Magnetic field topologies related to reconnections in the near-Earth magnetotail with southward IMF studied by three-dimensional electromagnetic particle code

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Short title: RECONNECTION BY A SOUTHWARD IMF
Abstract. We report three-dimensional topological magnetic field structures determined by the eigenvalues of magnetic null points (critical points) in the reconnection region near the Earth Magnetotail. The evolution of reconnection and associated particle ejections from the neighbors of null points, (critical points), with a southward IMF are important to understand the substorm onset. Recently, the timing of auroral breakup and its expansion are considered to be related to the kinetic instability, the onset of reconnection, and the associated high-speed ion flow. We have investigated the null points and the associated particle ejection near the reconnection region. We have found that the structure of null points is different from the schematic neutral line created by the reconnection which consists of a straight line from the dawn to the dusk. This comes from the fact that a kinetic (drift-kink) instability takes place prior to the reconnection. This instability creates the structure along the dawn-dusk direction and excites reconnection. Four different types of null (critical) points exist for the magnetic field with the condition, $\nabla \cdot \mathbf{B} = 0$. At the null points which have complex eigenvalues, the magnetic field has a spiral structure near the null point. Some paired null points are connected with the magnetic field lines in the sense that they are on the same separation-surfaces. The connected magnetic field lines may correspond to a part of the neutral line. However, the null points are not exactly lined up along the dawn-dusk direction. Instead null points are being created and destroyed. Due to this magnetic (electric) field, electrons (ions) are ejected from the reconnection region in a complex manner. Bursty bulk flows (BBFs) may be generated by these intermittent null points. Further investigation is necessary to understand the temporal and spatial evolution of null points and the associated phenomena better.
1. Introduction

The interaction of the solar wind with the Earth’s magnetic field gives rise to a number of important and intriguing phenomena, many of which are only partially understood. These include reconnections between the solar wind magnetic field and geomagnetic field lines at the dayside magnetopause (including flux transfer events), reconnection in the near-Earth magnetotail, and associated phenomena such as substorms. The mechanism of reconnection [e.g., Park, 1991] has been studied by MHD and particle simulations. In MHD codes (e.g., Fedder et al. [1995]) the microscopic processes can be represented by statistical (macroscopic) constants such as diffusion coefficients, anomalous resistivity, viscosity, temperature, equation of state, and the adiabatic constant. The near-Earth magnetotail is one of the regions where kinetic effects are critical and particle simulations become very important.

Recent evidence suggests that the breakup of the northern edge of the aurora is caused by energetic electrons ejected by the reconnection. The equatorial expansion of the aurora is related to the high-speed ion flow [Nagai et al., 1998]. Based on this idea, we have investigated the global simulation of the solar wind-magnetosphere interaction with time-varying interplanetary magnetic fields (IMFs) using a particle code that contains, in principle, the complete particle physics [Nishikawa 1997, 1998a,b; Nishikawa and Ohtani, 1999]. With a southward IMF due to the thinning of the plasma sheet, an increased current density excites a kinetic (drift-kink) instability [Nishikawa, 1997, 1998a, and references therein]. This instability kinks the current sheet along the dawn-dusk direction which excites reconnection [Nishikawa, 1998a].

In order to investigate the complicated evolution of the reconnection, the detailed three-dimensional topological structure of magnetic fields with null points and characteristic magnetic field lines and surfaces are plotted as shown later. Here the characteristic field line is in the direction of one eigenvector that is in a different direction towards the null point from the other two eigenvectors. The characteristic surface is spanned by the other two eigenvectors where both of them have the same direction towards the null point. The characteristic field line and surface are called γ-line and Σ-surface, respectively [Lau and Finn, 1990; Parnell et al., 1996; Cai, 1998]. Contrary to the schematic neutral line model [e.g., Fig. 8 in Baker et al. 1996], the several paired or connected null points are formed in the reconnection region which will be shown later. Note that these connected null points are usually discussed as the three-dimensional X-points [Cowley, 1973; Lau and Finn, 1990; Greene, 1988; Büchner, 1999]. The simulation method is discussed briefly in section 2. The three-dimensional topological magnetic field structures are investigated in section 3. In section 4, discussions on the topological magnetic field before and after the reconnections are described.
2. Three-Dimensional Electromagnetic Particle Simulation Model

For the simulation of solar wind-magnetosphere interactions, the following boundary conditions were used for the particles [Buneman et al., 1992, 1995; Nishikawa et al., 1995; Nishikawa, 1997, 1998a,b]: (1) Fresh particles representing the incoming solar wind (unmagnetized in our test run) are continuously injected across the $y-z$ plane at $x = x_{\text{min}}$ with a thermal velocity plus a bulk velocity in the $+x$ direction; (2) thermal solar particle flux is also injected across the sides of our rectangular computation domain; (3) escaping particles are arrested in a buffer zone, redistributed there more uniformly by making the zone conducting in order to simulate their escape out of the boundary, and finally written off. We use a simple model for the ionosphere where both electrons and ions are reflected by the Earth’s dipole magnetic field. Effects of a conducting ionospheric boundary will be developed in future simulations. The effects of the Earth’s rotation are not included.

For the fields, boundary conditions were imposed just outside these zones [Buneman et al., 1992, 1995; Nishikawa et al., 1995; Nishikawa, 1997, 1998a,b]: radiation is prevented from being reflected back inward, following Lindman’s ideas [Lindman, 1975]. The lowest order Lindman approximation was found adequate: radiation at glancing angles was no problem. However, special attention was given to conditions on the edges of the computational box.

In order to bring naturally disparate time scale and space scale closer together in this simulation of phenomena dominated by ion inertia and magnetic field interaction, the natural electron mass was raised to 1/16 of the ion mass and the velocity of light was lowered to twice the incoming solar wind velocity. This means that charge separation and kinetic phenomena are included qualitatively but perhaps not with quantitative accuracy. Likewise, radiation-related phenomena (e.g., whistler modes) are included qualitatively.

3. Simulation Results

The first test exploring the solar wind-magnetosphere interaction was run on the CRAY-YMP at NCAR using a modest 105 by 55 by 55 grid and only 200,000 electron-ion pairs [Buneman et al., 1992]. We also have reported on our second test run on the CRAY-2 at NCSA using a larger 215 by 95 by 95 grid and about 1,500,000 electron-ion pairs [Buneman et al., 1995]. Initially, these fill the entire box uniformly and drift with a velocity $v_{\text{sol}} = 0.5c$ in the $+x$ direction, representing the solar wind without an IMF. The electron and ion thermal velocities are $v_{\text{et}} = (T_e/m_e)^{1/2} = 0.2c$, and
\[ v_{it} = (T_i/m_i)^{1/2} = 0.05c (= v_s = (T_e/m_i)^{1/2}), \] respectively, while the magnetic field is initially zero. A circular-like current generating the dipole magnetic field is increased smoothly from 0 to a maximum value reached at time step 65 and kept constant at that value for the rest of the simulation. The center of the current loop is located at \((70.5\Delta, 47.5\Delta, 48\Delta)\) with the current in the \(x - y\) plane and the axis in the \(z\) direction. The initial expansion of the magnetic field cavity is found to expel a large fraction of the initial plasma. The injected solar wind density is about 0.8 electron-ion pairs per cell, the mass ratio is \(m_i/m_e = 16\), and \(\omega_{pe}\Delta t = 0.84\).

In this letter, we report the results of the magnetic field topologies near the magnetic reconnection region in the near-Earth magnetotail. At step 768 [Buneman et al., 1995; Nishikawa et al., 1995] a southward IMF \((B_z^{IMF} = -0.4)\) is switched on, and the southward IMF front reaches about \(x = 120\Delta\) at step 1280 [Nishikawa, 1997, 1998a]. The Alfvén velocity with this IMF is \(v_A/c = 0.1(\bar{n}_i)^{-1/2} = 0.1\) for the average ion density \(\bar{n}_i = 1\).

To display magnetic reconnection at the dayside magnetopause and in the magnetotail, Figure 1 shows the magnetic field lines in the noon-midnight meridian plane for four different times [Nishikawa, 1997, 1998a]. (Geocentric solar magnetospheric (GSM) coordinates are used in Figure 1.) At time step 1024, the solar wind with the southward IMF starts to interact with the dipole magnetic field at the dayside magnetopause (Figure 1a). Figure 1b shows the X-point (X-line) in two-dimension at the magnetopause (time step 1088) [Swift, 1996]. The southward IMF is bent by the magnetosphere as shown in Figure 1c (time step 1216). Figure 1c displays an interesting magnetic structure near the subsolar magnetopause. Three-dimensional analysis shows that the reconnection occurs three-dimensionally in the dayside magnetopause along the equator (e.g., Walker and Ogino [1996]). At the same time, the stretched dipole magnetic fields are observed particularly in Figure 1c. Furthermore, the magnetic fields are stretched in the magnetotail, which leads to the growth of a tearing instability. Figure 1d shows magnetic reconnection occurring at time step 1280, with the X-point (X-line) in two-dimension located near \(x = 85\Delta (\approx -15R_E)\) [Nishikawa, 1997, 1998a]. It should be noted that Figure 1 shows the two-dimensional magnetic field structure without finding null points that will be discussed later.

We have investigated null points at time steps 1216 and 1280 that correspond to Figs. 1c, and 1d, respectively. The numerical method used here is described in detail in [Cai, 1998]. The basic procedures are the followings. We explain the procedure used to investigate the magnetic field nulls with vector field \(\mathbf{v} = (u, v, w)^t\) instead of \(\mathbf{B} = (B_x, B_y, B_z)^t\). Since that analog with \(\mathbf{x}(t), \mathbf{v}(t)\), particle motion makes the physics clearer [Horton and Ichikawa, 1996]. The issue of the electron and ion orbits through
these reconnection will be complicated. However, we note that lower energy electrons will follow the field line closely except in a small sphere about the null points. We first Taylor-expand the magnetic field vector $\mathbf{v}(x, y, z)^T$ around the null point $\mathbf{x} = (x_0, y_0, z_0)^T$ to the first order:

$$
\mathbf{v} = \frac{d\mathbf{x}}{dt} = \begin{pmatrix}
  u(x_0, y_0, z_0) \\
  v(x_0, y_0, z_0) \\
  w(x_0, y_0, z_0)
\end{pmatrix} + \begin{pmatrix}
  \frac{\partial u}{\partial x} & \frac{\partial u}{\partial y} & \frac{\partial u}{\partial z} \\
  \frac{\partial v}{\partial x} & \frac{\partial v}{\partial y} & \frac{\partial v}{\partial z} \\
  \frac{\partial w}{\partial x} & \frac{\partial w}{\partial y} & \frac{\partial w}{\partial z}
\end{pmatrix} \begin{pmatrix}
  x - x_0 \\
  y - y_0 \\
  z - z_0
\end{pmatrix}
$$

(1)

Here at the null point

$$
\begin{pmatrix}
  u(x_0, y_0, z_0) \\
  v(x_0, y_0, z_0) \\
  w(x_0, y_0, z_0)
\end{pmatrix} = \begin{pmatrix}
  0 \\
  0 \\
  0
\end{pmatrix}
$$

and

$$
\mathbf{J} = \begin{pmatrix}
  \frac{\partial u}{\partial x} & \frac{\partial u}{\partial y} & \frac{\partial u}{\partial z} \\
  \frac{\partial v}{\partial x} & \frac{\partial v}{\partial y} & \frac{\partial v}{\partial z} \\
  \frac{\partial w}{\partial x} & \frac{\partial w}{\partial y} & \frac{\partial w}{\partial z}
\end{pmatrix}, \quad \mathbf{x} = \begin{pmatrix}
  u(x_0, y_0, z_0) \\
  v(x_0, y_0, z_0) \\
  w(x_0, y_0, z_0)
\end{pmatrix}.
$$

Thus one gets the linearized form of the magnetic vector field:

$$
\frac{d\mathbf{x}}{dt} = \mathbf{J}\mathbf{x}.
$$

Here to the first order approximation, a null point can be classified according to the eigenvalues of the Jacobian matrix $\mathbf{J}$ of the vector $\mathbf{v}$ with respect to the null point $\mathbf{x}$:

$$
\frac{\partial (u, v, w)}{\partial (x, y, z)} \bigg|_{(x_0, y_0, z_0)} = \begin{pmatrix}
  \frac{\partial u}{\partial x} & \frac{\partial u}{\partial y} & \frac{\partial u}{\partial z} \\
  \frac{\partial v}{\partial x} & \frac{\partial v}{\partial y} & \frac{\partial v}{\partial z} \\
  \frac{\partial w}{\partial x} & \frac{\partial w}{\partial y} & \frac{\partial w}{\partial z}
\end{pmatrix} \bigg|_{(x_0, y_0, z_0)}.
$$

(2)

Depending on the eigenvalues, the null (critical) points can be classified as an attracting node, a repelling node, an attracting focus (with imaginary eigenvalues), a repelling focus (with imaginary eigenvalues), or saddles [Parnell et al., 1996; Cai, 1998]. In the magnetic field case, the solenoidal condition $\nabla \cdot \mathbf{B} = 0$ must be satisfied, although in the simulation this is not exactly true due to the features of the liner interpolation in the TRISTAN code. However, $\nabla \cdot \mathbf{B}$ should be almost zero in the whole course of simulation runs. The three eigenvalues of the null point $\lambda_1, \lambda_2,$ and $\lambda_3$ should have the condition $\lambda_1 + \lambda_2 + \lambda_3 = 0$. Therefore, one sign of the real part of one eigenvalue is always different from
the other two. We define these cases as the saddle points. The null points are thus always classified as saddles. If the real parts of two eigenvalues are negative, and the other is positive, we call the null point “A-type.” If the real parts of two eigenvalues are positive, and the other is negative, we call the null point “B-type” [Lau and Finn, 1990]. The two eigenvectors whose signs of the real part of eigenvalues are the same, span a characteristic surface so-called the separation-surface or Σ-surface. The third eigenvector, hence whose real part of eigenvalue has the different sign of the other two, determines the detached or attached γ-line to the Σ-surface on the null point (critical point), which will be shown later. If two of the eigenvalues are not real and conjugate complex pairs, we call them Λs-type and Λs-type, respectively. The subscript “s” denotes “spiral,” and now the magnetic fields near the null points behave like vortex spirals.

In [Arnold, 1973; Guckenheimer and Holmes, 1986], Hartman–Grobman theorem and stable manifold theorem for a fixed point state that a necessary and sufficient condition for topological equivalence of two linear systems, all of whose eigenvalues have nonzero real parts, is that the number of eigenvalues with negative (and hence positive) real parts be the same in both systems. Based on this theorem, in our three-dimensional magnetic field case, if the eigenvalues of null points are not degenerated and once the null points are classified according to their eigenvalues, the topology of the three-dimensional magnetic field is uniquely determined [Cai, 1998]. The A- (A-) and B- (B-)types null points are always paired and form the three-dimensional X-points following the theory of topology [Büchner, 1999]. Based on this method, we have investigated all null points or the three-dimensional X-points in the near-Earth magnetotail region at two different time steps. The topological differences of the magnetic field are investigated for the two cases before and after the reconnection as will be described later.

At time step 1216 (Fig. 1 (c)), we found four null points near the duskside in the near-Earth magnetotail. The intermittent reconnections started to take place at this time. On the contrary, the reconnection is fully taking place at time step 1280 (Fig. 1 (d)) and the eight null points are shown in Plate 1 with a γ-line and four curves in the direction of the paired eigenvectors on the Σ surface for each null point. All the lines and curves are, respectively, started or terminated from or in the null points in the direction of the eigenvectors of the null points. The locations of these null points are at 

$$\begin{align*}
(1)(-12.4, 7.6, -0.3), (2)(-13.9, -2.7, -0.4), (3)(-14.1, -3.3, -0.3), (4)(-19.4, -5.5, -0.7), \\
(5)(-14.4, -7.3, -0.4), (6)(-15.4, -7.2, -0.3), (7)(-13.4, 7.3, 0.0), (8)(-14.4, -5.6, 0.0).
\end{align*}$$

(The GSM coordinates are used and the unit $R_E \approx \Delta$ is eliminated.) As expected, the z coordinate is nearly 0, since the total magnetic field becomes minimum at $z = 0$. At this time null points are dominantly
located in the dawnside \((y < 0)\). Among them, \((6)\) and \((5)\), \((8)\) and \((5)\), \((8)\) and \((6)\), and \((7)\) and \((1)\) are connected on the separation-surfaces or \(\Sigma\)-surfaces and form the three-dimensional X-points as will be shown in Plate 2 in a simplified way. The null points \((4)\) and \((6)\) have the \(\gamma\)-lines that are not connected to the Earth dipole magnetic field, but connect to the interplanetary magnetic field. The \(\gamma\)-lines of other null points are all connected to the Earth dipole magnetic field. Here the \(\Sigma\) surface is determined by the eigenvectors of the null points, whose real parts of the eigenvalues have the same sign. On the \(\Sigma\)-surface, we found four spiral types with conjugate complex eigenvalues, i. e. \(A_s\) or \(B_s\)-types, ((4), (6), (7), and (8)), and four expanding or repelling types with real eigenvalues, i. e. \(A\) and \(B\)-type ((1), (2), (4), and (5)). Based on these null points, the reconnection is considered as a transient and local phenomenon [Chang, 1998, 1999a,b; Büchner, 1999]. This view is also consistent with the fact that the instability along the \(y\) direction causes the reconnection [Nishikawa, 1997, 1998a]. The instability deforms the simple tail-like magnetic field and leads to the local reconnection with the complicated magnetic field near the null points that will be discussed later.

Among the null points, \((6)\) and \((5)\), \((8)\) and \((5)\), \((8)\) and \((6)\), and \((7)\) and \((1)\) are connected as shown in Plate 2. These paired or connected sets of null points form three-dimensional X-points, respectively [Lau and Finn, 1990; Büchner, 1999]. This connected curve may correspond to the so called “neutral line.” The connected curve is on the \(\Sigma\)-surface that is spanned by two eigenvectors in the vicinity of the null points, and the connected curves are considered to have no third component of the eigenvectors of the null point. Note that the third component of the eigenvector determines the \(\gamma\)-line of the null point. However, the length of this connected curve is short and localized in the region we investigated. It should be noted that the connected curves are not straight and the connected null points are not lined up along the dawn-dusk lines. Therefore, one need to pay attention to the conventional view of the neutral line due to the reconnection. In addition, the null points are connected from \((5)\) to \((6)\), from \((5)\) to \((8)\), and from \((6)\) to \((8)\). Thus null points form a triangle connection and construct complicated three X-points. This structure is topologically complex and differs from the typical X-points discussed in [Lau and Finn, 1990]. This topological structure of magnetic field reconnection may come from the microscopic processes that are responsive to the kinetic instability prior to the reconnection [Nishikawa, 1998a].

As shown in Plate 3, the ten magnetic fields on the \(\Sigma\) surface for each null point are whirled around the null points \((4)\), \((6)\), and \((8)\). Certainly, the \(B_y\) and \(B_z\) components are strongly involved with the reconnection [Nishikawa, 1998a]. Since in the vicinity of the null points, the \(B_{y,z}\) components are very weak prior to the instability, these components generated by the instability modify the magnetic field
structure near the null points as shown in Plate 3. It is natural to infer that the particles (in particular, electrons) respond to these complex magnetic fields.

To illustrate particle response to the complicated magnetic structure near the null points at time step 1280, the electron fluxes are plotted in the dawn-dusk cross section at the four different $x$ values in Plate 4 ($x = (a) -8R_E, (b) -10R_E, (c) -12R_E, \text{ and } (d) -14R_E$). The $x$ coordinate of the null points ranges from $-12.4R_E$ to $-19.4R_E$. If the reconnection takes place at the certain $x$ as previously considered, the direction of electron fluxes should be clearly reversed by the neutral line. However, as shown in Plate 4, the $x$ component of electron flux (in color) is mixed even though the earthward flux (blue) is more dominant and more intensive near the Earth. Moreover, the $y, z$ components of electron fluxes in the plasma sheet (shown by arrows) are also affected by the magnetic field near the null points [Büchner, 1999]. In Plate 4d in the near reconnection region the earthward electron flux (blue) is localized and the dawnward electron flux is disturbed by the magnetic field near the reconnection. The synergistic effects of the remnants (nonlinear stage) of the drift-kink instability and the null points are responsible for this magnetic topology and localized earthward fluxes. The recent statistical study shows that the plasma-sheet flow appears to be strongly ‘turbulent’ (i.e. the flow is dominated by fluctuations that are unpredictable, with rms velocities fields) [Borovsky et al., 1997]. The turbulent magnetic fields have also been observed with the cross-field current instability in the near-Earth magnetotail [Lui et al., 1988]. Furthermore, we suspect that null points are constantly being created and destroyed, which is consistent with the localized and sporadic nature of the reconnection signatures [Chang, 1998, 1999a,b; Büchner, 1999]. This idea is supported by the remote observations of the properties of energetic particles accelerated in the course of short “reconnection pulses” [Zelenyi et al., 1998]. We will investigate detailed temporal and spatial evolution of null points and its relationship with BBFs in the near future.

4. Discussion

The results presented here show that the complex topological magnetic structure at the reconnection comes from the microscale phenomena. This result leads to a new view on the reconnection; instead of a continuous neutral line, null points are created and destroyed temporally and spatially [Chang, 1998, 1999a,b; Büchner, 1999]. Some of null points are connected, which may correspond to the neutral line. The finely structured magnetic field is created by the kinetic (drift-kink) instability that kinks the sheet current along the dawn-dusk direction [Nishikawa, 1997, 1998a]. This study confirms that the kinetic processes are essential in the magnetotail and the flux generated at the reconnection region
can be investigated by particle simulations. Furthermore, bursty bulk flows (BBFs) may be generated by intermittent reconnections [Angelopoulos et al., 1994]. Recently, the localized earthward ion flow generated by the reconnection has been observed by the three GOES 7, 8, and 9 in the premidnight and postmidnight sectors [Ohtani et al., 1999].

Recently, the auroral breakup is considered to be caused by energetic electrons ejected from the reconnection region [e.g., Nagai et al., 1998]. Therefore, it is important in order to investigate the time and location of the break of the reconnection. The evolution of the kinetic instability prior to the reconnection is also equally important to investigate the current disruption model and the excitement of the reconnection [Nishikawa and Ohtani, 1999]. These new results show the need for reconsidering the test particle simulation [e.g., Horton and Ichikawa, 1996] in the reconnecting geotail with the A- and B- field null characteristic composed with earlier neutral line test particle simulations [Doxas et al., 1990; Doxas et al., 1994].

The numerical method used here to find null points is described in [Cai, 1998] in great detail. As described previously, this method is important not only mathematically but also physically to better understand the reconnection and the associated phenomena. Further investigation on the temporal and spatial evolution of null points will be reported at a later date.

Acknowledgements. Author (K.-I. N.) thanks Dr. Y. Ikebe for making it possible to visit Tsukuba University to complete this research (Kaken-hi). The authors thank Dr. Wendell Horton for the useful discussions. Support for this work was provided by NSF grants ATM-9730230 and ATM-9870072. The development of the simulation code was performed at the National Center for Supercomputing Applications, University of Illinois at Urbana-Champaign and the production runs were performed at Pittsburgh Supercomputing Center. The analyses of simulation results were performed at the National Partnership for Advanced Computing Infrastructure (NPACI). All centers are supported by the National Science Foundation.
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Received
**Figure 1.** Magnetic field lines in the $x - z$ plane containing the dipole center at step (a) 1024, (b) 1088, (c) 1216, and (d) 1280. The magnetic field lines are traced from near the Earth ($r = 3\Delta (\approx 3R_E)$) and subsolar line in the dayside and the magnetotail. Some magnetic field lines are moved toward dawn or duskward. The tracing was terminated due to the preset number of points or the minimum strength of total magnetic field.

**Plate 1.** The $\gamma$-lines and a few lines on the $\Sigma$ surface are plotted. The origin of the coordinate is located on the null point (6).

**Plate 2.** The null points (5), (6), and (8) are connected. The arrows show the direction of the curves. The origin of the coordinate is located on the null point (6).

**Plate 3.** Ten curves are plotted on the $\Sigma$ surface for the null points (2), (3), (4), (5), (6), and (8). The spiral are found for (4), (6), and (8). The origin of the coordinate is located on the null point (5).

**Plate 4.** Dawn-dusk cross-sectional slices show the complex electron flux structure (color: $x$ component, arrows: $y, z$ components) due to the instability and reconnection (at time step 1280), at $x = (a) 78(\approx -8R_E)$, (b) 80(\approx -10R_E), (c) 82(\approx -12R_E), and (d) 84(\approx -14R_E). The substorm line is located at $y = 47, z = 48$. 