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Particle dynamics in the Earth's magnetospheric tail

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RESUMEN

En este trabajo se discute el movimiento básico de partículas eléctricas en hojas de corriente. La hoja de corriente en la cauda magnetosférica de la Tierra es sólo un ejemplo de hojas de corriente que ocurren en la naturaleza. Otros ejemplos son: la hoja de corriente heliosférica en el viento solar; hojas de corriente en ráfagas y en prominencias solares; hojas de corriente en la magnetopausa del lado día de la Tierra; la hoja de corriente del magnetodisco de Júpiter, así como las galácticas y las de los pulsares. Para el caso de un campo magnético normal B_z pequeño y casi constante, las partículas oscilan alrededor de la hoja de corriente y "viven" en ella durante la mitad de su giroperíodo alrededor de ese campo. Este tiempo de vida remplaza al tiempo medio de colisión en la expresión Lorentziana de la conductividad eléctrica y, por tanto, da lugar al concepto de conductividad inercial. El modelo de subtormenta magnetosférica de Coroniti (1985) utiliza esta conductividad inercial para permitir que la reconexión ocurra sin procesos anómalos. Dependiendo de parámetros tales como la energía de las partículas, el grueso de la hoja de corriente y la curvatura de las líneas de campo magnético es posible que las órbitas caóticas de las partículas puedan, en ocasiones, ser importantes para su dinámica. Un modelo de hoja de corriente con una línea neutra predice una estructura tipo cresta y asimetrías en la función de distribución. Algunas observaciones recientes de distribuciones de iones obtenidas con los satélites ISEE y AMPTE son congruentes con las predicciones del modelo. Se mencionarán algunos problemas restantes.

PALABRAS CLAVE: Magnetosfera, partículas cargadas, hoja de corriente, subtormentas, caos.

ABSTRACT

In this paper, we will review basic particle motion in current sheets. The current sheet in the Earth's magnetospheric tail is but one example of naturally occurring current sheets. Other examples include: the heliospheric current sheet in the solar wind; solar flare and prominence ejection current sheets; the Earth's dayside magnetopause current sheet; Jupiter's magnetodisk; pulsar and galactic current sheets. For small, nearly constant normal magnetic field, B_z, particles oscillate about the current sheet and "live" within the sheet for one-half gyroperiod about B_z. This lifetime replaces the mean collision time in the Lorentzian electric conductivity expression, and thus gives rise to the concept of an inertial conductivity. A terrestrial magnetospheric substorm model by Coroniti (1985) utilizes this inertial conductivity to allow reconnection to proceed without anomalous processes. Chaotic particle orbits may, at times, be important to the dynamics, depending on parameters such as particle energy, current sheet thickness, and field line curvature. A current sheet model with a neutral line predicts a ridge structure and asymmetries in the distribution function. Some recent observations of ion distributions from the ISEE and AMPTE satellites are consistent with predictions of the model. Some remaining problems will be outlined.

KEY WORDS: Magnetosphere, charged particles, current sheet, substorms, chaos.

1. INTRODUCTION

Current sheets appear to be ubiquitous in the universe. Radio galaxies, pulsars, solar flares, the solar wind, and planetary magnetodisks all show the signatures of stretched out magnetic fields, i.e. current sheets. The basic problem of solar-terrestrial research is to understand how particles and fields from the sun couple to and interact with plasma and fields in the geospace environment. Three regions in the magnetosphere appear to play crucial roles in this interaction: the magnetopause; the magnetotail plasma sheet; and the auroral region (Figure 1). Excellent reviews of solar wind interaction with the magnetosphere are given by Haerendel and Paschmann (1982) and Alexander *et al.* (1984).

The magnetopause and its associated boundary layers is a key region where mass, momentum and energy are transferred from the solar wind to the magnetosphere. This transfer is dominantly controlled by reconnection when the interplanetary magnetic field (IMF) is southward, as originally suggested by Dungey (1961).

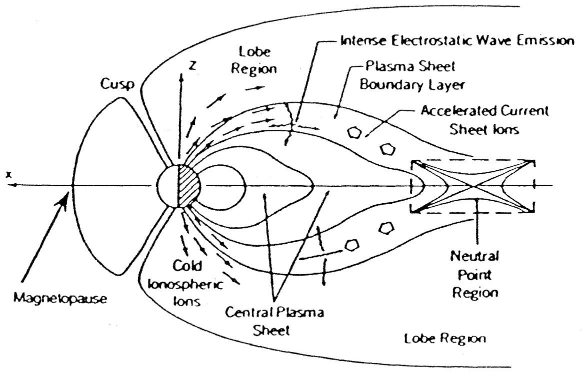

Fig. 1. Critical regions of the magnetosphere.

A magnetospheric substorm is an event during which magnetospheric plasma, particles and fields change dramatically (e.g. Galeev, 1982; Baker *et al.*, 1984). The magnetotail, including the plasma sheet and its boundary layer, plays a major role in energy storage and particle acceleration during substorms. Particle energization by magnetic reconnection (Dungey, 1961), which takes place near a neutral point is the basis of many models of magnetospheric substorms, yet the fundamental physics of this process is still not well understood. For recent reviews on reconnection, see Galeev (1982), Sonnerup *et al.* (1984) and Honès (1984).

In Figure 2, the topology for tail reconnection is illustrated. A diffusion region will exist around an x-type neutral point. A region with nearly constant normal field (B_z) within the current sheet may sometimes exist adjacent to the diffusion region. During reconnection, $\mathbf{E} = E_y e_y$ should exist across the tail in the dawn-dusk direction. This electric field can accelerate particles in the current sheet and is a measure of the reconnection rate in the tail. $E_y(t)$ probably grows explosively around substorm onset, and may be roughly constant when reconnection saturates (Coroniti, 1985).

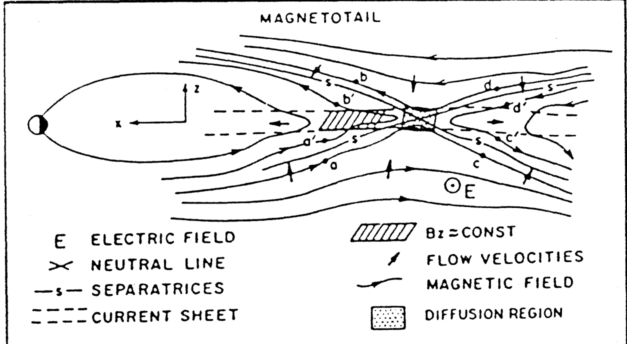

Fig. 2. Field topology in the magnetotail. Diffusion region highlighted around a neutral line. During reconnection, $a \rightarrow a'$.

The magnetohydrodynamic (MHD) approximation breaks down in the diffusion region where small scale phenomena and nonadiabatic motion become important. In order to provide the diffusion of the magnetic field, the resistivity needs to be large in the diffusion region (if the resistivity were zero, or conductivity infinite, the electric field is shorted out and reconnection would not occur). However, we will see (section 5) that finite resistivity need not imply particle-particle or particle-wave interactions. Because reconnection at the dayside magnetopause and in the magnetotail occur in regions which are essentially collisionless, a collisionless resistivity is required. A search for that resistivity involves either of two approaches, 1) an approach based on particle dynamics, or 2) one based on turbulence via noise (plasma waves).

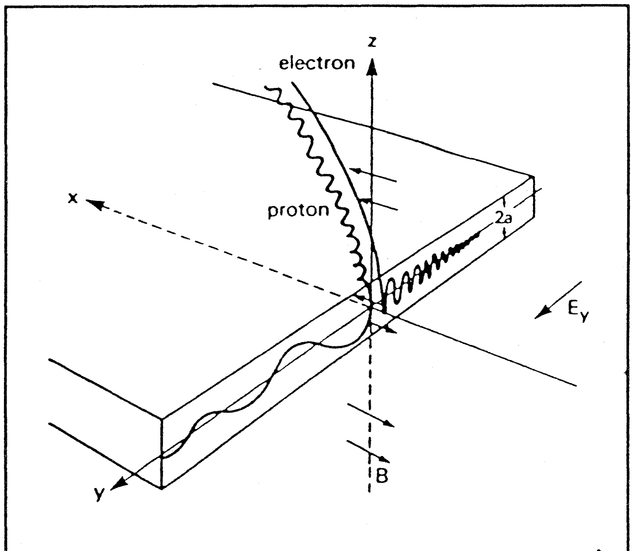

Fig. 3. Strictly "neutral" sheet, with constant B_0, and $E = E\hat{e}_y$.

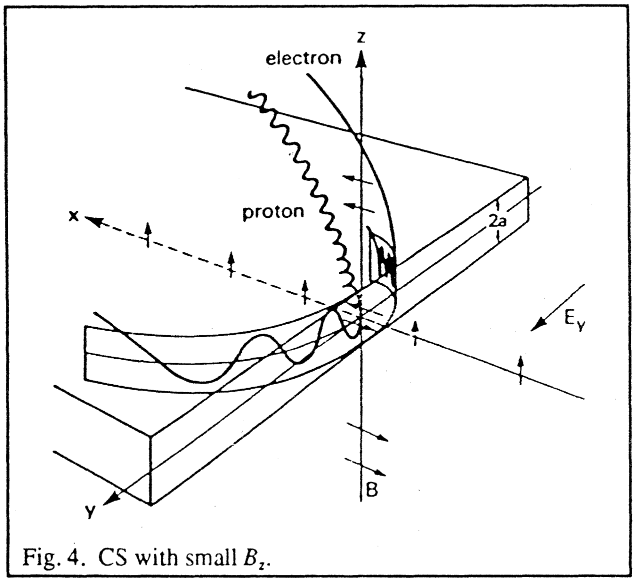

Fig. 4. CS with small B_z.

Plasma wave turbulence has been found to be associated with streaming particles and field aligned currents in boundary layers of the plasma sheet (Gurnett *et al.*, 1976), the so-called plasma sheet boundary layers (PSBL). However, such turbulence is either in the wrong place (PSBL), or of the wrong magnitude to be responsible for the resistivity required for reconnection. As pointed out by LaBelle and Treumann (1988), the observed plasma wave amplitudes near the magnetopause resulted in diffusion coefficients which were always too small to explain reconnection. A similar result was found by Anderson (1984) in the magnetotail, where wave intensities at the center of the current sheet decreased dramatically from the PSBL, making it difficult for turbulence to produce the required resistivity. In addition, Haerendel (1987) has noted that not once in eight AMPTE releases of heavy ions, has there been any evidence of anomalous resistivity processes (essentially, locally induced plasma wave turbulence), as diagnosed by *in situ* waves. These releases were in the solar wind, magnetosheath and magnetotail. Therefore, because of the problems with anomalous resistivity, we will concentrate on the dynamics of single particles in the current sheet (CS) and near neutral lines, to provide a dynamic collisionless resistivity. For a review of particle, field and plasma observations and theories of the geomagnetic tail, see Speiser (1991).

2. CURRENT SHEET MOTION

Figures 3 and 4, respectively, illustrate charged particle motion in a strictly neutral sheet, and in a current sheet with a small, approximately constant, B_z (Speiser, 1965, 1967, 1968, 1991).

When $0 < B_z \ll B_0$ (where B_0 is the tail field outside the current sheet), the motion is a simple combination of a fast oscillation about the current sheet and a slower gyromotion about B_z, until the particle is ejected from the current sheet. This ejection is caused by a change in sign of the Lorentz force z-component (see section 3).

3. CURRENT SHEETS AND CHAOS

The two fundamental motions of a charged particle in a current sheet can be described by the equations of two coupled one-dimensional oscillators. A nonlinear z-oscillation normal to the current sheet (ω_z) and a gyromotion about $B_z(\Omega_n)$. When the frequencies of the two oscillators ω_z and Ω_n become commensurate, the particle motion is chaotic.

In the study of deterministic nonlinear dynamical systems, we often encounter chaotic behavior. Chaotic behavior arises from extreme sensitivity to initial conditions, or equivalently, from the exponential divergence of nearby orbits in certain domains of phase space. Chaotic dynamics implies stochastic behavior, at least over long times, and leads to diffusion in phase space from which irreversible behavior can arise.

To investigate particle motion, we start with the Lorentz force equation:

$$m\mathbf{a} = q(\mathbf{E} + (\mathbf{v} \times \mathbf{B})) \qquad (1)$$

The basic field model assumes that $\mathbf{B} = B_x\hat{x} + B_z\hat{z}$, and $\mathbf{E} = E_0\hat{y}$, where

$$B_x = \begin{cases} B_0\,(z/a), & -a<z<a \\ B_0\;, & |z| > a \end{cases}$$

$$B_z = \text{constant}, \quad E_0 = \text{constant}$$

Because E_y and B_z are assumed constant, Speiser (1965) showed that E_y could be transformed away (the deHoffman-Teller frame). The force equation can then be written as

$$\begin{aligned} \ddot{x} &= C_2\dot{y} \\ \ddot{y} &= C_1 z\dot{z} - C_2\dot{x} \\ \ddot{z} &= -C_1\dot{y}z = -k(t)z \end{aligned} \qquad (2)$$

where $C_1 = qB_0/ma$, and $C_2 = qB_z/m$.

Neglecting the $C_1 z\dot{z}$ term in (2), the x and y equations imply circular motion about the z-axis with frequency $C_2 = \Omega_n$. That is, $x = -\rho_n \sin\Omega_n t$, and $y = -\rho_n \cos\Omega_n t$, where $\rho_n = v_\perp/\Omega_n$. The force in the z-direction is given by $\ddot{z} = -C_1\dot{y}z = -k(t)z = -\omega_z^2 z$. As $\dot{y} = v_\perp \sin\Omega_n t$, the z-motion is like a spring oscillator, but the spring constant, k, changes with time. If $k = C_1\dot{y}>0$, the z-motion is oscillatory (so-called "Speiser" or meandering orbit). (Thus, the $z\dot{z}$ term in (2) is bounded and may often, but not always, be neglected.) If $k = C_1\dot{y}<0$ for ions, the z-motion results in acceleration away from the $z = 0$ plane (ejection). Now, consider the ratio of fast to slow oscillation frequency;

$$\frac{(\omega_z)}{\Omega_n} = \frac{C_1^{1/2}}{C_2}\,(\dot{y}^{1/2}) = \frac{2.4}{\pi}\left(\frac{\rho_n}{a b_0}\right)^{1/2}$$

where $\rho_n = v_\perp/(qB_z/m)$, $b_0 = B_z/B_0$, and define a parameter $\kappa_\perp$,

$$\kappa_\perp \equiv \left(\frac{a b_0}{\rho_n}\right)^{1/2} = \left[\frac{\text{minimum radius of curvature of a field line in the current sheet}}{\text{particle gyroradius at the current sheet center}}\right]^{1/2}$$

In this expression, (ω_z) is the average of ω_z over the z-oscillation period. Therefore, we arrive at

$$\frac{\langle\omega_z\rangle}{\Omega_n} = \frac{2.4}{\pi}\,\frac{1}{\kappa_\perp} \qquad (3)$$

Thus, the $\kappa_\perp$ parameter controls the stochasticity of charged particle orbits and is closely related to the K parameter of Büchner and Zelenyi (1986).

For particle motion far from the current sheet we can distinguish three cases:

1. $\langle\omega_z\rangle \ll \Omega_n \qquad (\kappa_\perp \gg 1)$
   Guiding center motion is important and μ is a good adiabatic invariant.
2. $\langle\omega_z\rangle \gg \Omega_n \qquad (\kappa_\perp \ll 1)$
   Current sheet motion is important and a new current sheet invariant is defined.
3. $\langle\omega_z\rangle \approx \Omega_n \qquad (\kappa_\perp \approx 1)$
   There is no adiabatic invariant and particle motion is chaotic.

For a discussion of how the chaos parameter, $\kappa_\perp$, varies with energy, see Speiser *et al.* (1991).

4. NORMAL MOTION (z) IN A CURRENT SHEET

The z-component equation of motion is given by (see equation (2))

$$\ddot{z} + \omega_z^2 z = 0. \qquad (4)$$

For non-constant ω_z, Equation (4) is of the form of a nonlinear oscillator.

Since $\omega_z^2(t) \propto y$, we can write $\omega_z(t)/\Omega_n = (\sin\Omega_n t)^{1/2}/\kappa_\perp$. For $\kappa_\perp \ll 1$, $\omega_z/\Omega_n \gg 1$ over a large part of the interval. Equation (4) can be solved analytically over the range where $\omega_z/\Omega_n \gg 1$, using the WKB method (Schiff, 1955). The WKB solution is found by substituting $z = Ae^{i\phi(t)/\varepsilon}$ into our nonlinear oscillator equation, (4) (ε is the smallness parameter $\dot{\omega}_z/2\omega_z^2$). The result is (Speiser, 1968)

$$z(t) = [A \sin\phi(t) + B \cos\phi(t)]/(\sin\Omega_n t)^{1/4} \qquad (5)$$

where $\phi(t) = \int_0^t \omega_z(t')\,dt'$, and A and B are determined by initial conditions.

Figure 5 shows a numerically calculated orbit for a current sheet with constant B_z. This is a regime corresponding to (2), above, where $\omega_z \gg \Omega_n$ and $\kappa_\perp \ll 1$.

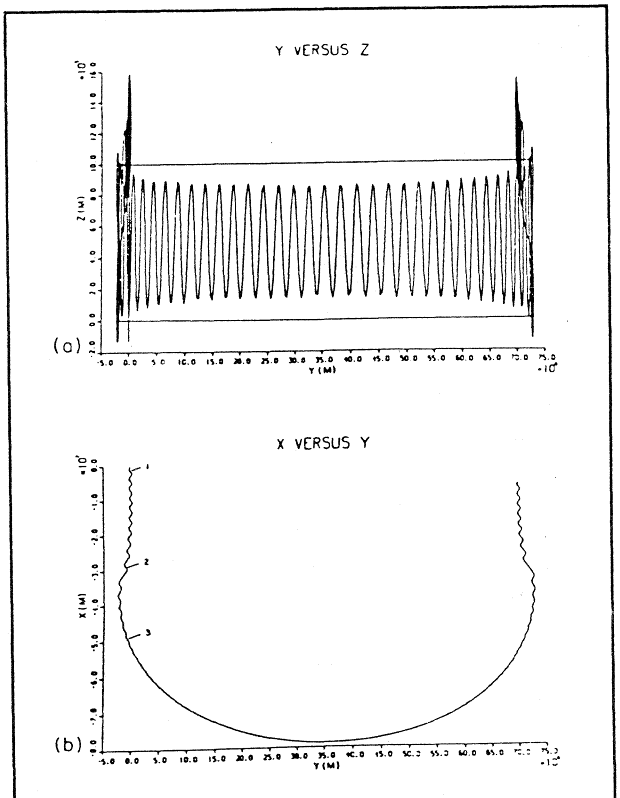

Fig. 5. Proton orbit. Model parameters: $B_xT = 20$ nT. $B_z = 1/4$ nT, $E = 0$, $D = 1000$ km, energy 5 keV, initial pitch angle 150°, final pitch angle 31.6° [Speiser and Lyons, 1984].

5. ELECTRICAL CONDUCTIVITY: INERTIAL AND CHAOTIC

From the simple current sheet motion, a particle is trapped by the field reversal and accelerated by E_y, while it executes gyromotion about the weak, constant B_z. Thus, the acceleration time, lifetime of the particle in the system, or coherence time, replaces the mean collision time in an expression for the electrical conductivity (Speiser, 1970, 1991; Lyons and Speiser, 1985).

In the transformed frame (low energy approximation), $\langle\dot{y}\rangle \approx E/B_z$ and $j = ne\langle\dot{y}\rangle$, or $j = (ne/B_z)E = \sigma_g E$. $\sigma_g = \omega_z = ne/B_z = ne^2/m\Omega_n \approx 10^{-4}$ mho/m, taking typical values $n \approx 1$ cm^{-3}, $B_z \approx 1$ nT. σ_g is thus a gyro or inertial coductivity. Coroniti (1985) utilizes this inertial property, σ_g, as the key dissipative element in his substorm model, and with it gets substorm growth time ~1 hour and explosive onset time ~minutes, in agreement with observations.

An alternate physical mechanism for a collisionless conductivity was suggested by Martin (1986): since the particle dynamics in tail-like models is chaotic, one can use the timescale for decay of velocity correlations as an analog to a collision time, resulting in a "chaotic conductivity" due to the diffusion in phase space produced by chaotic dynamics. Martin used a model with an X-type neutral line, utilizing the Lyapunov characteristic exponent, λ, as a preliminary estimate for the chaotic timescale (λ measures the timescale for exponential separation of chaotic orbits). With the same parameters as above, he obtained $\sigma_{ch} = ne^2/m\lambda \approx 10^{-4}$ mho/m, about the same as σ_g.

6. MOTION IN A CURRENT SHEET WITH NEUTRAL LINE

Martin and Speiser (1988) showed that current sheet orbits become modified with the inclusion of a neutral line, and the signature of such a neutral line is a ridge in velocity space.

In Martin and Speiser's Figure 3, the ion distribution function is modelled at the edge of the current sheet. Panels (a) to (f) show the distribution function as if a satellite were approaching a meutral line along the plasma sheet boundary layer. The model parameters are: $E_y = 1/4$ mV/m, a = 1000 km, $B_0 = 20$ nT, $B_z = 1$ nT, U_x (initial bulk flow speed) = -350 km/sec. In panel (a), the accelerated, Earthward directed, field-aligned beam is seen centered on $v_\parallel$ ~850 km/sec, which is just $2E_y/B_z + U_x$, as predicted by the analytic solutions (section 3).

As the neutral line is approached, the contours at large $v_\parallel$ start to be broken up (panel (b)), and then a ridge in velocity space appears which moves to larger pitch angles as the observing position gets close to the neutral line. In panel (f), the observing position is directly above the neutral line.

Speiser *et al.* (Figure 14, 1991) showed simulated distribution functions earthward and tailward of a model neutral line. Within the ridge, the distribution function appears asymmetric, comparing the earthward and tailward simulations. The depletion of f, along the $v_\perp = 0$ axis, is due to the assumed asymmetric initial bulk flow, U_x. That is, the particles within the ridge are not turned around by B_z, so they are initially earthward-going, and thus come from a reduced part of the assumed initial tailward flowing distribution. For the tailward simulation, the particles within the ridge are initially tailward-going, and thus come from an enhanced part of the assumed initial tailward flowing distribution. More details of these simulations, plus mappings of f throughout the current sheet, are found in the study of Speiser and Martin (1991).

Speiser *et al.* (1991) showed four consecutive 36-second ion observations from the MEPE(ISEE1) instrument (Williams *et al.*, 1978) for a plasma sheet boundary crossing, during the CDAW 6 (Coordinated Data Analysis Workshop) interval (Fritz *et al.*, 1984). These observations show qualitative agreement with our modelled ridge distributions (Martin and Speiser's Figure 3 and Speiser *et al.*'s Figure 12), in that ridge-like distributions are clearly evident, with some multiple ridge structure. We thus have some observational evidence for the ridge structures predicted by the model.

7. SUMMARY AND FUTURE PROBLEMS

Anomalous resistivity processes seem to be incapable of producing the finite resistivity required for magnetospheric reconnection processes. Particle inertia plays this role in Coroniti's (1985) substorm model. Particle chaos may, at times, be important and can also give rise to an effective resistivity. Whether chaos or inertia is dominant may depend on current sheet parameters such as sheet thickness. A tail magnetic neutral line produces a ridge structure in modelled distributions. This structure is asymmetric on the earthward and tailward sides of the neutral line. For a few 36-second ion observations near the plasma sheet boundary layer, during the CDAW 6 interval, ridge-like structure is observed and the asymmetry is consistent with a distribution tailward of the neutral line, which also agrees with the direction of the observed beam.

Some future problems:

- What physical mechanism is responsible for current diversion at times of substorms?
- What are the signatures of chaos in current sheets?
- Is chaos important for current sheets?
- What initiates current sheet instability? ....substorms? ....solar flares?
- What role does inertia (chaos)play in 3D current sheets?

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