Suprathermal electron acceleration in magnetic reconnection

M. Hoshino,1 T. Mukai,2 T. Terasawa,1 and I. Shinohara

Abstract. The suprathermal electrons of \( \geq 20 \) keV that extend from the hot thermal electron with 2 - 3 keV temperature are sometimes observed in Earth’s magnetosphere in association with reconnection. We study the origin of the hot and suprathermal electrons in terms of the kinetic magnetic reconnection process by using the two-dimensional particle-in-cell simulation. We find that the hot and suprathermal electrons can be formed in the nonlinear evolution of a large-scale magnetic reconnection. The electrons are, at the first stage, accelerated in the elongated, thin, X-type current sheet. Next the preheated/accelerated electrons are transported to the stronger magnetic field region produced by piling up of magnetic field lines due to colliding of the fast reconnection outflow with the preexisting plasma. In this region they are further accelerated owing to the \( \nabla B \) drift and the curvature drift. The mirror force of the reconnecting magnetic fields, the effective pitch angle scattering that occurs when the Larmor radius is comparable to the magnetic field line curvature radius, and the broadband waves excited by the Hall electric current are the other important agents to control the particle acceleration.

1. Introduction

The origin of nonthermal, high-energy particles is a long-standing problem in space. It is known that the energy spectrum in the high-energy regime can be often described by the power law spectrum. Over the last several decades, considerable effort has been devoted toward understanding the origin of suprathermal/nonthermal charged particles, and various mechanisms have been discussed. One of the popular mechanisms is diffusive shock acceleration [e.g., Blandford and Ostriker, 1978] based on the idea of the Fermi mechanism [Fermi, 1949]. This shock Fermi acceleration is widely applied for many nonthermal phenomena, because the mechanism can explain the observed ubiquitous power law spectrum with the power law index of 2. However, there are many outstanding questions regarding particle acceleration that motivate continuing research in the field.

Many plasma states in space have magnetic fields whose structure contains the neutral sheet where the magnetic field polarity changes its direction, and plasma heating/acceleration seems to occur over a broad range of the plasma sheet. Magnetic reconnection is believed to be particularly important, because the magnetic field energy can be rapidly released to the particle energy. Much of the work for magnetic reconnection has focused on understanding how fast magnetic field energy dissipates, and the energy conversion from the magnetic field energy into the particle energy has been debated. The X-type neutral region and a pair of slow mode shocks that develop from the X-type neutral line are thought to play a significant role in the plasma thermalization.

In addition to such plasma heating, the acceleration of the suprathermal particles by reconnection has been discussed. In early satellite observations, energetic particle bursts in Earth’s magnetotail have been reported by Sarris et al. [1976] and Hones et al. [1976]. The energetic electron burst with 0.3 - 1.0 MeV has been identified in association with the southward turning of the B\textsubscript{z} magnetic field at X = -20 ~ -30 R\textsubscript{E} in the magnetotail [Terasawa and Nishida, 1976]. Similar events are also discussed at X \( \sim \) -30 R\textsubscript{E} based on the survey of electrons of \( \varepsilon \geq 200 \) keV by Baker and Stone [1976, 1977], and they reported that the electron enhancement of \( \varepsilon \geq 1 \) MeV are usually associated with neutral sheet crossings. Möbius et al. [1983] analyzed energetic protons of 30 - 500 keV and energetic electrons of \( \geq 75 \) keV and discussed that the region near the X-type neutral line is a candidate for the acceleration site of the energetic particles. A number of observational facts suggest that the energetic particle bursts can be related to magnetic reconnection and the formation of a neutral line.

The energization of charged particles under collisionless plasmas is thought to be basically provided by the interaction of the charged particles with an inductive
electric field near the X-type neutral lines. The test particle studies based on the magnetic and electric fields structures obtained by the MHD simulation of reconnection demonstrated the production of the suprathermal particles by moving in the direction of the electric force over a substantial distance [e.g., Sato et al., 1982; Scholer and Jamitzky, 1987; Birn and Hesse, 1994]. Bulanov and Sasorov [1975], Zelenyi et al. [1990], and Deeg et al. [1991] have demonstrated the formation of the power law type spectrum by appealing to inductive electric fields that grow exponentially in time. Ambrosiano et al. [1988] suggested that a small-scale turbulence embedded in reconnection structure enhances the particle acceleration.

During the last decade there have been substantial advances in the study of magnetic reconnection, mainly due to modern satellite observations and kinetic simulation studies [e.g., Nishida, 2000]. Much attention has been paid to the plasma sheet structure beyond the MHD framework, and greater understanding of the kinetic structure of the X-type region is now possible [e.g., Cai et al.; 1994, Pritchett and Coroniti, 1995; Ma and Bhattacharjee, 1996; Biskamp et al., 1997; Shay et al., 1999; Hesse et al., 1999]. The evolution of the plasma distribution functions around the X-type region have been studied also in terms of comparison between the simulation modeling and the satellite observations, and ion dynamics of magnetic reconnection including ion plasma heating have been discussed in detail [Hoshino et al., 1998; Nakamura et al., 1998; Lottermoser et al., 1998]. The ion gyroradius is not necessarily smaller than the thickness of the plasma sheet, and the size of the magnetic diffusion region around the X-type neutral line is also known to be of the order of the ion inertia length. In such a thin plasma sheet, complexity of the ion velocity distribution function has been reported by the Galileo satellite [Frank et al., 1994], and a variety of the ion and electron velocity distribution functions are also observed by Geotail [Mukai et al., 1994]. The plasma heating/acceleration process based on the complexity of the velocity distribution function is being discussed.

On the basis of the recent understanding of kinetic reconnection structure, we revisit the origin of suprathermal electrons in the course of magnetic reconnection in a thin plasma sheet. Since the gyroradius of a suprathermal electron is not negligible compared with the characteristic scale length of the global plasma sheet structure, kinetic treatment of electron acceleration seems to be needed. In this paper we study the origin of nonthermal electrons on the basis of the Geotail satellite observation and simulation modeling. Specifically, we study that, in addition to the meandering/Speiser acceleration in the vicinity of the X-type region [Speiser, 1965], particle acceleration in the magnetic pileup region formed by colliding the reconnection outflow with the preexisting plasma sheet plays a significant role in the production of nonthermal electrons. We propose a two-step process such that the electrons accelerated near the X-type region are further energized around the magnetic pileup region.

2. Geotail Observation

Plate 1 shows one of the hot electron events observed by the Geotail satellite in Earth's magnetotail. These data are taken at a distance of ~24 Re from Earth. From the top to the bottom of Plate 1 are shown, the electron omni-directional energy spectrogram of ≤40 keV, the three magnetic field components in GSM coordinates, the ion flow velocity in the x component, the ion temperature, and the plasma density. The Geotail observes the plasma flow transition from tailward to earthward ~1752 UT, and during the fast flow region the weak magnetic field and the hot ion plasma are also observed. The magnetic field $B_z$ is negative during the tailward flow, while it becomes positive during earthward flow. This is suggestive of a magnetic reconnection event.

From the electron energy spectrogram we observe the enhancement of the electron flux from 1742 to 1804 UT, while before 1742 UT and after 1804 UT the energy spectrogram shows more or less the typical plasma sheet electron. The electron energy spectrum for the time interval of 1745-1800 UT is shown in Figure 1. The dashed line shows as a reference the thermal Maxwellian distribution function of 3.2 keV. The spectrum is well described by the thermal Maxwellian up to 20 keV, but over 20 keV one can find an enhancement of the phase space density above the Maxwellian level. The very low energy population is probably due to a contamination of photoelectrons.

We also observe the nongyrotropic ions in association with this high energy electron event (not shown here), which suggests that the thickness of the plasma sheet becomes of the order of ion inertia length. Nagai et al. [this issue] also discuss that the hot electron events including these data can be observed often near and in the Hall current dominant region. Therefore we think that the hot electron events are related to the magnetic reconnection in the thin plasma sheet.

It is important to note that the energetic electron burst phenomena in association with magnetic reconnection have been reported previously [Terasawa and Nishida, 1976; Baker and Stone, 1976, 1977]. The acceleration site for the energetic electrons, however, still remains unresolved. The energy range of the electron burst is quite different from the Geotail hot electron event with ≤40 keV, but we think that the hot electron event and the energetic burst event are cognate phenomena, because the suprathermal electron population in Figure 1 seems to extend to the higher-energy range.

Being motivated by this high-energy electron observation, we discuss how and where the energetic electrons
Plate 1. Plasma and magnetic field measurements taken by the Geotail satellite for the December 10, 1996, reconnection event. From top to bottom: the electron energy spectrogram of ≤40 keV; the magnetic fields $B_x$, $B_y$, and $B_z$ in units of nT in GSM coordinates; the plasma velocity $V_x$ in km/s; ion temperature $T_{ion}$ in eV; and plasma density $N$ in cm$^{-3}$.
Plate 2. Structure of the magnetic reconnection obtained by particle-in-cell code. From top to bottom: magnetic field lines in the $x$-$z$ plane, magnetic field $B_y$, electric field $E_y$, and amplitude of the electric field in the $x$-$z$ plane $(E_x^2 + E_z^2)^{1/2}$ at $t/\tau_A = 48.8$. The system size of the simulation is $-19.2 \leq X/\lambda \leq 19.2$ and $-4 \leq Z/\lambda \leq 12$ with double current sheets.
are produced in the course of magnetic reconnection by using the particle-in-cell simulation. It has been already reported that a charged particle is effectively accelerated through a meandering/Speiser motion in the reconnection region. In addition to the acceleration in the X-type region, it has been discussed that the curvature for the reconnecting magnetic field line with $\kappa \approx 1$ plays an important role in the electron heating [Smets et al., 1998], where $\kappa$ is defined as the square root of the ratio of the curvature radius of the magnetic field to the Larmor radius [e.g., Büchner and Zelenyi, 1989].

In this paper we discuss another new acceleration process working near the magnetic field pileup region between the X-type and the O-type region, where the reconnection outflow collides with the preexisting plasmas. Since the $\nabla B$ drift for electrons in the magnetic field pileup region is antiparallel against the dawn-dusk reconnection electric field, the electrons gain energy by drifting dawnward. More important, the accelerated electrons will be ejected from the plasma sheet along the reconnecting magnetic field, and some of them will be reflected back again by the mirror magnetic field in the lobe boundary. The multiple crossing of the plasma sheet enhances the acceleration. Furthermore, energetic electrons with $\kappa \approx 1$ are scattered toward the large pitch angle region [Delcourt et al., 1996; Smets et al., 1998], and their trapping effect may also enhance the acceleration efficiency. The strong wave activity excited by the strong Hall electric current in a thin plasma sheet may also be an important particle-scattering agent [Hoshino et al., 2001]. We find that these non-MHD effects are important in producing nonthermal, high-energy particles in the magnetic reconnection region.

3. Numerical Simulation

We use the particle-in-cell simulation to study the behavior of electron dynamics in reconnection. We assume the Harris equilibrium [Harris, 1962] as the initial condition, where the electric current flows only in the
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Figure 3. Electron energy spectra at $t/\tau_A = 7.8$, 41.6, and 48.8 integrated over pitch angle in the simulation domain of $-19.2 < X/\lambda < 19.2$ and $-4 < Z/\lambda < 4$.

y direction and neither $B_z$ nor $B_y$ magnetic fields exists across the plasma sheet. The initial hot plasma localized inside the plasma sheet balances the magnetic pressure produced self-consistently by the electric current. However, we added the low-density, cold plasma in the lobe region to demonstrate Earth's magnetotail situation. We also drive a localized external electric field outside the plasma sheet to initiate the reconnection in the center of the simulation box. The initial setup is almost the same as our previous simulation [Hoshino et al., 1998].

In our current study we simulate the nonlinear time evolution of magnetic reconnection with a high spatial resolution to resolve the electron inertia scale. The physical system size is $L_x/\lambda = 38.4$ and $L_z/\lambda = 16$, where $\lambda$ is the thickness of the initial plasma sheet. We assume the double-periodic boundary in the $x$ and $z$ directions. The numerical grid points are $N_x \times N_z = 1536 \times 640$, and the number of total particles is $\sim 2 \times 10^8$. The plasma parameters are as follows: Ion inertia length $V_A/\Omega_i$ is 1.15 $\lambda$ with 46 grids, and electron inertial length $c/\omega_{pe}$ is 0.14 $\lambda$ with 6 grids.

The mass ratio of ions to electrons $m_i/m_e$ is 64. The plasma temperatures are set as follows: $T_{i,ps}/T_{e,ps} = 4$, $T_{i,lobe}/T_{i,ps} = 1/25$, and $T_{e,lobe} = T_{e,ps}$, where the subscript $i$ denotes ion, $e$ is electron, $ps$ is the plasma sheet, and lobe is the lobe. The ratio of the Alfvén velocity $V_A$ to the ion thermal velocity $V_i = (2T_{i,ps}/m_i)^{1/2}$ is 1.15, where the Alfvén velocity is defined by the lobe magnetic field and the plasma sheet density. The initial lobe plasma density $N_{lobe}$ is set to be 20 % of the plasma sheet density $N_{ps}$.

In Earth's magnetotail it is known that the dipole magnetic field component $B_z$ plays an important role in the evolution of reconnection. However, once the reconnection occurs, the $X$-type magnetic field line topology is the same as the plasma sheet without the $B_z$ magnetic field. Therefore we think that the basic process of nonthermal particle acceleration can be demonstrated by using the Harris equilibrium without $B_z$. In the Geotail observations in Plate I the magnetic field $B_z$ actually changes from negative to positive in association with the plasma flow reversal. The constant magnetic field $B_y$ may strongly control the electron acceleration, because the electron motion can be guided by the $B_y$ field. However, it is difficult to know whether or not the constant $B_y$ exists in the satellite data because of the flapping motion of the magnetotail.

3.1. Reconnection Structure

The time evolution of reconnection is basically the same as other reconnection simulations done by MHD, hybrid, and full particle codes thus far. A snapshot of the magnetic field lines in the reconnection plane, the magnetic field and the electric field perpendicular to the reconnection plane, and the magnitude of the electric field in the reconnection plane are shown in Plate 2. A part of the reconnection region is shown. The $X$-type neutral point is formed in the center of the simulation box. The quadrupole magnetic fields out of the plane $B_y$ are formed around the $X$-type region because of the Hall electric current effect [Sonnerup, 1977; Terasawa, 1983]. The magnetic field $B_y$ is normalized by the initial lobe magnetic field $B_0$.

Figure 4. Positions for the energetic electrons of $E_{ele} > 0.15m_ec^2$ at $t/\tau_A = 48.8$ in the $x$-$z$ plane. The electrons are thinned out in the scattered plot.
The dawn-dusk electric field $E_y$ is positive in the reconnection region, and the strongest electric field $E_y$ is found between the $X$-type region and the $O$-type region. The electric field is normalized by $E_0 = B_0 V_A/c$. In addition to the global reconnection electric field, we find a patchy electric field structure. From the analysis of the time series of the electric fields, we found that the wave activity shows a broadband spectrum near the lower hybrid frequency [Hoshino et al., 2001].

In Plate 2 (bottom panel), the amplitude of the electric fields in the reconnect plane, $|E_{x,z}| = \sqrt{E_x^2 + E_z^2}$, is depicted. Strong intensity can be found in the quadrupole $B_y$ region (i.e., the Hall electric current region), which is explained by the polarization electric field produced by the inertia difference between ions and electrons [e.g., Hoshino, 1987]. In addition to the large-scale $X$-type structure of $|E_{x,z}|$, we can also observe a small-scale structure embedded in the Hall current region in our high spatial resolution simulation. The origin of this small-scale $E$ field is interpreted to be formed by the electron beams in the Hall current region, discussed later in detail. The similar turbulence of $|E_{x,z}|$ can also be found in the plasma sheet. Since we find the amplitude of the turbulence $|E_{x,z}|$ is large compared with the dawn-dusk $E_y$ electric field, we think that these electric field fluctuations play an important role in plasma heating. (Note that we have only six grids for the electron inertia scale $c/\omega_{pe}$ defined in the initial plasma sheet density. The small-scale structure seems to appear from the so-called hybrid scale $c/\sqrt{\omega_{pe}\omega_{pe}}$ to the electron inertia scale $c/\omega_{pe}$. In order to confirm the small-scale structure in detail, however, we need a better simulation with higher spatial resolution.)

Figure 2 shows the flow vectors in the reconnect plane for both electrons and ions. The ion flows are basically directed from the $X$-type region to the $O$-type region, and the electron flow is also in the same direction in the plasma sheet. In the outflow region of $|z| > 6$, both ions and electrons have the same bulk velocity of $\sim 0.6 V_A$ (or $\sim 0.5 V_A$). The electron flow in the boundary between the lobe and the plasma sheet, however, is directed toward the $X$-type region. This kind of behavior is the result of the Hall electric current in a thin plasma sheet, where the thickness of the plasma sheet is of the order of the ion inertia length or less [Terasawa, 1983]. Note that the ion and electron vectors are normalized by the ion thermal velocity $V_i = \sqrt{2 T_i/m_i}$ and electron thermal velocity $V_e = \sqrt{2 T_e/m_e}$, respectively. The ratio of $V_e/V_i$ is set to be 4. The electron flow can become faster than the ion flow near the $X$-type region where the ions are unmagnetized, because the $E \times B$ drift velocity for the magnetized electrons becomes larger than the Alfvén velocity in a weak magnetic field region.

### 3.2. Suprathermal Electrons

Figure 3 shows the electron energy spectra integrated over pitch angle in half of a simulation region of $-19.2 < X/\lambda < 19.2$ and $-4 < Z/\lambda < 4$. At $t/\tau_A = 7.8$ in the early stage, the spectrum is almost described by a Maxwellian, $f(\varepsilon_{ele}) \propto \exp(-\gamma m_e c^2/T_e)$, where $m_e c^2$ is the electron rest mass energy. The electron energy $\varepsilon_{ele}$ is measured by $(\gamma - 1) m_e c^2$, where the Lorentz factor is $\gamma$. As time goes on, one can observe the enhancement of the high-energy population. At $t/\tau_A = 48.8$ we clearly observe the nonthermal population above $\varepsilon_{ele}/m_e c^2 > 0.1$. The dashed line in Figure 3 is the Maxwellian fit as a reference. The results of the nonthermal particles seem to demonstrate the Geotail observation introduced in the section 2.

Let us discuss how and where the nonthermal electrons are produced in the course of magnetic reconnection. We study first the positions of the high-energy electrons obtained in the nonthermal energy spectrum at $t/\tau_A = 48.8$ in Figure 3. We pick up the electrons with energy greater than $\varepsilon_{ele}/m_e c^2 = 0.15$ and plot the positions in the $x$-$z$ plane in Figure 4. We find that the energetic electrons exist both in the outer boundary region and inside the plasma sheet, but there is a gap between the inner plasma sheet and the outer boundary region. By comparing this with the electron flow pattern in Figure 2, we find the energetic electrons in the outer boundary region exist in and around the electron fast outflow region.

The energetic electrons inside the $O$-type region are probably produced by the adiabatic compression motion of the electrons that existed inside the hot plasma sheet before the onset of reconnection. Our simulation is done in the periodic system in the $x$ axis, and the size of the magnetic island of the closed magnetic fields shrinks with the nonlinear time evolution.

The formation of the gap of the energetic electrons is probably understood as follows: the gap electrons were situated in the lobe with a low temperature before the onset of reconnection, and they were transported into the plasma sheet in the early phase of reconnection when the dawn-dusk $E_y$ field was still weak. Therefore the plasma sheet temperature occupied by newly injected electrons is lower than that of the preexisting plasmas. Although the gap electrons are heated by the adiabatic compression in a way that is similar to the energetic electrons seen inside the $O$-type point, the number of energetic electron is small because of the initial cold electrons.

### 3.3. Electron Distribution Functions

We now discuss the electron distribution functions in and around the boundary between the lobe and the plasma sheet. Plate 3 shows the electron distribution functions together with a map of the location superimposed on the electron flow vectors. The distributions are obtained by integrating the particles in the rectangles indicated in the diagram of the electron flow pattern. A slice of the three-dimensional distribution function is shown in the velocity plane including the magnetic field ($V_B$) and the $E \times B$ vector ($V_\perp$). The velocity
distribution function (a) (Plate 3, bottom, right) in the outer boundary region where the electron flow vectors are directed toward the X-type region consists of the cold electrons flowing toward the X-type region. Since we know that the distribution (a) is located at the outer edge of the quadrupole $B_y$ from Plate 2, we find that the outgoing field-aligned current is driven by the incoming cold electrons. Note that the Hall current direction is opposite of the electron flow vector.

In the plasma sheet side of the distribution (a), we can observe the distribution (b) (Plate 3, bottom, third panel) that consists of both the anisotropic hot electrons flowing away from the X-type region and the cold electrons flowing toward the X-type region. The high-speed electrons are accelerated up to almost the electron thermal velocity $V_e$. We call this high-speed electron population "the electron PSBL beam" from the analogy of the ion beam observed in the plasma sheet boundary layer (PSBL) [e.g., Lui et al., 1977; DeCoster and Frank, 1979].

In the distribution (c) observed in Plate 3 (bottom, second panel), a slightly downstream region, the hot beam component is further accelerated and is spread out in the velocity space perpendicular to the magnetic field. The energetic electron component with a crescent/lima beam distribution is still flowing away from the X-type region. From the top electron velocity pattern, we find that the electron flow vectors are directed away from the X-type region, almost along the magnetic field. Together with the ion and electron vectors in Figure 2, we find that the outgoing hot electron beams are the carrier of the incoming Hall electric current toward of the plasma sheet boundary layer.

The distribution (d) seen in the farther downstream region (Plate 3, bottom, left) becomes almost isotropic, and a number of the energetic electrons increase. The bulk velocity is slow, and the magnetic field $B_y$ is weak in this region. In the farther downstream region we find similar isotropic electron distribution. Toward the center of the magnetic island, i.e., the O-type region, the distribution becomes the hot and Maxwellian-like distribution.

### 3.4. Electron PSBL Beam I

We study how and where the electron PSBL beams discussed in section 3.3 are produced. In order to study the origin of the electron PSBL beams, we first pick up only the high-speed electrons with $|V_B/V_e| > 1$ from the distribution functions (b) in Plate 3 (bottom, third panel), and trace the position of particles backward in time, where $V_e$ is the initial electron thermal velocity $\sqrt{2T_{e,\text{pe}}/m_e}$. Plate 4 shows the positions of the electrons in four different snapshots of $t/\tau_A = 48.8$ (black), 48.0 (red), 47.0 (green), and 45.3 (blue).

The corresponding "partial" distribution functions constructed by the high-speed electrons at $t/\tau_A = 45.3$ are also shown in Plate 4, bottom. At $t/\tau_A = 45.3$ (blue), the particles are located outside the separatrix, i.e., in the lobe magnetic field lines, and the plasma is cold. At $t/\tau_A = 47.0$ (green), most of the electrons enter into the plasma sheet and gain energy quickly. From the time evolution of the partial distribution functions in Plate 4, bottom, we find a drastic energy change between $t/\tau_A = 47.0$ and 45.3 when the electrons enter into the X-type region. As time goes on, those electrons are transported outward along the reconnecting magnetic field, and they reach the observation point at $t/\tau_A = 48.8$. Since the partial distribution functions are almost unchanged after $t/\tau_A = 47.0$, we find that the main energization occurs near the X-type region.

Near the X-type region the particles are unmagnetized and are accelerated by the dawn-dusk electric field $E_y$ during the meandering/Speiser motion. Let us consider the region where ions are unmagnetized but electrons are still magnetized. For simplicity we may assume that the reconnecting magnetic field $B_z$ is approximated by

$$B_z(x) \approx \frac{x}{\Delta_i} B_z(\Delta_i)$$

near the X-type region, where $\Delta_i$ is the size of the ion unmagnetization region. Both ion and electrons are magnetized in $|x| > \Delta_i$, and then they are convected by the $E \times B$ motion with the speed of the Alfvén velocity $V_A$. Namely,

$$v_i(\Delta_i) = v_e(\Delta_i) = V_A = c \frac{E_y}{B_z(\Delta_i)}.$$  \hspace{1cm} (2)

Assuming that the electric field $E_y$ is almost constant in the reconnection region, the electron velocity just outside the electron unmagnetized region $\Delta_e$ is given by

$$v_e(\Delta_e) = c \frac{E_y}{B_z(\Delta_i)} \frac{\Delta_i}{\Delta_e} = V_A \frac{B_z(\Delta_i)}{B_z(\Delta_e)} = V_A \frac{\Delta_i}{\Delta_e}.$$  \hspace{1cm} (3)

The size of the unmagnetized region for a charged particle is given by equating the gyroradius in the local magnetic field to the distance from the X-type neutral line [Laval and Pellat, 1968], and for ions we have

$$\Delta_i = V_A \frac{m_i c}{e B_z(\Delta_e)},$$  \hspace{1cm} (4)

while for electrons,

$$\Delta_e = v_e(\Delta_e) \frac{m_e c}{e B_z(\Delta_e)}.$$  \hspace{1cm} (5)

Therefore we get from (1) and (3)-(5),

$$\Delta_i = \left( \frac{m_i}{m_e} \right)^{1/3},$$  \hspace{1cm} (6)

$$v_e(\Delta_e) = V_A \left( \frac{m_i}{m_e} \right)^{1/3} = V_{A,e} \left( \frac{m_e}{m_i} \right)^{1/6}.$$  \hspace{1cm} (7)

We find that the electron flow velocity reaches almost up to the electron Alfvén velocity $V_{A,e}$ defined by
Plate 3. (Top) Electron flow vectors and the locations of four typical electron distribution functions observed in the boundary region. (Bottom) A slice of a three-dimensional distribution function in a plane including the magnetic field $V_B$ and the $E \times B$ drift velocity $V_\perp$. 
Plate 4. Positions of electrons are traced backward in time from the black area at $t/\tau_A = 48.8$, which corresponds to the area of the distribution (b) in Plate 3. The red, green, and blue symbols show the positions of electrons at $t/\tau_A = 48.0$, 47.0, and 45.3, respectively. The bottom panels are the “partial” energy distribution functions obtained only from the energetic electrons $V_B/V_e > 1$ at $t/\tau_A = 48.8$. 
Plate 5. Backtrace of electrons for the distribution (c) in Plate 3. Same diagram as that in Plate 4.
Plate 6: Backtrace of electrons for the distribution (d) in Plate 3. Same diagram as that in Plate 4.
\[ V_A \sqrt{m_i/m_e} = B_0 / \sqrt{4 \pi m_e n_i}. \] Assuming that the ion temperature in the plasma sheet is of the order of the electron one, we get \( V_{Ae} \approx V_e \). This result is consistent with our simulation result in Figure 2.

Note that the size of \( \Delta_e \) is coupled with Hall electric current dynamics [Coroniti, 1985], and the self-consistent understanding of the closure of the Hall electric current and the size of the diffusion region are open questions. If a large Hall electric current flows in the diffusion region, there is a large velocity difference between ions and electrons across the magnetic field \( B_z \). In such a situation the Buneman-like instability may be expected if an ion is unmagnetized on \( B_z \) [e.g., Dieckmann et al., 2000; Shimada and Hoshino, 2001]. Therefore electrons will be heated by the waves exited by the Buneman-like instability, and the electron unmagnetized region \( \Delta_e \) will become wider so as to reduce the Hall electric current. Understanding of this feedback process seems to be a critical issue in collisionless magnetic reconnection.

3.5. Electron PSBL Beam II

The electron beams are accelerated further in a slightly downstream region, as seen in the distribution function (c) of Plate 3 (bottom, second panel). We study the origin of such energetic electrons in the same manner as that discussed in Plate 4. We select first the high-energy electrons satisfying \( |V| > 2V_e \) from this distribution (c) shown in Plate 3 at \( t/\tau_A = 48.8 \), and trace the position of electrons backward in time. The result is given in Plate 5, in the same format as Plate 4. We find that the history of electron trajectories is almost similar to that studied in Plate 4, and they are transported from the X-type region toward the O-type region along the reconnecting magnetic field. However, electrons are distributed in both the positive and negative \( Z \) domains near \( X/\lambda = -8 \sim -4 \) at \( t/\tau_A = 48.0 \) (red) and 47.0 (green). From the partial distribution functions depicted in Plate 5 (bottom), we find that the energetic particles are accelerated as time goes on (see \( \varepsilon_{ele}/m_e c^2 \gtrsim 0.1 \)). By comparing this result with Plate 4, one can see that the number of energetic electrons of \( \varepsilon_{ele}/m_e c^2 \gtrsim 0.05 \) increases between \( t/\tau_A = 47.0 \) and 48.8.

From the fact that such particles are distributed both in the positive and the negative \( Z \) domain, i.e., the south and the north hemisphere in the course of acceleration, we can deduce that the energetic electrons are produced after bouncing in the magnetic flux tube. Since the magnetic mirror ratio is quite different between the plasma sheet and the boundary region between the lobe and the plasma sheet, some electrons ejected from the plasma sheet can be reflected backward the plasma sheet again, depending on their pitch angles. On the other hand, for the case of the distribution (b) in Plate 3 (bottom), most electrons come directly from the X-point region without such a bouncing motion, and the energy gain is limited.

From the magnetic field structure in Plate 2, we know that the strong magnetic field gradient and curvature region exists near \( X/\lambda = -6 \). The magnetic field pileup is produced by the collision of the reconnection outflow with the preexisting plasma. Since the direction of the electric field \( E_y \) is opposite to the \( \nabla B \) drift and the curvature drift for electrons, they can gain energy from the dawn-dusk electric field during the bouncing motion. We think that not only the acceleration in the X-type region but also this acceleration in the magnetic field pileup region is important.

3.6. Particle Trajectories

To understand further the behavior of electrons, we show several particle trajectories both in the \( x-z \) plane and in the \( x-y \) plane. Our simulation is carried out with a two-dimensional assumption with \( \partial/\partial y = 0 \), but we calculated the positions of particles in three-dimensional space in order to study how the particle gains its energy from the inductive electric field \( E_y \) and/or the wave electric fields. Figures 5 shows the electrons’ orbits for the time interval from \( t/\tau_A = 48.8 \) to 52.4. The start points are denoted by S1, S2, etc., while the end points are shown by E1, E2 etc. Figure 5 (top) shows the trajectories in the \( x-z \) plane, and Figure 5 (bottom) shows the \( x-y \) plane. Particles numbered 1 to 4 are shown in Figure 5 (left), while particle numbered 5 is in Figure 5 (right). Note that from the reconnection structure in Plate 2 the X-type region is located in \( X \sim 0 \) and the magnetic pileup region is \( X/\lambda \sim -8 \).

The particle’s orbit S1-E1 is the most typical one that contributes to the electron PSBL beam such as seen in the distribution (b) of Plate 3. The electron is transported from the X-type region to the lobe boundary region almost along the magnetic field line. In the magnetic diffusion region near \( -6 < X/\lambda < 0 \), it moves toward the negative \( y \) direction, this is suggestive of the energy gain from the \( E_y \) electric field. From \( X/\lambda = -6 \) to \( X/\lambda = -11 \), the \( y \) displacement is very small, and the electron is ejected from the plasma sheet to the lobe boundary region with the stronger magnetic field. This trajectory can be basically understood in terms of the Speiser motion [Speiser, 1965]. (Note that the reconnection plane is not flat because of the Hall current effect, and the discussion on the energy gain from the convection electric field should be done in the tilted plane. Therefore the positive displacement \( y \) of the S1-E1 orbit around \( X/\lambda = -7.5 \sim -10 \) does not necessarily mean energy loss.)

The particle’s orbit S2-E2 is another example that contributes to the energetic electron population seen in the distribution (c) of Plate 3. The electron is preaccelerated in the magnetic diffusion region, and next in the magnetic field pileup region in \( X/\lambda \sim -6 \), it drifts toward the negative \( y \) direction mainly owing to the \( \nabla B \) drift. During this drift motion it strongly gains energy from the dawn-dusk \( E_y \) electric field. This process is ba-
sically similar to the shock drift acceleration that is extensively discussed in quasi-perpendicular shock waves [e.g., Hudson, 1965]. This effect can be clearly observed from the trajectory in the x-z plane.

In this reconnection situation the accelerated electrons by $\nabla B$ drift are ejected from the plasma sheet, but some of them are reflected back because of the mirror magnetic field in the lobe boundary, and then enter again the acceleration region. This multiple acceleration process due to the mirror field enhances the acceleration efficiency.

Another important effect is the curvature drift with $\kappa \sim 1$, which makes the particle motion complicated and/or chaotic, where $\kappa^2$ is the ratio of the curvature for the magnetic field and the Larmor radius. Since the particles with $\kappa \sim 1$ are scattered toward the larger pitch angle region because of a centrifugal force perturbing the particle gyromotion in a weak magnetic field region [Delcourt et al., 1996; Smets et al., 1998], they have a tendency to stay for a longer time in the plasma sheet, which in turn contributes to the preferential acceleration for the energetic electrons with $\kappa \sim 1$. The particle’s motion S5-E5, which is being confined in the plasma sheet during the $\nabla B$ drift, may be understood by the chaotic trapping with $\kappa \sim 1$. We think that this motion is due to wave scattering with the broadband waves excited in the plasma sheet (see the electric fields in Plate 2). The particle’s motion of S4-E4 is another example. The pitches of the sinusoidal motion become narrow in three locations of $(X/\lambda, Z/\lambda) \sim (-7.5, 0), (-10, 2),$ and $(-11, 2.5)$, which means the pitch angles are larger. Since the particle is moving in one direction toward the lobe boundary region, the repetition of the pitch angle changes cannot be understood by the simple mirror force. We think standard wave scattering may explain such behavior.

We believe that standard particle scattering by electromagnetic waves is one of the important agents of acceleration. As shown in Plate 2, the strong, localized waves are excited in the boundary region. Hoshino et al. [2001] discussed that a broadband wave spectrum form the lower hybrid frequency to the plasma frequency is generated in association with the strong Hall current region and concluded that the electron beams seen in the distributions (b) and (c) in Plate 3 (bottom) is the free energy source of the broadband waves. Although the spatial resolution in our simulation is not good so far, we think that the strong wave activity in our simulation is also related to the mechanism of exciting the electrostatic solitary wave (ESW) in the magnetotail [Kojima et al., 1994] due to the bump-on-tail instability [e.g., Omura et al., 1994]. In the strong Hall current region, the current-driven electromagnetic ion cyclotron instability may also play an important role in the parallel heating of electrons [e.g., Perraut et al., 2000].

From the orbit of S3-E3 we find a cross-field motion in $(X/\lambda, Z/\lambda) \sim (-7.5, -0.5)$. Since the Larmor radius is much smaller than the curvature radius for the magnetic field line, the strange motion cannot be understood by the chaotic behavior with $\kappa \sim 1$. We think that this motion is due to wave scattering with the broadband waves excited in the plasma sheet (see the electric fields in Plate 2). The particle’s motion of S4-E4 is another example. The pitches of the sinusoidal motion become narrow in three locations of $(X/\lambda, Z/\lambda) \sim (-7.5, 0), (-10, 2),$ and $(-11, 2.5)$, which means the pitch angles are larger. Since the particle is moving in one direction toward the lobe boundary region, the repetition of the pitch angle changes cannot be understood by the simple mirror force. We think standard wave scattering may explain such behavior.

This complexity of the particle’s trajectory is summarized in Figure 6. Region I is the meandering/Speiser motion in the magnetic diffusion region where the Hall current dynamics is important, region II is the magnetic
Figure 6. Sketch of several important processes in the x-z plane near the magnetic reconnection region. The contour lines are the magnetic field lines for reference.

3.7. Isotropic Energetic Electrons

The isotropic and energetic electron distribution function (d) appears downstream of the electron PSBL beams in Plate 3. To understand the mechanism producing the isotropic and energetic electrons, we trace the position of the high-energy electrons backward in time again and discuss where and how the high electrons are produced. We select the energetic electrons with $|V/V_e| > 1.5$ at $t/\tau_A = 48.8$. Plate 6 shows the result of the backtrace of electrons in the same format as Plate 4. One can see that the electrons at $t/\tau_A = 41.6$ are situated on the lobe magnetic fields that are not yet reconnected at the X-type region, and after $t/\tau_A > 44.4$, they enter into the plasma sheet with the reconnecting magnetic fields. From the partial distribution functions constructed from only the selected particles with $|V/V_e| > 1.5$ at $t/\tau_A = 48.8$, we find that the electrons are cold at $t/\tau_A = 41.6$, but after $t/\tau_A > 44.4$, the particles are heated up, and a number of energetic particles increase with time.

As contrasted with Plates 4 and 5, the electrons in Plate 6 are distributed in the right-hand and left-hand side of the plasma sheet. Our simulation is performed with the periodic boundary condition in the x direction, and the left and right boundaries are $X/\Lambda = \pm 19.2$. We find that most electrons distributed in the right-hand side of the plasma sheet at $t/\tau_A = 45.3$ (green) propagate farther downstream of the right-hand side of the plasma sheet and appear from the left-hand boundary. Therefore the isotropic energetic particles in the distribution (d) in Plate 3 are produced under the closed field line topology in our case. Of course, the bouncing motion due to the mirror force is important in this transport process, and we think that the energization from $t/\tau_A = 44.4$ to $t/\tau_A = 45.3$ is due to the $VB$ and curvature drift with $\kappa \sim 1$.

4. Discussion and Conclusions

Motivated by the nonthermal electron observations of Geotail, we studied the electron acceleration process in the course of magnetic reconnection by using the particle-in-cell simulation. We found that not only the acceleration process due to the meandering/Speiser motion in and around the X-type region but also the $VB$ and the curvature drift near the magnetic field pileup region are important to origins of nonthermal electrons.

In the vicinity of the X-type region the electron unmagnetized region is extended to $|X| \sim \Delta_s = \Delta_s (m_e/m_i)^{1/3}$, and during the meandering/Speiser motion electrons can be accelerated to the order of the electron Alfvén velocity, $V_{A,e} (m_e/m_i)^{1/6}$. This is the first stage of acceleration, and the accelerated electrons are transported outward. During the second stage, some of them are further accelerated around the pileup magnetic field region because of $VB$ drift and curvature drift under the nonadiabatic motion of $\kappa \sim 1$. The broadband waves excited by the strong Hall current seem to be the other important agent for controlling particle acceleration. Several other important issues on acceleration are discussed in the following subsections.

4.1. Structure of Pileup Magnetic Field Region

The pileup of the magnetic field can be formed by the collision of the reconnection outflow with the pre-existing plasma sheet. A tangential discontinuity that separates the plasma with and without the reconnecting...
magnetic field \( B_z \) is formed in the colliding region, and the plasma compression launches the fast mode magnetosonic waves propagating in both the positive and negative \( z \) directions, which in turn may form the forward shock and the reverse shock, respectively. The front of the reverse shock corresponds to the front of the magnetic pileup region, if the reconnection outflow exceeds the Mach number in the high-\( \beta \) plasma sheet.

The stronger is the magnetic field in the pileup region, the more energization of electrons can be expected. In our simulation results in Plate 2, the pileup region is formed just ahead of the thin, elongated current region, and the pileup region is not well separated from the edge of the diffusion region. From another simulation with a large system size, however, we confirmed that the two boundaries are clearly separated, and we also find the intensity of the pileup magnetic field is of the order of that of the lobe magnetic field. Estimating theoretically the intensity of the pileup magnetic field is an open question.

### 4.2. Electron Energy in Pileup Magnetic Field Region

The energy gain due to the \( \nabla B \) drift near the magnetic pileup region may be discussed by using of the shock drift acceleration [e.g., Hudson, 1965]. For quasi-perpendicular shock waves it can be shown that the magnetic moment of an energetic particle whose Larmor radius exceeds the shock thickness is approximately conserved across the shock front [Terasawa, 1979]. Some particles approaching the shock can be reflected from the shock, depending on their particle pitch angles, and then the \( \nabla B \) drift parallel/antiparallel to the electric field can accelerate ions/electrons. In our reconnection case the pileup magnetic field \( B_{\text{pile}} \) is of the order of the lobe magnetic field, and the magnetic field intensity at the edge of the magnetic diffusion region, \( B_{\text{xp}} \), may be estimated by

\[
B_{\text{xp}} \approx B_{\text{lobe}} M ,
\]

where \( M \) is the reconnection rate of the order of \( 10^{-1} \). Therefore the change of the reconnecting magnetic field intensity \( \Delta B_z \) at the magnetic pileup region is given by

\[
\Delta B_z = \frac{B_{\text{pile}}}{B_{\text{xp}}} \approx 10 \left( \frac{0.1}{M} \right) ,
\]

and assuming an adiabatic process, the corresponding energy gain of electron \( \Delta e_{\text{ele}} \) may be estimated by

\[
\Delta e_{\text{ele}} = \frac{e B_{\text{pile}}^2}{2 m_e c} = \Delta B_z \approx 10 \left( \frac{0.1}{M} \right) .
\]

This is a rather minimal estimate of accelerated particles. The particles can be further accelerated by being trapped in the plasma sheet because of the mirror magnetic field. As discussed in the particles’ trajectories in Figure 5, some particles ejected from the plasma sheet into the lobe boundary can be reflected back toward the acceleration region in the plasma sheet owing to the mirror force in the lobe magnetic field. In addition to the mirror force, the curvature drift and the chaotic pitchangle scattering process with \( \kappa \sim 1 \) are also important. The particles with \( \kappa \sim 1 \) have a tendency to be scattered toward the large pitch angle region in the velocity space owing to the centrifugal force [Delcourt et al., 1996; Smets et al., 1998]. Therefore they can gain more energy than that estimated above.

### 4.3. Energy Range of Nonadiabatic Electron

Let us briefly discuss what electron energy \( e_{\text{ele}} \) can satisfy \( \kappa \sim 1 \) in the magnetotail. For a simple, parabolic magnetic field case, \( \kappa \) can be express by

\[
\kappa \approx \left( \frac{e B_{n}^2}{e B_0} \right)^{1/2} \left( \frac{1}{2m_e e_{\text{ele}}} \right)^{1/4} ,
\]

where \( B_n \) is the reconnecting magnetic field, \( B_0 \) is the lobe magnetic field, \( e \) is the electric charge, and \( m_e \) is its mass [e.g., B"uchner and Zelenyi, 1989]. Therefore the electron energy \( e_{\text{ele}} \) with \( \kappa \sim 1 \) can be estimated by

\[
e_{\text{ele}} \sim 1.7 \text{ keV} \left( \frac{1}{\kappa} \right)^4 \left( \frac{M}{0.1} \right)^2 \left( \frac{B_n}{2 \text{ nT}} \right)^2 \left( \frac{\lambda}{720 \text{ km}} \right)^2 ,
\]

where we assumed that \( B_n/B_0 \) is given by the reconnection rate \( M \) and \( \lambda \) is of the order of the ion inertia length \( c/\omega_{pi} \), which can be estimated by

\[
\frac{c}{\omega_{pi}} \sim 720 \text{ km} \left( \frac{n_e}{0.1 \text{ cm}^{-3}} \right)^{-1/2} .
\]

From the above simple estimation we think that the electron nonadiabatic behavior is important for \( e_{\text{ele}} \geq 4 \) a few keV in the magnetotail reconnection region. However, the plasma sheet probably becomes thick with increasing distance from the \( X \)-type region, and the electron energy \( e_{\text{ele}} \) satisfying \( \kappa \sim 1 \) will increase.

### 4.4. Acceleration Site

In the satellite observations in the magnetotail, energetic particles \( \geq 4 \) several hundred keV are often observed, and a number of convincing energetic particle observations that are related to magnetic reconnection have been reported [Terasawa and Nishida, 1976; Baker and Stone, 1996, 1997; Möbius et al., 1983]. If we re-examine Terasawa and Nishida’s [1976] figures on the relationship between the energetic electron burst and magnetic fields, it seems that the electron burst is often observed in a relatively large \( B_n \) magnetic field region. However, now to determine observationally the site of the energetic particle is still an open question owing to the difficulty in detecting a small number of energetic particles. For electrons with middle energy of \( \leq 40 \) keV, however, Nagai et al. [1998] reported that the hot electron enhancement of several tens of keV is often asso-
associated with the strong reconnecting magnetic fields \( B_z \). So far, these observations are in a good agreement with our study.

### 4.5. Energy Spectrum

We did not discuss the type of nonthermal spectrum. It is important to know the energy spectrum and the efficiency of the high-energy particle production. We think that a Fermi-type acceleration may occur near the magnetic pileup region. Namely, the multiple crossing of the plasma sheet, depending on the particle's gyrophase, may lead to a stochastic acceleration. In our simulation study, it is still difficult to discuss very suprathermal particles because of the limitation of our computer resources. We cannot have enough particles to resolve high-energy particles. We think that a test particle treatment that takes into account several modules of our acceleration processes summarized in Figure 6 is a better approach for understanding the nonthermal spectrum. We are planning to study the evolution of the high-energy spectrum in another paper.

### 4.6. Dawn-Dusk Asymmetry

It is interesting to know how the energetic particles are distributed in the magnetotail, namely, to study the so-called dawn-dusk asymmetry. Figure 7 shows the relationship between the energy gain \( \Delta \varepsilon \) versus the travel distance of \( \Delta Y \) for electrons. If the energy gain is due only to the dawn-dusk electric field \( E_y \) under the two-dimensional, steady state reconnection, \( \Delta \varepsilon \) should be proportional to \( E_y \Delta Y \). From our simulation result in Figure 7 we find a good correlation between \( \Delta \varepsilon \) and \( \Delta Y \), but the data points are rather scattered around the linear relation. Several reasons are proposed: (1) the electric field \( E_y \) is not uniform in space (see Plate 2); therefore the drift motion in the plasma sheet with a negative displacement \( \Delta Y \) gains kinetic energy from the dawn-dusk \( E_y \) field, but the drift motion in the lobe boundary with a positive displacement \( \Delta Y \) loses kinetic energy in a different rate. (2) Since the strong wave activity exists in the boundary between the lobe and the plasma sheet and in the plasma sheet, electrons can gain kinetic energy from those waves during the scattering process; these waves may lead to a stochastic, Fermi-type acceleration [e.g., Shimada et al., 1997]. (3) The time evolutional effects should be taken into account.

In the statistical survey on the dawn-dusk asymmetry for the energetic electrons of \( \sim 40 \) keV by Geotail, the count rate for the energetic electrons is found to be only slightly asymmetric [I. Shinohara; private communication, 2000]. In our simulation result the particle distribution in Figure 7 is broad, but the accelerated electrons are transported only to the negative \( Y \), i.e., to the duskside region. This large asymmetry is not consistent with the Geotail observations. In our simulation we confirmed that wave scattering is occurring, but it seems to play a minor role compared with the energization by a large-scale reconnection electric field.

![Figure 7. Relationship between total displacement in the y direction and the energy gain for randomly sampled electrons in the reconnection region. They are measured from \( t/r_A = 48.8 \) to \( t/r_A = 52.4 \).](image)

Since a strong turbulence is observed in Earth's magnetotail, the wave scattering might be more significant in the magnetotail than is implied by our simulation modeling. The three-dimensional particle transport in the magnetotail might be taken into account [e.g., Ashour-Abdalla et al., 1997]. These are unresolved issues.

### 4.7. Other Comments

In the Geotail reconnection observations we often observe isotropic energetic electrons in velocity space. We demonstrated the formation of a similar type of the distribution in Plate 3 (d) in our simulation study, but we need a closed magnetic field to produce an isotropic distribution. In Earth’s magnetotail the electrons transported to Earth are reflected back from the lower altitude, but this situation may not be applicable to the distribution observed in the tailside reconnection region. Whether the magnetic field is open or closed is an open question for the plasmoid propagating tailward. The closed magnetic island may be often formed by multiple active reconnections [e.g., Mukai et al., 1996; Hoshino et al., 1996].

We think that the acceleration mechanism discussed here can be applied to magnetic reconnection in other planetary magnetospheres and in the solar corona. In the first stage of acceleration the energization occurs near and at the \( X \)-type neutral region. In the second stage the \( \nabla B \) and curvature drift near the magnetic pileup region play an important role in stochastic acceleration. If the energetic electron acceleration occurs only in the vicinity of the \( X \)-type neutral line, the efficiency of acceleration normalized in the system size seems to be small. However, the size of the pileup region is not small compared with the reconnection system size, and we think that total efficiency of acceleration may become significant for the second stage of acceleration.
The electron energy spectrum obtained in the simulation is normalized by the electron rest mass energy, and we found the enhancement of the phase space density above the Maxwellian level for $e_{\text{dyn}} > 0.1m_e c^2$. We used the artificial mass ratio between ion and electron, and the acceleration process is strongly coupled with both ion and electron dynamics. Therefore the scaling of $\sim 0.1m_e c^2$ to the energetic particles in the magnetotail still remains an open question.

Finally, thus far, we discussed electron acceleration focusing on the magnetic pileup region. We think that our acceleration mechanism can be applied for ions.

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M. Hoshino and T. Terasawa, Department of Earth and Planetary Physics, Faculty of Science, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan. (hoshino@eps.s.u-tokyo.ac.jp) T. Mukai and I. Shinohara, Institute of Space and Astronautical Science (ISAS), Sagamihara, Kanagawa, Japan.

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