Journal of Atmospheric and Solar-Terrestrial Physics 99 (2013) 47–52

Contents lists available at SciVerse ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

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

Propagation of plasmoids generated by fast reconnection in the geomagnetic tail

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ARTICLE INFO

Article history:
Received 27 February 2012
Received in revised form
14 May 2012
Accepted 15 September 2012
Available online 9 October 2012

Keywords:
Magnetosphere
Substorms
Plasmoid
Reconnection

ABSTRACT

So-called plasmoids are most fundamental signatures of geomagnetic substorms, and precise measurements of magnetic fields have been obtained by in situ satellite observations. Hence, in understanding substorm phenomena, it is essential to clarify the physical mechanism of plasmoid dynamics. The present paper studies on the basis of the spontaneous fast reconnection model how a large-scale plasmoid is generated and propagates in weakly sheared current sheets. It is demonstrated that the basic structure and dynamics of the plasmoid, generated by the fast reconnection, are both qualitatively and quantitatively in good agreement with actual satellite observations. In particular, magnetic field lines inside the generated plasmoid deviate from a helical geometry.

1. Introduction

Magnetic reconnection is fundamental for geomagnetic substorms, so an essential question is to clarify how magnetic reconnection is triggered and proceeds explosively in space plasmas. A possible fast reconnection configuration with standing slow shocks was first proposed by Petshcek (1964). The Petschek mechanism has been extensively studied in two-dimensional (2D) steady MHD flows, and it was suggested that the basic configuration was controlled by external conditions, since the reconnection inflow was taken to be the free parameter (Vasyliunas, 1975; Priest and Forbes, 1986). On the other hand, Ugai and Tsuda (1977, 1979) first demonstrated that the fast reconnection can be realized as an eventual solution if an anomalous resistivity is locally enhanced around an X neutral point. Their results have been confirmed by many authors (e.g., Scholer, 1989; Yokoyama and Shibata, 1994), and we have proposed the spontaneous fast reconnection model, which will be shown in Section 2.

Magnetic reconnection involves complicated nonlinear processes, so computer simulations are crucial. However, special care must be paid to physical dissipation (effective resistivity) in the diffusion region (Ugai, 2012). In collisionless plasmas with no resistivity, extreme current concentration (current sheet thinning) occurs around the X point as shown by MHD simulations (Ugai, 1986) and by particle simulations (Birn et al., 2001). Hence, if physical dissipations are not sufficiently large, reconnection occurs by numerical resistivities. Many simulations, such as so-called global simulations and Hall reconnection simulations, often ignore any definite physical dissipation (resistivity), leading to reconnections due to numerical resistivities. Such artificial reconnections cannot be applied to actual phenomena, since numerical resistivities are out of the plasma physics.

Any theoretical model must explain basic observational features. Regarding geomagentic substorms, precise measurements by in situ satellite observations are possible. One of the most basic substorm signatures is plasmoid propagation in the geomagnetic tail. Historically, tailward moving plasmoid is considered to be formed between reconnected field lines and pre-existing northward field lines on the basis of reconnection cartoon (Hones, 1977). Regarding earthward moving plasmoid, Fig. 1 shows typical satellite observations, where the B_z field has the bipolar structure when the sheared field B_y has the peak value, so the plasmoid is considered to be the flux rope with helical field lines (Slavin et al., 2003). As shown in Fig. 2(a), the similar field structure is observed for the tailward moving plasmoid (Ieda et al., 1998). Also, as shown in Fig. 2(b), so-called traveling compression regions (TCRs) are observed in the tail lobe (Slavin et al., 1993). These clear observations indicate the basic plasmoid features to be resolved theoretically in a unified manner.

The theme of the present paper is to study plasmoid dynamics in the geomagnetic tail on the basis of the spontaneous fast reconnection model. Fig. 3 shows the schematic drawing of plasmoid propagation in the tail. Somewhere in the tail, magnetic neutral sheet with $B_z \sim 0$ is formed [Fig. 3(a)], and when the current sheet width $2W$ becomes three to four times larger than its thickness $2d_0$, say $W > 3-4d_0$, the fast reconnection grows and causes a pair of plasmoids propagating in the tailward and earthward directions, and Fig. 3(b) shows the earthward moving plasmoid. This plasmoid,

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1364-6826/$ - see front matter
http://dx.doi.org/10.1016/j.jastp.2012.09.015

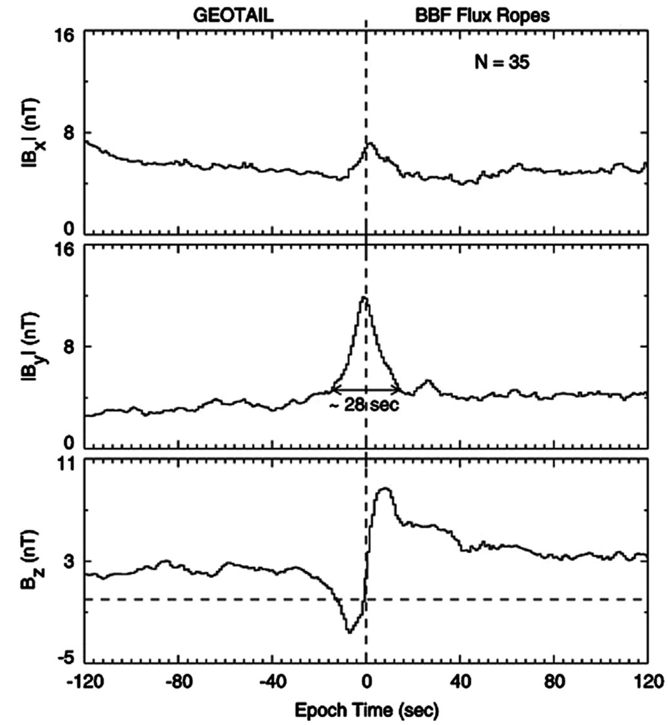

Fig. 1. Superposed epoch analysis performed using 1 s averages of the Geotail magnetic field measurements for all 35 BBF flux rope events (after Slavin et al., 2003).

directly generated by the fast reconnection jet as a current sheet bulge, was first demonstrated by Ugai (1989, 1995) and extensively studied (Nitta, 2004; Zenitani and Miyoshi, 2011).

2. Spontaneous fast reconnection model

Plasmas in the geomagnetic tail are collisionless, since Spitzer resistivity due to Coulomb collisions is negligible. Hence, an essential question is to clarify how the fast reconnection mechanism can be realized in space plasmas of extremely large magnetic Reynolds number. In this direction, Petschek mechanism has been widely accepted, so many people believe that physical dissipation (resistivity) is not essential for fast reconnection evolution.

Regarding the evolution mechanism, the spontaneous fast reconnection model is quite different from the Petschek model, so it is essential to understand why the fast reconnection can grow for the spontaneous model. Localized resistivity simply causes the sheet current to be redistributed so as to avoid the diffusion region of enhanced resistivity, so magnetic reconnection is soon terminated. The underlying physics lies in the subsequent hydrodynamic stage, when the $\mathbf{J} \times \mathbf{B}$ force due to reconnection drives plasma flows so as to vitally concentrate current density into the diffusion region to enhance reconnection evolution (Ugai and Tsuda, 1977). The remarkable reconnection dynamics results from properties inherent in current sheets in collisionless plasmas. Hence, the fast reconnection evolves by a nonlinear instability due to positive feedback between current-driven anomalous resistivities and global reconnection flows (Ugai, 1984, 1999).

In three-dimensional (3*D*) current sheet systems (Fig. 3(a)), the key condition for the fast reconnection evolution is that the current sheet width is about three times larger than its thickness (Ugai, 2007). Once such a thin current sheet is formed in collisionless plasmas, extreme current sheet thinning (current concentration) occurs around the *X* neutral point, which cannot be suppressed by MHD effects (Ugai, 1986, 2008). Therefore, current sheet thinning should proceed, until current-driven anomalous resistivities are caused (e.g., Lui, 2004). In laboratory experiments too, current-driven anomalous resistivities are definitely detected in the diffusion region (e.g., Ji et al., 1998). Note that the current concentration by reconnection flows is essential for the spontaneous reconnection evolution. We then find that the fast reconnection process is little influenced by the functional form nor the parameter value of current-driven anomalous resistivity model (Ugai, 1984, 1992, 1999, 2008).

The key for the fast reconnection mechanism is that effective resistivity is locally enhanced at the *X* point. Hence, the fast reconnection cannot evolve for uniform resistivity (Scholer, 1989; Ugai, 1992), although uniform resistivity is not realistic in space plasmas. For the Spitzer resistivity, fast reconnection cannot be realized, since the resistivity is reduced around the *X* point where temperature notably increases (Ugai, 1992, 1999). Therefore, anomalous resistivities are required for any fast reconnection evolution (Ugai and Zheng, 2005).

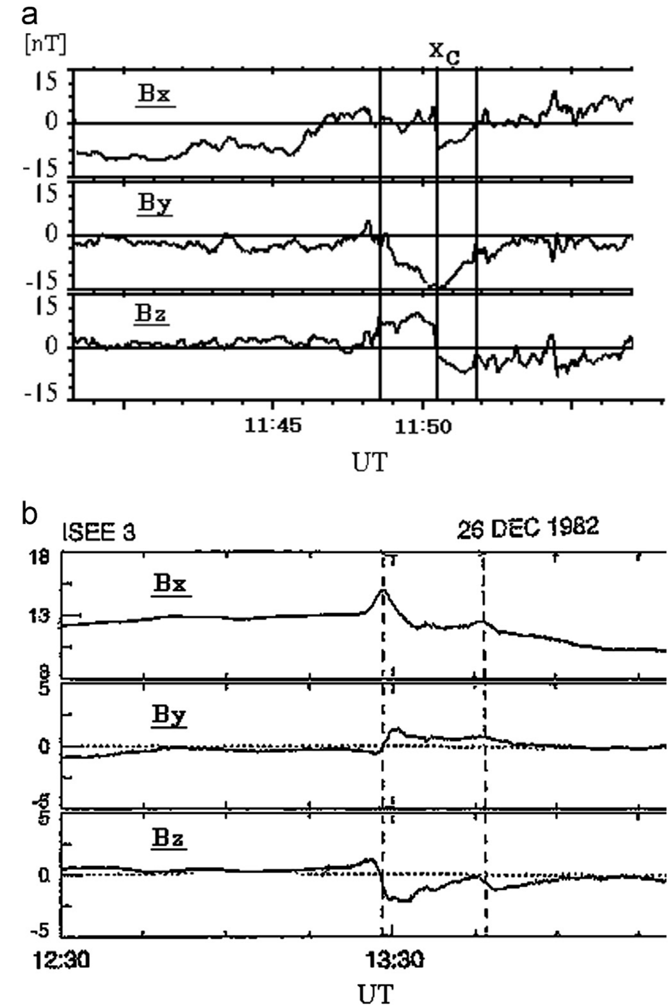

Fig. 2. (a) Geotail satellite observations of magnetic fields of a plasmoid at $x = -94.9R_e$ (after Ieda et al., 1998); (b) ISEE3 magnetic field observations in the north lobe of the tail at $x = -73R_e$ (after Slavin et al., 1993).

3. Simulation modeling

Details of the MHD simulations are described in Ugai (2008), which assures that the numerical resistivity is much smaller than the physical resistivity. Initially, a long current sheet with