Multilayered structure of thin current sheets: multiscale ”Matreshka” model

A. S. Sharma, L. M. Zelenyi, H. V. Malova, V. Yu. Popov, and D. C. Delcourt

Abstract: Current sheets in the Earth's magnetosphere are the sites where the plasma processes leading to magnetic energy storage and subsequent fast release are initiated. Analytical self-consistent model of multicomponent thin current sheets has benn developed in which the tension due to the magnetic field lines is balanced by particle inertia, and the plasma consists of ions of both solar wind and ionospheric origin. The influence of electron population is taken into account assuming Boltzman-like quasi-equilibrium distribution in the ambipolar field, and can lead to a sharp peak in the electron current density in the center. The inclusion of non-adiabatic O+ ions in the model leads to a new source of current in the Grad-Shafranov-like system of equations describing the quasi-equilibrium configuration. The O+ current dominates in the outer parts of the current sheet, yielding a multilayered or ”Matreshka”-like structure. Thus the magnetotail itself exhibits multiscale behavior evident in the magnetosphere.

Key words: Multilayered thin current sheet, Multiscale phenomena, Recoonection onset, CLUSTER, MMS.

1. Introduction

The magnetosphere is a strongly coupled system due to the cross–scale coupling among the many phenomena in the different regions, viz. magnetosheath, tail lobes, plasma sheet, ring current and ionosphere. The thin current sheet in the magnetotail is a key boundary region where the processes responsible for the onset of explosive release of energy takes place during substorms. Although these processes are kinetic in nature with scale sizes as short as the electron gyro radius, the strong cross-scale coupling leads to the global magnetospheric features such as plasmoid formation and release.

The basic plasma processes that transport, accelerate, and energize plasmas in the thin boundary and current layers are crucial to the understanding of geospace and this has motivated the recent multi-spacecaft missions. The CLUSTER mission has provided unprecedented measurements of the plasma parameters to spatial scales corresponding to the ion gyro radius and has led to a new understanding of the plasma boundaries and sheets, e. g., the magnetopause and magnetotail. The Magnetospheric Multiscale (MMS) mission will explore the whole range of microscale processes associated with magnetic reconnection on scales that have been inaccessible so far [18].

The coupling of the solar wind mass, momentum and energy leads to the thinning of the magnetotail current sheet and eventually to magnetic reconnection. A key to the understanding of the current sheet, and hence of magnetic reconnection, is its equilibrium. The plasma equilibria underlying the magnetotail current sheet have been studied extensively since its discovery. Recent in-situ measurements by CLUSTER spacecraft [17, 13, 1] demonstrated that current sheets in the Earth's magnetotail can be as thin as to $1-2$ ion Larmor radii and have complicated internal structures with a hierarchy of spatial scales [16]. The cross-tail current profiles are observed to be substantially different from the well-known Harris model [6] and a schematic of the magnetotail current sheet is shown in Fig. 1 where the magnetic field has a finite B_z or B_n component.

The plasma mantle is usually considered to be a primary source for populating the Earth's magnetotail [12]. However measurements of the magnetospheric plasma composition [10] have shown the important role of particles of ionospheric origin. The spacecraft measurements of ion composition in the lobes at distances $10R_E > X > 22R_E$ have shown the presence of relatively low energy ($\sim 10eV - 1keV$) heavy ions streaming anti-sunward [4, 21, 15]. It was demonstrated that O^+ ions dominate both the pressure and density of the plasma sheet before the substorm onset and their contribution increases even more after substorm expansion begins. In moodeling the current sheet of the Earth's magnetotail it is therefore important to take into account its multicomponent composition including solar wind (H^+, He^{++}) and ionospheric (O^+, He^+) ions. The effects of such complicated compositions both on the structure of kinetic quasi-equilibria and dynamical processes are not well understood till recently [27]. Recent estimates [8] of the upper limit for the contribution of oxygen ions to the total cross-tail current has shown it to be as much as 10%. This is already a considerable effect and the presence of oxygen ions is found to have important consequences , viz. it dominates the cross-tail current outside the rather narrow tail midplane [27].

The contribution of O^+ ions to the magnetotail plasma equilibrium has been modeled on the lines of the thin current sheet models developed earlier [9, 20, 23, 26]. In the first attempt [27] to model the effect of ions other than H^+, the other relatively minor ions such as He^+,He^{++} were neglected. Using the semi-analytical Vlasov model of magnetotail quasi-equilibria the dependence of the shape of the cross-tail current profile on a number of parameters, viz. B_n/B_0, n_{O^+}/n_{H^+}, T_{O^+}/T_{H^+}, and $T_{e\perp}/T_i$, $T_{e\|}/T_{e\perp}$ were obtained. Here B_n is

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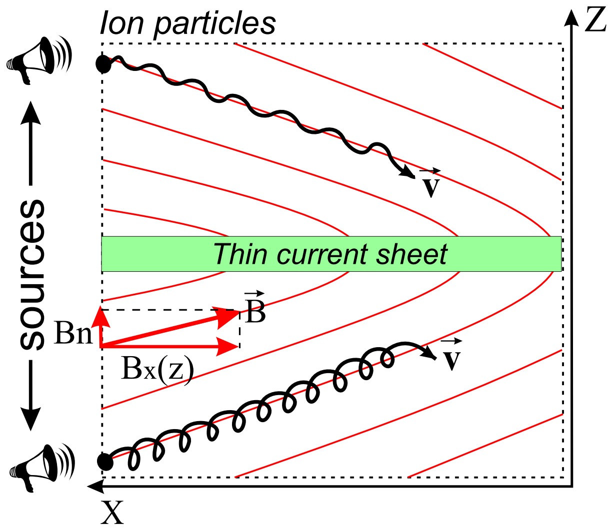

Fig. 1. The schematic diagram of the 1D model of the magnetotail current sheet. The particles entering the region on the left execute different orbits depending on their energy and location in the inhomogeneous magnetic field. The different types of particle trajectories are shown in Fig.2.

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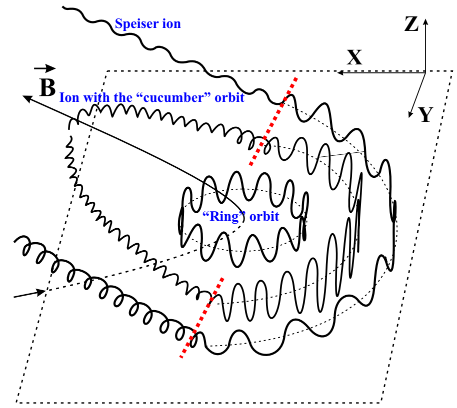

Fig. 2. The three different types of particle trajectories in the current sheet with finite B_z, viz. trapped, quasi-trapped and transient particles.

the normal component of the magnetic field and B_0 is the total magnetic field, n and T are the density and temperature (with parallel and perpendicular components), respectively.

2. Multi-component model of the magnetotail current sheet

A self-consistent equilibrium model of $1D$ anisotropic current sheet with a small normal component of the magnetic field (B_z in GSM system of reference) has been developed considering the particle orbits to be quasi-adiabatic [9, 20]. The tension of the curved magnetic field lines is balanced by the centrifugal force acting on ions crossing the sheet midplane, leading to a 1D equilibria with $\partial/\partial x = 0$ (e.g. without pressure gradient along tail axis). The plasma in the source region enters the central region (as shown on the outer regions on the left) in Fig. 1) where they carry a cross-tail current (J_y in our geometry) consistent with the magnetic field reversal in the vicinity of the $z = 0$ plane. The electric field component E_y can be neglected without any loss of generality by selecting a suitable deHoffmann-Teller frame of reference. The dynamics of ions and electrons are different inside the thin current sheet (TCS), so a hybrid approach can be used to describe the behavior of the different particle species. The non-adiabatic hydrogen (H^+) and oxygen (O^+) ions moving across the sheet with Speiser orbits will be described in the so called quasi-adiabatic approximation [20, 22]. The electrons are considered magnetized with finite inertia across the field lines and negligible inertia for field-aligned motion. The resulting charge separation generates an ambipolar electric field E_z supporting the quasi-neutrality of the plasma. The problem is then reduced to the solution of a Grad-Shafranov type equation, where currents from all particles species are self-consistently calculated from the equations of motion in the electric and magnetic fields generated by these currents.

When the ions cross the current sheet (CS) region, their motion is characterized by three integrals of motion: the total energy $W_0 = m(v_x^2 + v_y^2 + v_z^2)/2 + e\phi$, the canonical momentum $P_y = mv_y - (e/c)A_y(z)$ and the approximate integral of motion or adiabatic invariant $I_z = \frac{1}{2\pi}\oint mv_z dz$ (here $\vec{v}$ is the particle velocity, $A_y(z)$ is the vector-potential, and ϕ is the electrostatic potential). I_z, the so called Speiser CS invariant, is approximately conserved in a TCS where particle oscillations along the z and x coordinates are decoupled because of the widely separated oscillation frequencies: $\omega_x/\omega_z \ll 1$ [2, 3]. In the quasi-adiabatic approximation, the invariant $I_z \approx const.$ is used to render the equations of motion integrable and to determine the ion distribution at any position using the Liouville theorem. The value of B_n, the small normal component of the magnetic field is a parameter with a specified value, and the only assumption is that it is strong enough to keep the electrons magnetized. In these studies it is set to the value of $B_n = 0.1B_0$, and the electron motion along the field lines is assumed to be fast ehough to support a quasi-equilibrium Boltzmann distribution in the presence of an electrostatic potential and mirror forces.

3. Magnetotail equilibrium with oxygen ions

The current sheet model in the presence of O^+ is derived following the theoretical model developed earlier [24, 25]. In the previous models only two plasma components, protons and electrons, were taken into account. The Ampere's equation in the 1D case acquires the simple form:

$$\frac{dB_x}{dz} = \frac{4\pi}{c}\left(j_H + j_O + j_e\right) \qquad (1)$$

The total magnetic field B_x arises from the contributions from the currents carried by H^+, O^+ and electrons e^-. The boundary condition is $B_x(\infty) = B_0$ and the current densities j_H and j_O are given by

$$j_{H,O}(z) = e\int_0^\infty dv_x \int_0^\infty dv_z \int_0^\infty v_y f_{H,O}(\vec{v}, z)dv_y \qquad (2)$$

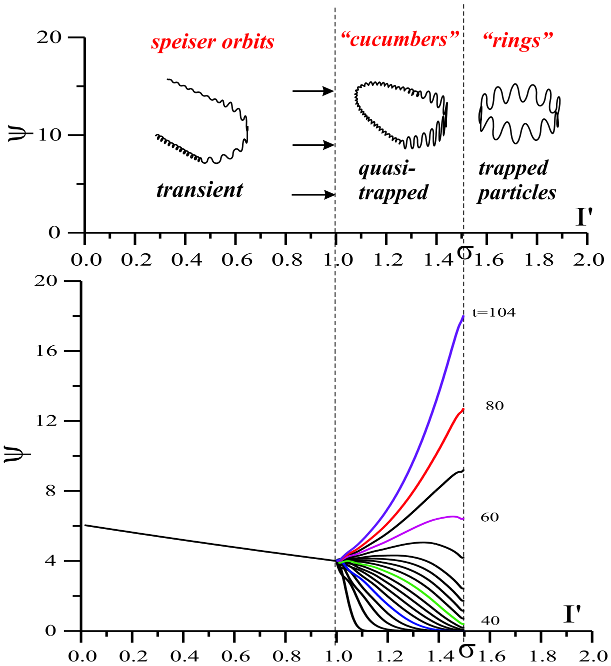

Fig. 3. The distribution functions of the different types of particles for an intially maxwellian distribution [23]. The different lines for the quasi-trapped particles correspond to different stages of evolution, starting with the left most.

with the distribution function $f_{H,O}$ to be taken in the form of a shifted Maxwellian function at the location of the plasma source, i.e., at the boundary of the system $z = \pm L$ (Fig. 1): $f_{H,O} \sim \exp\left\{-(v_\parallel - v_{D_{H,O}})^2 + v_\perp^2/v_{T_{H,O}}^2\right\}$ where $v_{T_{H,O}}$ are the thermal velocities, and $v_{D_{H,O}}$ are the drift velocities of the H^+/O^+ ions. The electron motion is described by fluid-like equation, but with the pressure anisotropy ($p_\parallel \neq p_\perp$) taken into account:

$$m d\vec{r}/dt = -e\left(\vec{E} + \frac{1}{c}\left[\vec{v}\times\vec{B}\right]\right) - \frac{\hat{\nabla} p_e}{n_e} - \mu\vec{\nabla} B \qquad (3)$$

A semi-hydrodynamic approach has been developed for obtaining the electron current j_e, the ambipolar electric field $E_z(z)$ and its influence on electrons and protons [24]. Finally the full system of equations for B_x, j_y, ϕ and n (plasma density) is solved using the integrals of motion W_0, P_y and I_z for the particle orbits shown in Fig. 2. The distribution function corresponding to these different types of orbits is shown in Fig. 3. The evolution of the distribution of quasi-trapped particles due to the scattering is shown by the different lines in the middle panel, with the lowest curve corresponding to the earliest instant.

4. Multilayered structure of thin current sheets

The self-consistent system of equations for the magnetic and electric fields, the total and partial current densities as well as the electrostatic potential and the plasma densities are solved numerically using a two-step iteration procedure for the ions and electrons [24, 25]. The results of this model are

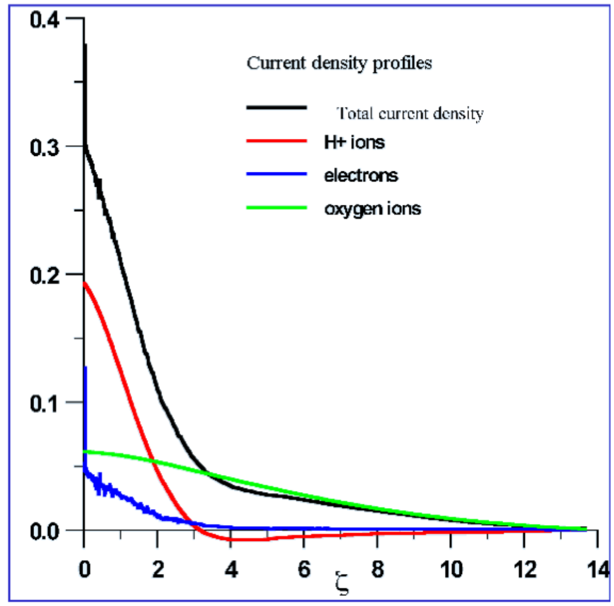

Fig. 4. The current densities of the different plasma species. The contributions of the different species have different characteristic lengths, with the oxygen having the broadest and the electrons the narrowest profile [27].

shown in Fig. 4, where the partial profiles of current densities and the corresponding magnetic fields of different plasma constituents, and the total profiles are plotted. The plasma parameters were chosen to be close to the observed values, e.g., the oxygen to hydrogen temperature ratio outside the sheet is $T_0/T_H = 1, 0.5, 0.25$, 0.1, and 0.0. The values of the initial density of oxygen is chosen to be (0, 0.1, 0.25, 0.5, 1.0) n_H outside the sheet. The case of $n_{O^+}/n_{H^+} = 1$ is shown Fig. 4 for reference. The role of electrons is the most substantial in the center of the current sheet, where the electrons dominate and support a very narrow and peaked current embedded in the proton current, which in turn is embedded in the oxygen current. The currents of the O^+ ions are comparable with that of the H^+ ions, but the half- thickness of the oxygen current density ($\sim 6\rho_L$) is three times larger than that of the protons ($\sim 2\rho_L$). It is clear from this figure that both the ion populations contribute approximately equally to the total cross-tail current, although the total CS thickness is determined generally by the oxygen ion current. Also the net contribution of O^+ is seen to be about 30% of the total current density.

The role of O^+ shown in Fig. 4 could be somewhat exagerated, and additional studies are shown in Fig. 5. The observations [21, 4, 15] show that the relative fraction of oxygen in the magnetotail may vary widely during different phases of magnetospheric activity (but very rarely exceed the density of hydrogen ions) and accordingly the dependence of I_O/I_{total} (where I_O and I_{total} are the O^+ and total currents, respectively) are investigated as a function of the ratio of densities n_O and n_H (Fig. 5). A similar variation is found for different values of the temperature ratio T_O/T_H [27]. An increase of oxygen ion content in the magnetotail plasma from 25% to 100% leads to an enhancement of its the relative contribution to cross-tail current from 18% to $\sim 30\%$. Similar results were

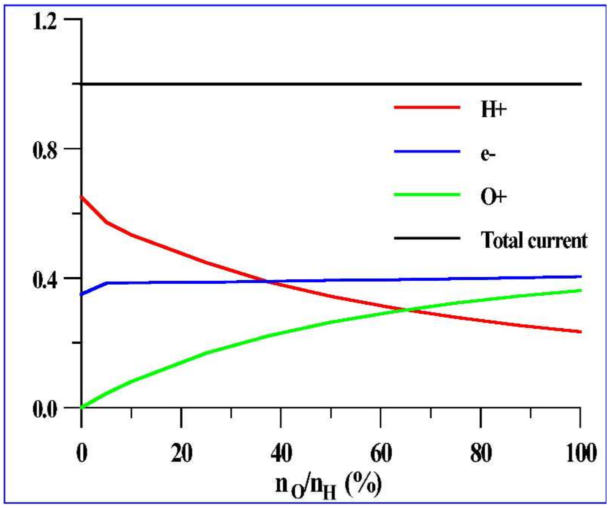

Fig. 5. The cross-tail currents carried by the different species as a function of the relative densities of the oxyen to hydrogen ions [27].

achieved if one decreases O^+ temperature in comparison with that of H^+. The oxygen current contribution, although being sensitive to O^+ temperature, still remain in the $(20-30)\%$ range.

The contributions of oxygen ions to the magnetotail current, shown in Fig. 5, can be compared with the estimates from the spacecraft observations. Estimates using CLUSTER measurements [8] yield the relative density of oxygen ions to be of the order of 15%. It should be noted that the estimate of 30% is the upper limit, and it depends strongly on the oxygen flux at the source and on the oxygen temperature. In general these results provide estimates of the same order as the observations. The main conclusion concerning the role of oxygen in the structure of thin current sheets in the Earth's magnetotail is that the current of the O^+ ions leads to an effective thickening of the total current profile and is dominant at the outer regions of the sheet.

A combination of the contributions of the oxygen ions, as shown in Fig. 4, and the earlier results of thin current sheets [24, 25], yields an interesting multilayer structure of the current sheet resembling a ”matreshka”, a popular Russian nesting doll. A very thin electron layer $L \sim 0.05-0.1\rho_i$ is embedded in a thin proton sheet with ($L \sim \rho_i$), which in turn is embedded in a thick oxygen sheet ($L \sim 7-10\rho_i$). Further, the CS as a whole is embedded inside the thicker plasma sheet, i.e., generally there are four levels of embedding (Fig. 4).

5. Bifurcated thin current sheet

The profile of the magnetotail current sheet is generally found to be peaked on the axis, in agreement with the plasma equilibrium conditions. However some observations have shown the current density to be depleted in the center [7, 14, 17] resulting into double humped profiles. Such cases are widely referred to as bifurcated current sheets and can be a consequence of the nature of particle trajectories in the vicinity of the center of the current sheet. A simplified picture of the particle trajectory corresponding to the Harris sheet is shown in Fig. 6 to illustrate this. The particles with meandering or Speiser orbits can carry a current which is opposed to that carried by the bulk of the plasma away from the center. The population of such particles can increase due to the unavoidable quasi-adiabatic scattering of transient particles near the neutral plane due to the jumps in their adiabtic invariants. Consequently there can be a net reduction in the current locally when the scatterings are significant, e.g., when the current sheet is highly stretched during late growth phase of substorms. The model of thin current sheets for such conditions leads to the bifurcated current profiles, as shown in Fig. 7 [26].

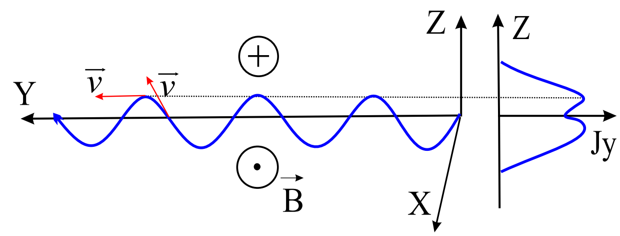

Fig. 6. The simplified particle trajectories in the case of a Harris-like current sheet. The meandering or Speiser orbit particles are confined to the central region of the current sheet and carries a current whose direction is opposite to the current carried by the particles located away from the axis. This can lead to a depletion in the current density in the center of the current sheeet, as shown by the right panel.

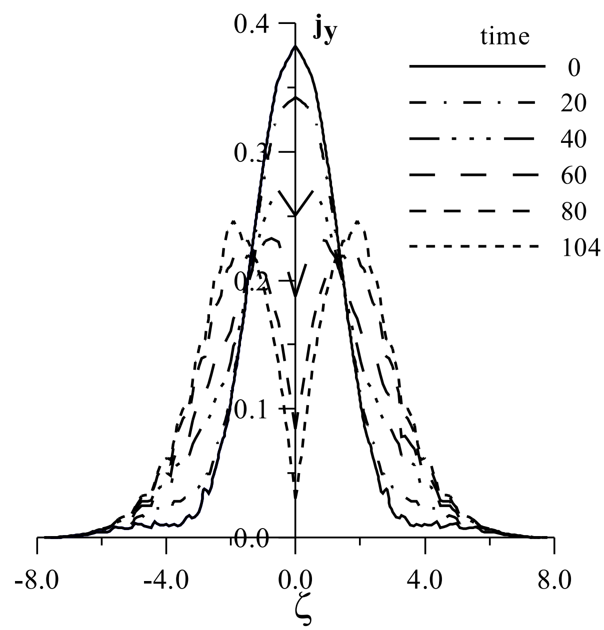

Fig. 7. The bifurcated current density inside a thin current sheet at different instants in its evolution, starting with an initial current density peaked on the axis [26].

The bifurcated current sheets can lead to further deterioration of the current sheet and ”aging” [23]. The scenario of current sheet evolution that emerges from these considerations is that the initially peaked current profile leads to a bifurcated profile due to an increase in the quasi-adiabatic scattering during the growth phase of substorms. As the magnetotail is driven further and becomes more stretched the scattering increases till the current sheet disrupts [23]. The GEOTAIL observation of bifurcated current sheets has been associated with the electron dynamics during magnetic reconnection [7]. It should be noted that CLUSTER observations associate the bifurcated current sheet with finite B_z and thus may not be associated with magnetic reconnection. This implies that the bifurcated current sheets observed by CLUSTER are more likely a feature of the quiet time or stable magnetotail, rather than those associated with reconnection during the expansion phase of substorms. The model of the bifurcated current sheet developed from the plasma equilibrium, presented above, is in agreement with the observations in this aspect also.

6. Multiscale phenomena in the magnetosphere

The two features of the current sheet discussed above, viz. the multilayered structure and bifurcated profile, leads to a picture of the magnetotail in which many scales are involved. This recognition is closely tied with the multiscale characteristics of the magnetosphere [19]. The magnetospheric multiscale phenomena has three main origins, viz. the driving by the turbulent solar wind, nonlinearity and cross-scale coupling among the plasma processes. Due to the wide range of space and time scales underlying the plasma processes in the magnetosphere, the multiscale phenomena are not described by a single first principles model at present. The extensive observational data, especially the long time series data from ground-based and spacecraft-borne measurements, have been used fruitfully to model the global and multiscale phenomena of the magnetosphere [19]. These models are enabled by recent developments in the theory of nonlinear dynamics and complexity, and represent the features inherent in the data, independent of modeling assumptions. The reconstruction of the dynamics of the solar wind - magnetosphere coupling from observational data has led to models which have been used to develop reliable space weather forecasting tools.

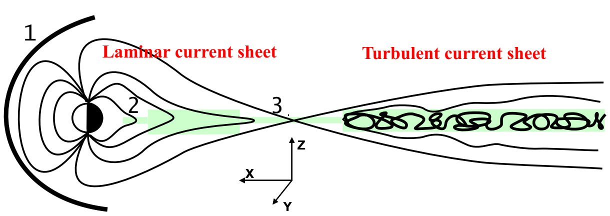

Fig. 8. The different types of current sheets in the magnetosphere. The near-Earth tail current sheet is mostly laminar, while the current sheet beyond the neutral sheet can be turbulent. The multiscale nature of the magnetosphere is influenced by the turbulent solar wind, the internal dynamics of the magnetosphere and the turbulent current sheet.

The multiscale features of the magnetosphere is often expressed in terms of power law distributions of the scale sizes. Such power law distributions have been obtained from the extensive data of auroral electrojet indices and solar wind variables. The burst life time distribution of the solar wind variables show scale-free behavior but the magnetosphere exhibits a significant deviation with preferred lifetimes of 2-5 h, showing the co-existence of global and multiscale features [5]. These results [5], [19] show that the magnetotail processes play an important role in the global as well as multiscale phenomena in the magnetosphere, as shown schematically in Fig. 8.

7. Summary

The magnetotail plays an important role in the understanding of geospace in general and the magnetosphere in particular. The global processes such as plasmoid formation and ejection are initiated in the magnetotail current sheet and thus the plasma processes span from the microphysics at kinetic scales to the macroscale physics at MHD scales though cross-scale coupling. This also points to the importance of the magnetotail in the global and multiscale phenomena in the magnetosphere.

The theory of thin current sheets based on the complicated particle trajectories in the strongly inhomogeneous magnetic field of the magnetotail has been successful in describing some of its observed features, such as its embedded structure, bifurcated profile, multilayered nature, etc. It should however be noted that in order to understand the dynamical behavior of the magnetotail, such as plasmoid formation and dipolarization, it is essential to consider its multidimensional nature. For example, the well known Harris sheet is unstable to tearing instability and thus lead to island formation but these islands are stationary due to the one dimensionality of the equilibrium. An equilibrium with dependence on the Sun-Earth axis will naturally lead to the dynamics of the islands or plasmoids and dipolarization of the magnetic field [11]. Also multi-dimensional equilibria are appropriate for modeling the interaction of the magnetotail processes with the inner magnetosphere.

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