Preferential Acceleration of Coherent Magnetic Structures and Bursty Bulk Flows in Earth's Magnetotail

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Abstract

Observations indicate that the magnetotail convection is turbulent and bi-modal, consisting of fast bursty bulk flows (BBF) and a nearly stagnant background. We demonstrate that this observed phenomenon may be understood in terms of the intermittent interactions, dynamic mergings and preferential accelerations of coherent magnetic structures under the influence of a background magnetic field geometry that is consistent with the development of an X-point mean-field structure.

1. Introduction

Recent satellite observations indicate that the Earth's magnetotail is generally in a state of intermittent turbulence constantly intermixed with localized fast bursty bulk flows (BBF) [1,2]. A model of sporadic and localized merging of coherent magnetic structures has been proposed by Chang [3] (and references contained therein) to describe the dynamics of the magnetotail. When conditions are favorable, the coherent structures may merge, interact, convect and evolve into forced and/or self-organized critical (FSOC) states [4], a condition satisfied by the observational statistics of the burst duration characteristics of the BBF [5]. When considered with the realistic magnetotail geometry, the coarse-grained dissipation of turbulent fluctuations produced by the interacting multi-scale coherent structures may trigger "fluctuation-induced nonlinear instabilities" and possibly initiate substorms. Some of the above ideas have been demonstrated by direct numerical simulations [6]. In this paper, we address the dynamics, particularly the preferential acceleration, of the coherent structures in sheared magnetic field geometry. Preliminary comparisons of the theoretical ideas and new numerical results with the observed characteristics of BBF will also be presented.

2. Observational properties of BBF

In situ observations [5, 7, and references contained therein] indicate that BBF are an important means of magnetotail transport. Removing the fast BBF, the remaining flow state has a small average convection. The BBF are seen during precursor activity, at substorm expansion and recovery phases.

Near-Earth BBF are primarily Earthward and consist of multiple, short-lived flow bursts, i.e., they are intermittent. Distribution functions of mid-tail BBF near the source region of a tailward-retreating reconnection site at late substorm expansion phase show that multiple, localized acceleration sites are responsible for the observed flows [1]. Distant tail fast flows are tailward, they are associated with plasmoids, they also have multiple flow peaks and multiple current filaments within them, and they are likely localized in the cross-tail dimension (e.g. [8] and references therein). Thus although preferential acceleration is observed on either side of a mid-tail region, probably associated with the gross formation of an X-point topology, the flows and the currents within them are rather intermittent.

When considered in connection with an observed X-point, the primary directions of convection of BBF are earthward (tailward) when they are situated earthward (tailward) of the X-point [7]. It is therefore of preponderate interest to decipher the fundamental physical mechanism that are responsible for the preferential acceleration and convective nature of the observed BBF.

It had been suggested by Chang [4] that the magnetotail could exhibit dynamic forced and/or self-organized critical (FSOC) behavior. Statistical studies of the AE index [9] and global auroral imagery [10] during substorm times seem to indicate consistency with such a dynamic description. More recently, Angelopoulos *et al.* [5] demonstrated specifically that the probability distribution of the BBF duration could also be described by a power law, an indication of dynamic criticality. A physically realistic topological model based on the coherent magnetic structures was proposed by Chang [3,11] to explain the multiscale nature of the intermittent turbulence that can lead to the FSOC state in the magnetotail and its low dimensional behavior [12]. It was also suggested that the coarse-grained dissipation of the fluctuations associated with FSOC could lead to nonlinear instabilities and trigger the development of mean-field X-point magnetic structures in sheared magnetic fields. We shall demonstrate below that these ideas lead naturally to the preferential acceleration and observed convective nature of the fast BBF.

3. Coherent magnetic structures in earth's magnetotail

There is considerable evidence that many turbulent flows are far from being totally disorganized. Indeed they can posses "coherent structures," as indicated by experiments and numerical simulations [e.g., 13]. Chang [11] suggested that the coherent structures are basically current filaments in the neutral sheet region of the magnetotail.

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Most field theoretical discussions begin with the concept of propagation of waves. For example, in the MHD formulation, one can combine the basic equations and express them in the following propagation forms:

$$\rho \mathrm{d}V/\mathrm{d}t = B \cdot \nabla B + \dots, \tag{1}$$

$$\mathrm{d}B/\mathrm{d}t = B \cdot \nabla V + \dots, \tag{2}$$

where the ellipsis represents the effects of the anisotropic pressure tensor, the compressible and dissipative effects, and all notations are standard. Equations (1,2) admit the well-known Alfvén waves. For such waves to propagate, the propagation vector k must contain a field-aligned component, i.e., $B \cdot \nabla \rightarrow \mathrm{i}k \cdot B \neq 0$. However, near the singularities where the parallel component of the propagation vector vanishes (the resonance sites), the fluctuations are localized. That is, around these resonance sites (usually in the form of curves in physical space), it may be shown that the fluctuations are held back by the background magnetic field, forming coherent structures in the form of flux tubes [3,11]. For the neutral sheet region of the magnetotail, these coherent structures are essentially force-free and in the form of current filaments in the cross-tall direction [11]. If the cross-tall current is primarily carried by the coherent magnetic structures, these structures will be strongly affected by the magnetic field due to the Lorentz force. As they are being preferentially accelerated they will dynamically deform and dissipate fluctuations to produce smaller structures, while occasionally interact and merge with neighboring structures.

4. Preferential acceleration of BBF

Consider the coherent magnetic structures discussed above, which in the neutral sheet region of the plasma sheet are essentially filaments of concentrated currents in the cross-tail direction. As we have argued previously, in a sheared magnetic field, these multiscale fluctuations can supply the required coarse-graining dissipation that can produce nonlinear instabilities leading to X-point-like structures of the average magnetic field lines. For a sheared magnetic field $B_x(z)$, upon the onset of such fluctuation-induced nonlinear instabilities, the average magnetic field will generally acquire a z-component. Let us choose x as the Earth-magnetotail direction (positive toward the Earth) and y in the cross-tail current direction. Then the deformed magnetic field geometry after the development of an X-point structure will generally have a positive (negative) B_z component earthward (tailward) of the X-point. Near the neutral sheet region, the Lorentz force will therefore preferentially accelerate the coherent structures earthward if they are situated earthward of the X-point and tailward if they are situated tailward of the X-point, Fig. 1. These results would therefore match the general directions of motion of the observed BBF in the magnetotail [7].

We have performed two-dimensional numerical simulations to verify these conjectures. The simulations are based on a compressible MHD model that has been used in previously studies of coherent magnetic structures [6]. In the first example we started the numerical simulation initially consisting of randomly distributed magnetic fluctuations
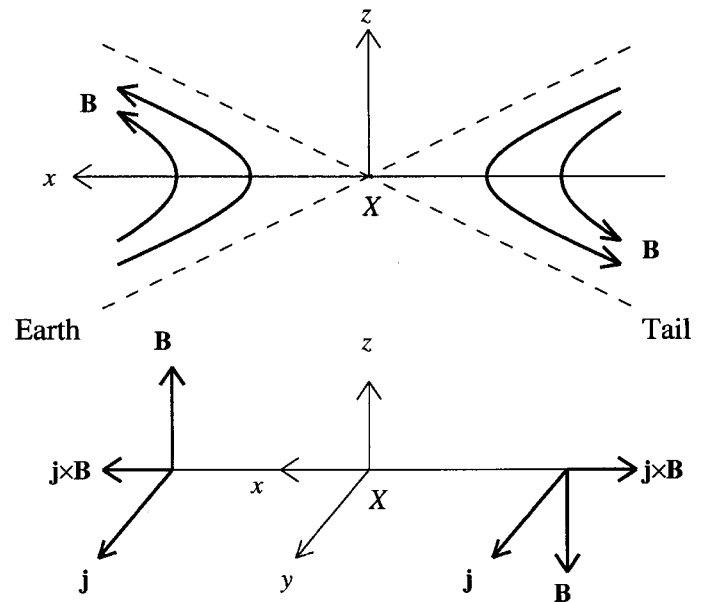

Fig. 1. Top panel: Schematic of a mean field X-point magnetic geometry. Bottom panel: Heavy arrows depicting the directions of the Lorentz ($J \times B$) forces acting on two typical coherent magnetic structures (cross-tail current filaments) near the neutral sheet.

with zero mean magnetic field. The calculation was carried out with 256 by 256 grid points in a doubly periodic (x,z) domain of length 2π in both directions. Eventually, after some elapsed time, multiscale coherent magnetic structures are formed, which are shown in Fig. 2(a) for $1.5\pi \leq x \leq 2\pi$ and $1.1\pi \leq z \leq 1.6\pi$. The maximum magnitude of the magnetic field is 0.014. In this and following examples, both pressure and density are about 1; the system has a large plasma β to mimic the current sheet region. At this time, a uniform $B_z = 0.002$ is introduced. In the middle panels of Fig. 2, the effect of the Lorentz force is clearly seen through the motions of the coherent structures after an additional elapsed time of 100. (For all numerical examples, the unit of time was based on the wave speeds. For instance, the sound speed is about 1.3; thus a sound wave would traverse a distance of π in a time of 2.4.) If the direction of B_z is reversed, the motions of the coherent structures are also reversed as seen in the bottom panels of Fig. 2.

In the second example, we have considered the motions of the coherent magnetic structures that developed in a sheared mean magnetic field upon the initial introduction of random magnetic fluctuations. The calculation was carried out with 1280 by 256 grid points in a doubly periodic (x, z) domain of length 10π in the x-direction and 2π in the z-direction with a sheared magnetic mean field $B_x = 0.025 \cos(z)$. The system again has a high plasma β with both pressure and density about 1. These structures were generally aligned in the x-direction near the neutral line, $z = 1.5\pi$, after some elapsed time. A positive $B_z = 0.001$ was then applied. It can be seen (Fig. 3) that, after an additional elapsed time of 50, the coherent structures (mostly oriented by currents in the positive y-direction), are generally accelerated in the positive x-direction; with one exception where a pair of magnetic structures with oppositely directed currents effectively canceled out the net effect of the Lorentz force on these structures. The acceleration continues in time. We have plotted the x-component of the flow velocities, v_x, due to
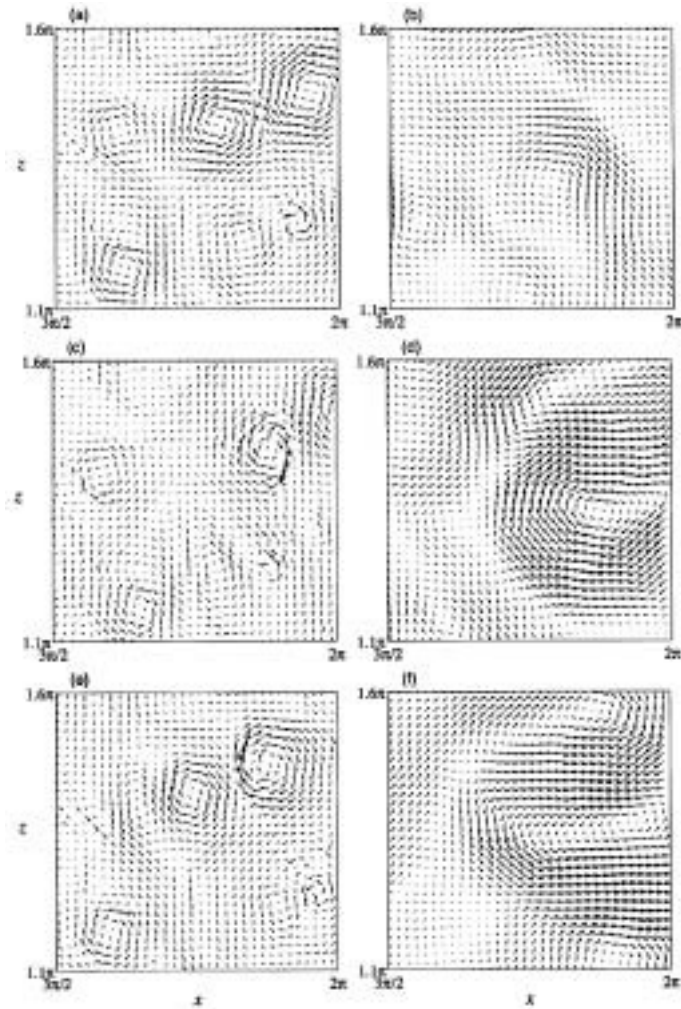
Fig. 2. Effect of the Lorentz force on the motion of the coherent structures. The magnetic fields are shown in the left three panels and the flow vectors are plotted in the right three panels. All three plots for the magnetic fields have the same scale, with max($|B|$) = 0.014 in (a). The flow-vector plots also have the same scale, with max($|v|$) = 0.0015, 0.0026, and 0.025 in (b), (d), and (e), respectively. The top panels show the formation of multiscale coherent magnetic structures. At this time, a uniform B_z is introduced. The middle panels show the result with $B_z = 0.002$ while the bottom plots provide the result with $B_z = -0.002$, both after an additional elapsed time of 100.
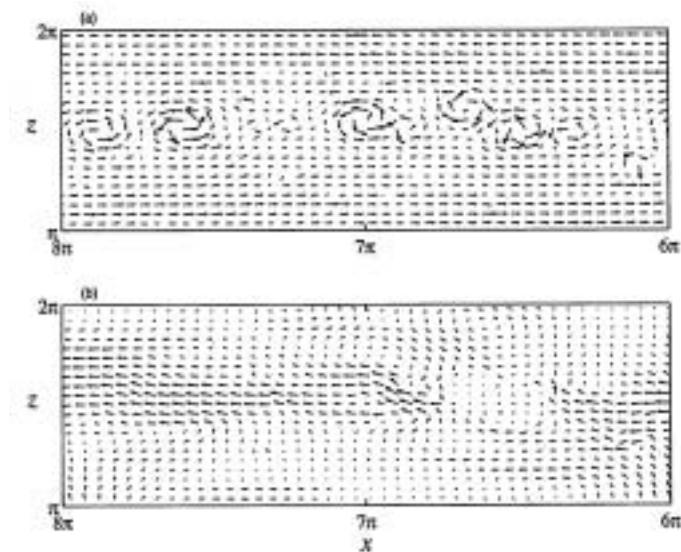

Fig. 3. Effect of the Lorentz force on the motions of the coherent structures in a sheared magnetic field due to the application of a uniform magnetic field B_z. The magnetic fields (a) and flow velocities (b) are plotted in a domain $6\pi \leq x \leq 8\pi$ and $\pi \leq z \leq 2\pi$. The maximum velocity in (b) is 0.006.

the cumulative effect of the Lorentz (and pressure) forces acting on the flow (and in particular the coherent structures) after additional duration of 400 has elapsed (Fig. 4). We note that there are a number of peaks and valleys in the 3-dimensional display, with peak velocities of about 0.02, nearly approaching that of the Alfvén speed (about 0.025 based on $|B| = 0.025$) mimicking the fast BBF that were observed in the magnetotail. It is to be noted that an individual BBF event may be composed of one, two, or several coherent structures.

In the final plot (Fig. 5), we demonstrate in a self-consistent picture what might occur near the neutral sheet region of the magnetotail. We injected randomly distributed magnetic fluctuations in a predominantly sheared magnetic field, prescribed by $B_x = 0.1 \cos(z)$ and $B_z = 0.002 \sin(x/5)$.
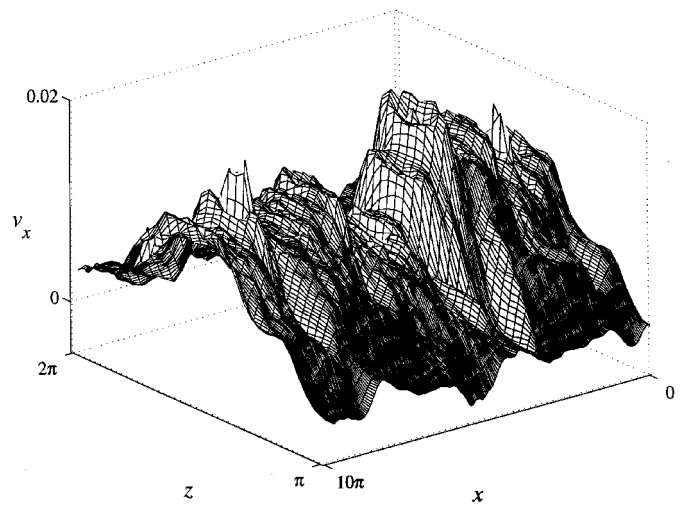

Fig. 4. A 3D perspective plot of v_x. Its peak velocities are about 0.02, nearly approaching that of the Alfvén speed (about 0.025 based on $|B| = 0.025$). The maximum velocity is about 3 times higher than that at earlier time shown in Fig. 3. Note that, because of the difference of scales in x and z in the plot, the accelerated structures have the over-emphasized sheet-like shapes.
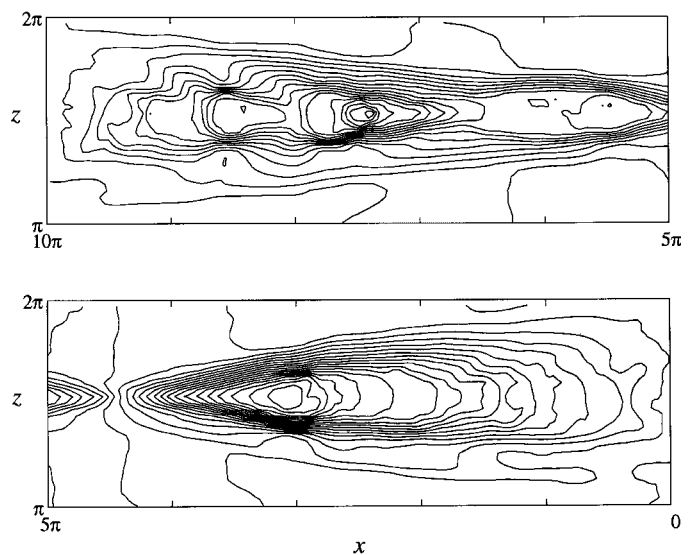

Fig. 5. A contour plot of v_x in an X-point mean field geometry. There are 21 contour levels, with a contour interval of 0.0045. The highest level is 0.045 near $(x, z) \sim (7.5\pi, 1.5\pi)$ and the lowest level is -0.045 near $(x, z) \sim (3\pi, 1.5\pi)$. The periodic boundary condition forces $v_x \sim 0$ near the boundary at $x \sim 0$ and 10π.

The calculation was again carried out with 1280 by 256 grid points in a doubly periodic (x, z) domain of length 10π in the x-direction and 2π in the z-direction. Eventually, a large-scale X-point like mean field magnetic structure is produced. The coherent structures (aligned in the neutral sheet region) are subsequently accelerated away from the X-point in both the positive and negative x-directions. Contour plots of v_x after some elapsed time clearly indicated such effects.

5. Summary

In summary, we demonstrated that dynamical evolutions of coherent magnetic structures in an initially sheared magnetic field might provide a convenient description of the observed fast BBF in the Earth's magnetotail, particularly near the neutral sheet region. In the magnetotail, the coherent structures are essentially current filaments in the cross-tail direction. In an X-point mean magnetic field geometry, selective acceleration of these coherent structures can be accomplished by the Lorentz force. Simulation results demonstrate that the coherent magnetic structures can indeed be preferentially accelerated this way near the neutral sheet and in the appropriate directions.

Although the X-point mean magnetic field can be formed by nonlinear instabilities due to the stochastic behavior of the coherent magnetic structures, it is not necessary for the X-point to occur this way. An X-point magnetic field geometry formed by forced magnetic reconnection is likely to cause preferential acceleration of the coherent structures in a similar manner.

Our work is just at the beginning. In the future, we shall consider more general initial two-dimensional mean magnetic field geometries. Moreover, the coherent magnetic structures and interactions are usually three-dimensional, characterized by sporadic and localized current disruptions [14], and the dynamics of the coherent structures, intermittent turbulence, and global interactions are very complicated. We shall look into such complexities. The characteristics of the ion velocity distributions of the observed BBF generally have a crescent-moon shape in the $x - z$ plane [7]. The localized merging of the coherent structures aligned in the neutral sheet region would produce particle jets at the merging point normal to the neutral sheet both in the north and south directions with velocities of the order of the Alfvén speed. We suggest that the combined consequence of such localized merging and the preferential acceleration of the coherent structures would produce ion distributions in the BBF of the form as observed. We shall begin a study of such detailed kinetic effects.

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