Reconnection of Magnetic Field Lines by Clouds-in-Cells Plasma Model

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A plasma computer experiment by the clouds-in-cells method is presented for the study of the evolutionary process of the reconnection of magnetic field lines, where initially there is a plane current sheet, i.e. antiparallel magnetic field lines. A plasma flow from outside toward the magnetic neutral sheet will cause the reconnection. The model is two-dimensional and positive and negative charges have the same mass. It is shown that rapid reconnection can easily take place, though the solution is obtained only for the vicinity of the resulting magnetic neutral point. The diffusion rate of the magnetic field at the neutral point is self-adjustable to a given reconnection rate, so that the reconnection rate can take any value up to the local Alfvén velocity immediately outside the field reversal region.

1. Introduction

The reconnection of magnetic field lines that occurs at the magnetic neutral sheet has been regarded as a basic process in the theories of astrophysical and geophysical phenomena. Figure 1 shows the schematic magnetic field and plasma flow patterns with a magnetic neutral point in its center. Stored magnetic energy is here converted into plasma energy and may cause solar flares and aurora flares.

After the first proposal by Dungey (1953), a number of theoretical models have been presented by Parker (1963), Petschek (1964), Sonnerup (1970), Yeh and Axford (1970), etc., based on stationary MHD (magnetohydrodynamic) solutions. These are critically reviewed by Vasyliunas (1975). The problem is usually divided into the external flow region (where the magnetic field is frozen in the fluid and transported by convection) and the field reversal region (the boundary layer in Petschek's terminology) made up of the standing MHD slow mode compressional waves. The latter consists of the diffusion region (vicinity of the neutral point where diffusion is dominant) and the wave region (where wave propagation becomes dominant and faster than diffusion). The recon-
connection rate (the rate of merging of the magnetic field, measured by the speed of transportation of them toward the vicinity of the neutral point) should be large enough to account for the flares.

We present here a plasma computer experiment by the CIC (clouds-in-cells) method to study the evolutionary process of the reconnection, starting with a plane current sheet, i.e. antiparallel magnetic field lines. A plasma flow from outside toward the magnetic neutral sheet, which has a locally enhanced velocity profile, will cause the reconnection. We solve the equations of motion of charged particles together with Maxwell’s equations consistently under such initial and boundary conditions.

The model is two-dimensional in the sense that there is no magnetic field in the z-direction and every quantity depends on x and y but not on z. Electric current flows only in the z-direction. The plasma is represented by a set of charged rods infinitely long in the z-direction. Therefore, finite electric conductivity necessary for the reconnection at the neutral point is determined by the inertia of charged particles but not by their inter-collisions.

In view of numerical instability, a solution is obtained only for the vicinity of the magnetic neutral point, which will be shown to agree with the field reversal region of the stationary MHD solution by Vasyliunas. This numerical limitation is serious and regrettable, since one of the most interesting but difficult aspects of the problem is the nonlinear interactions between the vicinity of the neutral point and the surrounding regions. However, it is shown that rapid reconnection can easily take place in a collisionless plasma where electric conductivity is determined by the inertia of charged particles. The diffusion rate of the magnetic field at the neutral point is self-adjustable to a given reconnection rate at the boundary, so that the reconnection rate can take any value up to the local Alfvén speed immediately outside the field reversal region.
2. Governing Equations

The governing equations are the equations of motion of charged particles together with Maxwell's equations:

\[
\frac{d^2r}{dt^2} = \frac{q}{m} (E + v \times B),
\]

\[
B = \nabla \times A,
\]

\[
E = -\nabla P - \frac{\partial A}{\partial t},
\]

\[
\nabla^2 A = -\mu_0 J,
\]

\[
\nabla^2 P = -\rho_s / \varepsilon_0,
\]

\[
J = \sum_s \int q_s f_s(r, v, t) dv,
\]

\[
\rho_e = \sum_s \int q_s f_s(r, v, t) dv.
\]

Here \( m, q, r \) and \( v \) are the mass, electric charge, position and velocity of a particle, respectively. Magnetic potential \( A \) and electric potential \( P \) are introduced to compute the magnetic field \( B \) and the electric field \( E \). \( J, \rho_e, \mu_0 \) and \( \varepsilon_0 \) are the electric current density, charge density, vacuum permeability and dielectric constant, respectively. \( f(r, v, t) \) is the velocity distribution function. The subscript \( s \) denotes the species of particles, \( s=i \) for ion and \( s=e \) for electron, and \( \sum_s \) denotes the sum of both species. The relevant velocities should be much smaller than the velocity of light.

We make a simplifying assumption that the phenomenon studied here is two-dimensional; namely, there is no magnetic field in the \( z \)-direction and every quantity depends only on \( x \) and \( y \) but not on \( z \). Electric current flows only in the \( z \)-direction. A plasma is represented by a set of charged lines infinitely long in the \( z \)-direction. Then the model becomes boundless in the \( z \)-direction and we see an arbitrary section parallel to the \( x \times y \) plane. The relevant vector components are

\[
r = (x, y, z),
\]

\[
v = (v_x, v_y, v_z),
\]

\[
B = (B_x, B_y, 0),
\]

\[
E = (E_x, E_y, E_z),
\]

\[
A = (0, 0, A_z),
\]

\[
J = (0, 0, J_z).
\]
The position \( z \) is not considered. Electric field components \( E_x \) and \( E_y \) are static, and \( E_z \) is induced by the reconnection.

Finite electric conductivity is necessary for the reconnection of the magnetic field at the neutral point. The two-dimensional model adopted here excludes, in the direction of the electric current, both inter-collisions of charged particles and wave-particle interactions which usually cause the conductivity to remain finite. Therefore, the effective conductivity must be determined by the inertia of charged particles. That is, as suggested by Speiser (1970), the flight time of particles in the diffusion region, where they can be accelerated free from the strong magnetic field, plays the role of an inter-collision time in the expression of the electric conductivity.

3. Computer Experiment

3.1 CIC method

The \( L_x \times L_y \) region of the problem is covered by the Eulerian mesh lines with the intervals of \( dx \) and \( dy \) (see Fig. 2). Each field quantity is defined at the mesh points, i.e. intersections of mesh lines. The \( dx \times dy \) area with a mesh point at its center is called a cell. The plasma is represented by a set of rectangular, positively and negatively charged clouds (charged rods in this case), each with the same extent as the cell size. These clouds are always far fewer in number than the real particles. Each cloud moves according to the same equations of motion as a real particle, but is assigned the charge of an appropriately

![Fig. 2. Configuration for the computer experiment and the initial state. Symmetry condition on both the \( x \) and \( y \) axes is assumed. Arrows with a cosine envelope show the velocity profile of the plasma injection, which sets up the reconnection.](image-url)
large number of real particles for the purpose of computing the field quantities.

First, the initial positions and velocities of the clouds are given in such a way that they satisfy an equilibrium solution of the Vlasov equation. Then the following procedures are repeated.

1) The electric current and charge densities are obtained from the positions and velocities of the clouds at the current time.

2) The electromagnetic field is obtained by solving Maxwell's equations under the suitable boundary conditions.

3) The positions and velocities of the clouds at the next time step are obtained by a finite difference scheme, using the electromagnetic field at the positions of the clouds themselves.

A complete simulation is, of course, impossible. The plasma must be represented by a set of simulation particles, which are far fewer in number and assigned an appropriately larger amount of charge than the real particles. This results in increasing the fluctuations of the densities and the particle noise called shot noise. The finite-size effect of the spatial and temporal grids also results in increasing the noise called grid noise. The cloud, i.e. the finite-size particle, is used, as suggested by Birksall and Fuss (1969), to reduce these non-physical noises. Finite-size particle physics has been precisely studied, and reviewed critically by, for example, Birksall et al. (1970). To reduce the non-physical noises without significant modification of the plasma properties, the following conditions should be satisfied.

1) cloud density; $N_{el} \gg 1$, where $N_{el}$ is the number of clouds per cloud volume, i.e., they should overlap many times.

2) cloud radius; large enough to mask unwanted interactions at short range and small enough to allow the interactions sought at long range.

3) cloud radius to spatial grid size; $2R \geq \Delta x$.

4) spatial grid size; $\Delta x \ll \lambda_p$, where $\lambda_p$ is the Debye length.

5) temporal grid size; $\Delta t \ll$ the relevant periods.

In this computer experiment, as shown later, we used (1) $N_{el} \approx 3$, (2) $R \approx \lambda_p/3$, (3) $2R \approx \Delta x$, (4) $\Delta x = \lambda_p/1.5$ and (5) $\Delta t = T_{pe}/40 = T_{gé}/400$, where $T_{pe}$ and $T_{gé}$ are the electron plasma and gyration periods, respectively.

3.2 Initial conditions

We start with a one-dimensional sheet pinch type equilibrium solution by HoH (1966), that consists of a sheet current flowing along the $z$ axis and the antiparallel magnetic field directed along the $y$ axis.

$$f_s(x, v) = \left(\frac{m_s}{2\pi kT_s}\right)^{3/2} \frac{n_0}{\cosh^3(x/\lambda)} \exp \left(-\frac{m_s}{2kT_s}(v_x^2 + v_y^2 + (v_z - u_{sz})^2)\right).$$ (8)
Here $u_s$ and $T$ are the shifted velocity and temperature of the charged particles, and $k$ is Boltzmann’s constant. The plasma density becomes

$$n(x) = n_0 / \cosh^2 (x/\lambda), \quad (13)$$

so that $\lambda$ is the half width of the current sheet. $B_\phi(x)$ and $n(x)$ are shown in Fig. 2. The sum of the magnetic pressure and plasma pressure is spatially constant.

The initial conditions for the computer experiment are prepared, using random numbers, by setting the positions and velocities of $N_s (=3,000)$ clouds for each species to satisfy the equilibrium solution inside the boundary $|x| = L_y = \lambda \sinh^{-1}(1)$. At the boundary, the $\beta$-value of the plasma is unity and Alfvén velocity takes the value $V_A$ based on $n_0 = n(x=0)$ and $B_0 = B_0(x \to \infty)$. Outside the boundary, i.e. for $|x| > L_y$, the plasma density and magnetic field are assumed to be constant and take the boundary values.

We need no electrostatic field in the $z$-direction in order to sustain the initial current or antiparallel magnetic field. In the model adopted here, both inter-collisions of charged particles and wave-particle interactions in the $z$-direction are out of consideration, so that the initial sheet current does not decay resistively in the form of Joule dissipation.

3.3 Boundary conditions

We assume a symmetry condition on both the $x$ and $y$ axes with the origin at the magnetic neutral point. The $L_x \times L_y$ region for computation is a rectangular domain of the first quadrant subdivided into $32 \times 32$ cells. The length ratio of two sides of the region is such that $L_y/L_x = 2$, i.e., $Ay/Ax = 2$. A plasma flow from outside toward the initial magnetic neutral sheet, with the velocity profile of a cosine function, $u_x(y) = -u_{se} \cos (\pi y/2L_y)$ shown in Fig. 2, will set up the reconnection.

For clouds: The clouds of which number is given by $\frac{1}{Q} \int_0^{L_y} n(L_x)u_x(y)dy$
are injected from the boundary \( x = L_x \) at each time step, where \( Q \) is the number of real particles represented by a cloud. Their positions are given to be consistent with the plasma influx density profile and the velocities consistent with those given by Eq. (8), on which the background component \( u(y) \) is superimposed. All the clouds which cross the boundary \( y = L_y \) are regarded as being ejected out of the region of the present problem.

For electromagnetic field: The electric potential at the boundary \( x = L_x \) and the normal component of its gradient at the boundary \( y = L_y \) are assumed to be zero. That is, \( E_y \) is zero both at \( x = L_x \) and \( y = L_y \). We assume the frozen-in condition at the boundary \( x = L_x \) to be

\[
\partial A_x(L_x, y, t)/\partial t = -u(y) \times B_y(L_y, t = 0),
\]

since the plasma is frozen in the strong magnetic field at a distance from the initial neutral sheet. Then the plasma flow with the velocity profile \( u(y) \), which is given at the boundary and causes the reconnection, is equivalent to the electric field \( -\partial A_x/\partial t \) given at the same boundary. The magnetic potential at the boundary \( x = L_x \) becomes time-dependent according to Eq. (14), and the normal component of its gradient at the boundary \( y = L_y \) is assumed to be zero, i.e., \( B_x = 0 \) at \( y = L_y \).

### 3.4 Procedures of computation

1. The electric current and charge densities at the mesh points are given by

\[
J_z = \sum_s (Q \sum_{s \in N_c} q_s v_z) / \Delta x \Delta y,
\]

\[
\rho_z = \sum_s (Q \sum_{s \in N_c} q_s) / \Delta x \Delta y,
\]

where \( \sum_{s \in N_c} \) represents the sum over the clouds in a given cell. \( N_c \) is the number of clouds.
involved. Here the contribution of a cloud must be distributed to the four nearest mesh points, i.e. cell centers, in proportion to the area overlapped by the cloud, since each cloud has the same extent as the cell size. Using the notations in Fig. 3, the contribution of a cloud to the mesh point $i$ should be respectively $q_i \cdot S_i/(S_1 + S_2 + S_3 + S_4)$ and $q_i \cdot S_i/(S_1 + S_2 + S_3 + S_4)$ in Eqs. (15) and (16), here $S_1 + S_2 + S_3 + S_4 = \Delta x \Delta y$. These are the Monte Carlo integrations of Eqs. (6) and (7).

2) The magnetic and electric potentials are obtained by solving Poisson's Eqs. (4) and (5). These, defined in a rectangular region with such boundary conditions as stated before, can be solved quickly and accurately by FACR (fourier analysis and cyclic reduction) method of HOCKNEY (1970). This method is based on a Fourier analysis in one dimension, followed by the solution of the harmonic equations in the other direction. Readers are referred to his paper.
The electromagnetic field is given by

$$B_x = \partial A_y/\partial y, \quad B_y = -\partial A_x/\partial x,$$
$$E_x = -\partial B/\partial x, \quad E_y = -\partial B/\partial y,$$
$$E_z = -\partial A/\partial t.$$

3) Hitherto, $x$, $y$, and $v_z$ are known at the current time, and $v_x$ and $v_y$ at the time $\Delta t/2$ earlier. Now the clouds are moved according to the following finite difference scheme,

$$v_x,_{\Delta t/2} = v_x,_{-\Delta t/2} + q_s/m_s(E_x - v_y B_y) \Delta t,$$
$$v_y,_{\Delta t/2} = v_y,_{-\Delta t/2} + q_s/m_s(E_y + v_z B_x) \Delta t,$$
$$x_{\Delta t} = x + v_x,_{\Delta t/2} \Delta t,$$
$$y_{\Delta t} = y + v_y,_{\Delta t/2} \Delta t,$$
$$v_z,_{\Delta t} = v_z + (E_z + v_x B_y - v_y B_x)_{\Delta t/2} \Delta t,$$

where the quantities without the time subscripts show the values at the current time. It should be remarked that the field quantities in the rhs are those at the center of the cloud itself, which are obtained by bilinear interpolation between the four nearest mesh points. For example, $B_z$ for the cloud in Fig. 3 is given by $(S_1 B_{z1} + S_2 B_{z2} + S_3 B_{z3} + S_4 B_{z4})/(S_1 + S_2 + S_3 + S_4)$. $B_x$, $B_y$ and $E_z$ at the time $\Delta t/2$ later are approximated by linear extrapolation with respect to time. If $y_{\Delta t} \geq L_y$, the cloud is regarded as being ejected out of the region of the present problem. Then a number of clouds are injected and the magnetic potential at the boundary mesh points are given according to the boundary conditions. The entire procedures (1)-(3) are repeated.
We confirm the consistency of the results by using different values of $\Delta t$ to check the accuracy of the difference scheme.

The necessary and sufficient parameters to determine the system are given in Table 1. Their numerical values are also shown. The computation does not depend on $n_0$ and represents any system that satisfies the similarity law as a result of the scaling adopted here. The other important parameters are shown for reference in Table 2. It is assumed that positive and negative charges have the same mass.
4. Computed Results and Discussion

The peak value of the inflow velocity of the plasma is such that $M_e \equiv u_e/v_t = 1$ or 0.5, so the corresponding Alfvén Mach number is $M_A \equiv u_e/V_A = 1/\sqrt{2}$ or $1/\sqrt{2}/2$. Unless otherwise specified, all the results presented here are for the same case $M_e = 1$, and the time is scaled by the gyration period.

4.1 Magnetic field

Figures 4(a)–(d) are the time-sequential behavior of the magnetic field lines. The initial neutral sheet exists between the antiparallel magnetic field lines along the y axis. Then the plasma flow from outside given at the boundary sets up the reconnection. A reconnected field line also should have appeared in (b) if a smaller contour interval is used. The magnetic field is not accompanied by transition layers such as slow mode compressional waves or expansion waves. We can be convinced that the solution is obtained only for the field reversal region as follows.

It is shown by Vasylunias (1975) that, when the reconnection proceeds with the stationary convection velocity $V_x = (M_A V_A)$ into the field reversal region with half width $X(y)$, the following relations must be satisfied in this region;

$$X = (M_A^2 y^2 + \lambda^2)^{1/2},$$

$$V_y/V_A = M_A y/X,$$

$$B_x/B_0 = M_A (2 M_A y/X - M_A^2 y^2/X^3),$$

$$\lambda = c(nq^2/e m)^{1/2} = c/\omega_{pe}.\tag{28}$$

Here it is assumed that electric conductivity is not determined by the intercollisions of charged particles or wave-particle interactions, but determined by the flow time of the fluid in the diffusion region, $\tau_f \approx Y/V_A = \lambda_y/M_A V_A$, where $Y$ is the half length of the diffusion region. On the other hand the relation

$$c/\omega_{pe} = r_{ge}(2(1 + T_i/T_e))^{1/2}$$

is satisfied at the initial state, which is obtained by eliminating $\lambda$ from Eqs. (10) and (11), so that

$$X(y=0)/L_z = r_{ge}/L_z \cdot (2(1 + T_i/T_e))^{1/2}.$$

Substituting the numerical values of $r_{ge}/L_z = 15/32$ and $T_i/T_e = 1$, it becomes $X(y=0)/L_z = 15/16$. The parameter $r_{ge}/L_z$ is very important and must be smaller than $1/(2(1 + T_i/T_e))^{1/2}$ to include consistently both the field reversal region and the external flow region. However, computations for smaller values of $r_{ge}/L_z$ have not been possible because of numerical instability.

Figure 5 is the magnetic flux density along the axes at different times. $B_y$ along the x axis shows the characteristic profile in the diffusion region, and
increases with time but not infinitely in spite of the continuous convection of the magnetic field to the inner region. Therefore, it is suggested that the diffusion rate of the magnetic field at the neutral point is self-adjustable to a given reconnection rate, so that the reconnection rate can take any value up to the
local Alfvén speed immediately outside the field reversal region. $B_x$ along the $y$ axis appears as the reconnection proceeds. The decrease near the boundary $y=L_y$ is caused by a somewhat improper boundary condition that $B_x$, which is to be the dominant component near the $y$ axis, is uniformly zero at $y=L_y$.

The reconnection sets in with a delay time of sound wave propagation in response to the plasma injection, as shown in Fig. 6.

4.2 Plasma

Figures 7(a) and (b) show the plasma convection at two different times. At the initial state there exists only a small noise due to random numbers but not a collective motion. This macroscopic convection can be induced in a
short time and makes a wider turn with time. Each cloud is first accelerated by the induced electric field in the direction parallel to the electric current. It comes to the initial magnetic neutral sheet by the Lorentz force with the dominant component $B_y$, then leaves the region of the neutral point by the smaller

Fig. 7. (a) and (b). Plasma convection at two different times. The neutral point is at the left bottom corner. Each arrow has the length proportional to the flow velocity at its rear end.

Fig. 8. Plasma flow velocity $u_x(x)$ along $x$ axis and $u_y(y)$ along $y$ axis.
component $B_x$. During this process it is accelerated along the meandering orbit crossing the initial neutral sheet.

Figure 8 is the plasma flow velocity along the axes at different times. The magnetic neutral point is also the stagnation point of the plasma convection. Apparently the global flow pattern seems to be determined by the length ratio of two sides of the region. However, the results support the viewpoint that the size of the diffusion region can be adjusted by the reconnection rate.

Figure 9 shows $B_x(y)$ and $V_x(y)$ in the field reversal region analytically obtained by Vasyliunas (Eqs. (26) and (27)) together with the numerical values at the time our computation was terminated. The flow velocity numerically obtained along the $y$ axis agrees well with the analytical result. The decrease of the magnetic field component $B_x$ numerically obtained near the boundary $y=L_y$ is due to the somewhat improper boundary conditions stated before.

4.3 Electric current

Figure 10 is the electric current density distribution at the time $t=5 \times 10^{-1}$,
measured by $J_z = -D^2 A_z / \mu_0$. The current is strongly concentrated to the vicinity of the magnetic neutral point, and the current-free region scarcely exists. This profile agrees well with that in the diffusion region of the numerical MHD solutions by FUKAO and TSUDA (1973a, b).

4.4 Electric field

Figure 11 is the induced electric field $E_z = -\partial A_z / \partial t$ along the axes at different times. This is also an index of the reconnection rate and should become

![Induced electric field E_z along the axes at different times, scaled by $E_0 = \nu B_0$.](image)

Fig. 11. Induced electric field $E_z$ along the axes at different times, scaled by $E_0 = \nu B_0$.

![Time variation of the number of the clouds, scaled by $N_t$. $N$, $N_{t,\text{inj}}$, and $N_{t,\text{ej}}$ denote the number of the clouds that are present in the region, the number of those injected and ejected, respectively.](image)

Fig. 12. (a) and (b). Time variation of the number of the clouds, scaled by $N_t$. $N$, $N_{t,\text{inj}}$, and $N_{t,\text{ej}}$ denote the number of the clouds that are present in the region, the number of those injected and ejected, respectively.
uniform in the steady state. The electrostatic plasma wave with the wave length of about $L_x$ and the period of $T_p$ are observed if we plot the electric potential $P$.

4.5 Energy

Figures 12(a) and (b) are the time variation of the number of clouds for $M_x=1$ and 0.5, respectively. We assume the constant injection of the same number of positively and negatively charged clouds and the ejection of all clouds which cross the boundary $y=L_y$. However, the charge neutrality of the system is maintained as the whole.

Figures 13(a) and (b) show the time variation of the energy for $M_x=1$ and 0.5, respectively. The magnetic energy is smaller than the kinetic energy of the plasma, since the region in the present problem is restricted to the field reversal region. Now we recall the motion of the clouds. They are accelerated along the meandering orbits and then come into the wave region transverse to the magnetic field. This is a sort of the Joule heating mechanism for a collisionless plasma, where the electric conductivity is determined by the inertia of charged particles. Poynting's vector $E \times B/\mu_0$ has here no normal component at the boundary $y=L_y$, so that the electromagnetic energy convected into the region should be equal to the sum of the increase of the magnetic energy and kinetic energy. However, this heating rate could not be sufficient for such explosive energy release as observed. Eqs. (25)–(28) show that neither plasma influx to the diffusion region $nV_xY$ (here $V_x=M_xV_d$ and $Y=\lambda/\lambda_1$) nor average

![Fig. 13. (a) and (b). Time variation of the energy scaled by $2nokTL_xL_0$ = $B_0^2L_xL_0/2\mu_0$. $E_k$, $E_{k,\text{inj}}$, $E_{k,\text{ej}}$, $E_m$ and $E_p$ are the kinetic, injected, ejected, magnetic and electrostatic energies, respectively.](image)
velocity components out of the region $V_y(\approx V_d)$ and $V_z(\propto E_y/V_y$, here $E_y \propto M_d)$ depend on the reconnection rate.

Figure 14 is the time variation of the energy per cloud and the average velocity component $|v_{ze}|$. They increase with time due to the induced electric field with the reconnection.

Now we will consider the controlling conditions of the reconnection. The solution is obtained only for the field reversal region. However, the results show that the diffusion rate of the magnetic field at the neutral point is self-adjustable to a given reconnection rate, so that the reconnection rate can take any value up to the local Alfvén speed immediately outside the field reversal region. The Alfvén Mach number $1/\sqrt{2}$ or $1/2\sqrt{2}$ is not so much smaller than unity. This results from the fact that the effective conductivity is determined by the inertia of charged particles as suggested by Speiser, and the inertia conductivity is inversely proportional to the given reconnection rate. The mean flight time of the charged particles in the diffusion region, which plays the role of an inter-collision time and is proportional to the inertial conductivity, is such that $Y/V_d = \lambda_d/M_d V_d \propto 1/M_d$.

We started with a one-dimensional plane current sheet. It might be a possible solution that the current sheet simply gets squeezed, maintaining the antiparallel magnetic field configuration. This solution occurs actually when a spatially uniform plasma flow from outside toward the initial magnetic neutral sheet is given as the boundary conditions. The plasma flow must have a locally enhanced velocity profile to cause the reconnection.

5. Conclusion

We have shown an evolutionary process of the reconnection starting with
a plane current sheet, i.e. antiparallel magnetic field lines. The solution is obtained only for the field reversal region. With this in mind, we come to the following conclusion.

1) *Evolutionary process* Rapid reconnection of magnetic field lines can easily take place in the collisionless plasma where electric conductivity is determined by the inertia of charged particles. The reconnection sets in with a delay time of sound wave propagation in response to the plasma injection.

2) *Field configurations* We could not clarify the self-consistent field configurations in both the field reversal region and the external flow region. The solution obtained agrees with the properties of the field reversal region expected by MHD solutions.

3) *Controlling conditions* The inter-collisions of charged particles and wave-particle interactions, which in most cases cause the electric conductivity to remain finite, is not necessarily required. The effective conductivity can be determined by the inertia of charged particles and inversely proportional to the reconnection rate given as the boundary conditions. Therefore, the diffusion rate of the magnetic field at the neutral point is self-adjustable to a given reconnection rate, so that the reconnection rate can take any value up to the local Alfvén speed immediately outside the field reversal region. The plasma flow toward the initial magnetic neutral sheet should have a locally enhanced velocity profile to cause the reconnection.

4) *Particle acceleration and plasma heating* Joule heating in the diffusion region is not sufficient for the explosive energy release such as that observed in astrophysical and geophysical phenomena.

It was a crucial limitation that we could not solve consistently both the field reversal region (diffusion region and wave region) and the external flow region because of numerical instability.

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