEOTAIL and GOES observations. These conclusions by Ohtani and his colleagues were drawn based on only observational results obtained at the locations where the fast plasma flows occurred and dipolarized regions near geosynchronous altitudes. Takada et al. (2006) showed an agreement in their results, and proposed further two different models why the plasma flows in the plasma sheet could not see around a geosynchronous orbit. However, because the locations of Cluster and TC-1 were almost near earth tail region in Takada et al. (2006), detailed relationship between the fast flows at $X_{GSM} < -25\ R_E$ and the flux transport profiles near/at geosynchronous altitudes remained unclear. In previous studies, it obviously became "missing link" in the magnetic energy transport (convection) in the magnetotail plasma sheet how the profiles of the fast flows at mid-tail regions and associated magnetic flux transports would change closer to the Earth (the geosynchronous orbit).

BBFs and plasma flow bursts are almost accompanied by significant enhancement of the north–southward magnetic field component (B_Z) (e.g., Angelopoulos et al., 1992, 1994; Hesse and Birn, 1991; Bamjohann et al., 1999), and simultaneous intensity of the B_X component decreases. These magnetic field variations occur in association with the magnetotail field configuration changes during which substorm begins and develops, and are identified as tail magnetic dipolarization. Therefore, they are considered as "key" phenomena for the substorm occurrence and development, but are not clear "indicator" of substorm occurrence. The profile of the B_Z enhancement has two types; persistent/gradual B_Z enhancements and transient/steep increases of the B_Z component. The former case is well-known as clear evidence for substorm occurrence, but the latter one is associated with not only the substorms but also the other physical magnetospheric phenomena (i.e., magnetic storm). Because BBFs and plasma flow bursts are associated with persistent/gradual tail magnetic dipolarization, they might be closely related with substorm (Angelopoulos et al., 1992, 1994). However, it is still debatable topic whether or not there is precise "one-to-one" correlation between them.

The substorm duration and its onset is roughly estimated by an interval of the negative (positive) bay variations and their starting time in geomagnetic indices, such as *AL* and *AU*. Typical duration of substorm is ranged over a few hours (2–3 h), including "growth", "expansion" and "recovery" phases, but is strongly dependent on the solar wind conditions (McPherron, 1970, 1979; Baumjohann and Treumann, 1996 and references therein). MHD waves with the Pi 2 range between 40 s and 150 s (6.7 mHz and 25 mHz) observed at the ground magnetic observatories, whereas, have been utilized to know the precise onset time. This is because Pi 2 waves at particular low-/mid-latitudes and/or high-latitudinal observatories around the satellite's footpoints are very closely related with the formation of a pair of downward (on the dawnside) and upward (on the duskside) field-aligned currents (cf. current-wedge, McPherron et al., 1973) resulted in substorm (Saito et al., 1976; Sakurai and Saito, 1976). Therefore, in our study, not only geomagnetic index variation but also Pi 2 range MHD waves are used as a remote sensitive indicator for the onset of substorm.

In addition to tail magnetic dipolarization and Pi 2 range MHD waves, strong and sharp increases of energetic particle flux in the dipolar(-like) magnetosphere, which are hereafter referred to as "energetic (high-energy) particle injections" (e.g., Arnoldy and Chan, 1969; Belian et al., 1981), are also clear evidence for the substorm signature. The enhanced energetic particle fluxes can be formed by double accelerations; first plasma acceleration is made by possible tail magnetic reconnection, and second acceleration occurs during their earthward transport (e.g., Birn et al., 1997). A plausible phenomenon closely related with the particle injections is also Ultra-Low-Frequency (ULF) waves, in particular, Pc 5 range MHD waves whose period (frequency) ranges are from 150 s to 600 s (from 1.68 mHz to about 6.7 mHz) at geosynchronous altitudes and on the ground. The generation mechanism of these waves can be addressed by instabilities from complicated wave-particle resonances in the inner-magnetosphere. Further spatio-temporal evolution of the wave field is a key mechanism of the ULF wave transmission (Zolotukhina et al., 2008). However, detailed generation and wave evolution theory/mechanism have still been discussed. The high-energy plasma injections at geosynchronous altitudes result from intrusion of the magnetotail fast flows. The physical link between energetic particle injections and high-speed plasma flows was illustrated by both case studies (Henderson et al., 1998; Sergeev et al., 1999, 2000, 2012) and numerical simulations (Yang et al., 2011), but detailed relationship between them is not simple. This is because injection events do not frequently occur even during substorm, compared to a plasma sheet fast flow occurrence.

Making a full use of the advantage of a line formation flight of five THEMIS probes at $X_{GSM} = -26\ R_E$, $-18\ R_E$, and near geosynchronous altitudes, we investigate how the profiles of the magnetotail fast flows/associated magnetic flux transport change closer to the Earth. Furthermore, it was examined how the resultant magnetic field near geosynchronous altitudes is varied. Fortunately, since the mid-tail fast flow event in this study had a long duration, a long-lasting magnetic flux transport profile from mid- to near earth tail regions was able to be followed. A flux transport's influence that gives to "fate (duration)" of causal fast plasma flows will be discussed in detail. In this study, it is also examined whether or not observed earthward consecutive and gradual magnetic flux transport was related with substorm, if yes, substorm was associated with or without the energetic particle injections at geosynchronous altitudes.

This paper is organized in six sections. The background and purpose of this study (introduction) and the instrumentation on board THEMIS are described in Sections 1 and 2. Section 3 shows the results of space-based observations; the solar wind conditions during long-lasting and gradual magnetic flux transport, and the observational results for consecutive magnetic flux transport due to long-lasting fast plasma flows as provided by two probes of THEMIS. The geomagnetic field variations associated with long-lasting and gradual magnetic flux transport at ground magnetic observatories are described in Section 4. Discussion and summary for the observations are made in Section 5. The conclusions obtained from this study are described in Section 6.

2. Instrumentations onboard THEMIS

The THEMIS spacecraft consists of five probes, and was launched on February 17, 2007, in order to reveal the spatial–temporal structures of magnetospheric processes (Angelopoulos, 2008). In this study, we used the magnetic field data obtained from the Fluxgate magnetometers (FGM) that is capable of measuring the low-frequency fluctuations up to 64 Hz, and detecting the magnetic field variations within an accuracy of ±0.01 nT