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Relativistic Reconnection and Particle Acceleration

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Abstract This chapter mainly deals with magnetic reconnection and particle acceleration in relativistic astrophysical plasmas, where the temperature of the current sheet exceeds the rest mass energy and the Alfvén velocity is close to the speed of light. Magnetic reconnection now receives a great deal of interest for its role in many astrophysical systems such as pulsars, magnetars, galaxy clusters, and active galactic nucleus jets. We review recent advances that emphasize the roles of reconnection in high-energy astrophysical phenomena.

Keywords Magnetic reconnection · Relativistic plasma · Astrophysics · Particle acceleration

1 Introduction

The basic concept of magnetic reconnection was established by Parker, Sweet, and Petschek in the mid-sixties, following earlier ideas proposed by Giovanni and Dungey. They proposed that the rapid release of magnetic energy in a highly conductive plasma medium is possibly due to the introduction of a change in magnetic field topology. Following their pioneering ideas, magnetic reconnection became widely accepted as being important to the plasma universe, because space and astroplasma states often have magnetic fields whose structure contains a neutral sheet where the magnetic field polarity changes direction. During reconnection, there is plasma heating/acceleration and mixing over a broad range of plasma regions. In fact, magnetic reconnection is known to produce nonthermal particles as well as hot plasma during substorms in the Earth's magnetosphere and during a solar flare event in the solar corona. Since magnetic field shear can be expected in many astrophysical settings such as jets, accretion disks, and the pulsar magnetosphere, reconnection is also actively discussed as a possible mechanism for energy release.

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In this chapter, we discuss highlights of reconnection mainly in relativistic astrophysical plasmas, where the temperature of the current sheet exceeds the rest mass energy and the Alfvén speed approaches the speed of light. The nonrelativistic reconnection, that plays an important role in the solar corona, in the Earth's magnetosphere, and in the interplanetary space and so on, is discussed in other chapters in this book.

Section 2 of this chapter briefly reviews several interesting applications of reconnection in various high-energy astrophysical objects, such as accretion disks around a massive central object, a relativistic jet in an active galactic nucleus, a magnetar with an extremely strong magnetic field, and pulsar magnetosphere and relativistic wind. Section 3 discusses particle acceleration and plasma instability for a relativistic current sheet. In the relativistic plasma sheet with pair plasma, not only magnetic reconnection, but also drift-kink instability, excited along the electric current direction becomes important for the energy dissipation of the magnetic field.

2 Relativistic Magnetohydrodynamics (MHD) Reconnection in Astrophysics

Reconnection becomes relativistic if the energy available per particle exceeds the particle rest energy. The energy source for the reconnection process is the magnetic field; therefore, the reconnection becomes relativistic if the so-called magnetization parameter,

$$\sigma = \frac{B^2}{4\pi\rho c^2}, \tag{1}$$

exceeds unity. In this case, the Alfvén velocity in the cold plasma limit approaches the speed of light:

$$v_A = c\sqrt{\frac{\sigma}{1+\sigma}}. \tag{2}$$

The classical reconnection models can be generalized to the relativistic case straightforwardly (Lyubarsky 2005). The general picture remains the same as in the nonrelativistic reconnection; in most cases, one obtains reasonable estimates simply by substituting the speed of light instead of the Alfvén velocity in the classical formulas. Still, some important specific features should be taken into account.

In the Sweet–Parker regime, the thickness of the current sheet and the reconnection rate are respectively estimated as

$$v_{\rm rec} \approx \frac{c}{\sqrt{S}}, \qquad \Delta \approx \frac{L}{\sqrt{S}}. \tag{3}$$

Here, S is the Lundquist number and L the length of the sheet. The condition of the pressure equilibrium implies that the plasma in the current sheet is relativistically hot:

$$kT \approx \frac{1}{2}\sigma mc^2, \tag{4}$$

where m is the average particle mass. In the relativistic case, one has to take into account the production of electron–positron pairs; therefore, the average particle mass could differ from the proton mass. The plasma is ejected from the current sheet with mildly relativistic velocities so that the Lorentz factor is of the order of unity.

In the Petschek regime, the reconnection rate is estimated as

$$v_{\text{rec}} \approx \frac{c}{\ln S} \approx 0.1c. \tag{5}$$

The plasma is ejected from the system between two pairs of slow shocks with Alfvén velocity (2); in the high-σ limit, the outflow becomes highly relativistic with the Lorentz factor $\gamma = \sqrt{\sigma}$.

An important point is that at the relativistic slow shock, the plasma is strongly compressed $\sim\sigma$ times. Therefore, the plasma is ejected in the form of two very narrow and dense plane jets. A very high compression implies an important difference with the nonrelativistic regime. In the case of nonrelativistic shocks, the compression ratio is finite; therefore, even if the magnetic fields are not strictly antiparallel, a small guide field (the component parallel to the current in the current sheet) remains small and does not affect the structure of the flow. In the relativistic case, even a small guide field is greatly enhanced by compression so that the plasma outflow can become highly magnetized. This does not affect the reconnection rate however, and most of the energy of the reconnecting fields is not transferred to the plasma but removed by two exhausts in the form of Poynting flux. The dissipation occurs at a later stage: the highly magnetized outflows excite MHD turbulence in the main plasma volume so that a turbulent cascade transfers the energy towards smaller scales where it is eventually absorbed. Turbulent cascades in high-σ plasmas have recently attracted much attention (Thompson and Blaes 1998; Cho 2005; Luo and Melrose 2006); however, plasma heating and the possible particle acceleration in this regime have not been studied yet.

For astrophysical applications, the fast Petschek regime is of special interest. Transition to this regime occurs when the Sweet–Parker thickness of the current sheet becomes smaller than the particle Larmor radius (for the ion in electron–ion plasma and electron in pair plasma) (Cassak et al. 2005; Bessho and Bhattacharjee 2007).

Since the particles acquire relativistic energies in the course of relativistic reconnection, the pair production and radiation effects could become important. First, the structure of the reconnecting layer could be strongly affected by radiation cooling (Jaroschek and Hoshino 2009). In some extreme cases, one should take into account even the radiation pressure. The Compton drag in the dense radiation field could give rise to strong resistivity. Pair production makes these effects even stronger because the optical depth of the region increases. Moreover, since the particle density in the current sheet increases because of both radiation cooling and pair production, these effects could lead to enhanced collisional resistivity. These issues were recently reviewed by Uzdensky (2011).

Astrophysical applications of the relativistic reconnection are associated with highly magnetized, compact bodies such as neutron stars and black holes. In the last case, the magnetic field is attributed to currents in the accretion disc surrounding a black hole. Magnetic reconnection could occur both in the magnetosphere of the magnetized bodies and in relativistic, magnetized outflows emanating from these objects.

If some free magnetic energy is built up in a magnetosphere, it could be released in explosions resembling solar flares. The necessary conditions could naturally arise in coronae around accretion disks as shown in Fig. 1a. Uzdensky and Goodman (2008) and Goodman and Uzdensky (2008) recently analyzed the properties of the magnetically structured corona taking into account the buildup of the magnetic field due to the emergence of magnetic loops into the corona, random foot-point motions, and Keplerian shear on the one hand and magnetic reconnection on the other.

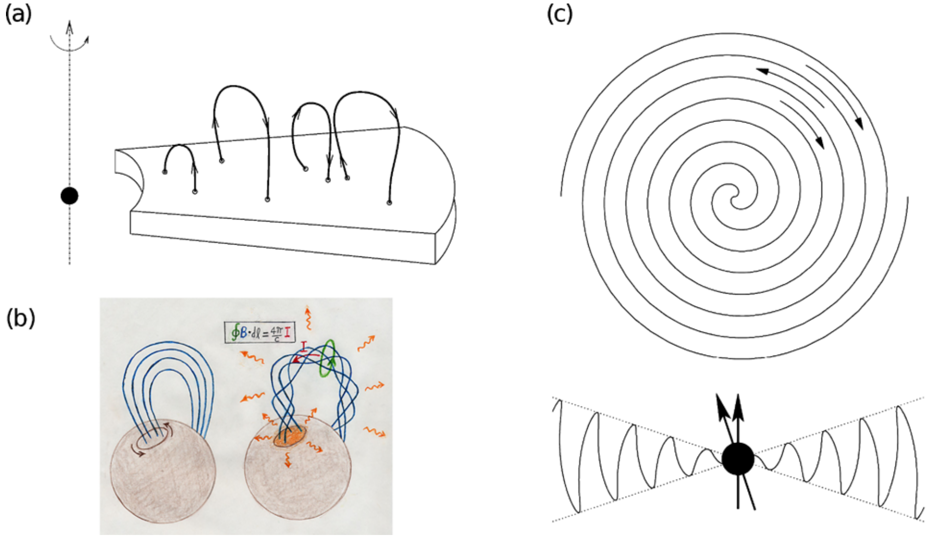

Fig. 1 Family of magnetic reconnections in astrophysics. (**a**) Schematic view of the accretion disk corona, adapted from Uzdensky and Goodman (2008). (**b**) Sketch of a magnetar model showing how a seismic shift in the magnetar's crust can twist the strong magnetic field lines, which may lead to magnetic reconnection. Courtesy R. Duncan. (**c**) Striped pulsar wind model, adapted from Kirk and Skjæraasen (2003). At *top* are Parker spiral magnetic field lines in the equatorial plane, while at *bottom* is the poloidal structure of the current sheet with the reversal of the magnetic field polarity. The *arrows* denote the spin axis (*vertical*) and magnetic dipole axis (*inclined*)

Magnetospheres of neutron stars are mostly quiet because there is no motion in the interior of these stars. Magnetars are exceptions because their magnetic fields are so large that the magnetospheres cannot be entirely fixed even within the neutron stars. Therefore, slow magnetically driven motions of the star interiors distort the coronal magnetic field, producing unstable magnetic configurations (see Fig. 1b), which give rise to powerful flares observed in the spectrum of hard X-rays (Thompson and Duncan 1995). Magnetic reconnection is a crucial element of the process; however, an important point is that immediately after the onset of the energy release, the copious pair production totally obscures the energy release zone. Therefore, the observed properties of the flare are practically independent of the reconnection physics. The observer can see only thermalized emission from the photosphere of the fireball. Additionally, the time variations are determined not by the physics of the energy release mechanism but by the dynamics of the fireball and by the radiation cooling processes.

Relativistic winds and jets are an important domain for the application of reconnection theory. It is now widely agreed that relativistic outflows are launched hydromagnetically. The scenario commonly invoked is that a strong magnetic field in a rapidly rotating compact object serves to convert the rotational energy into the energy of the outflow (see, e.g., Belloni 2010). The main advantage of the magnetic launch mechanism is that the magnetic field lines, like driving belts, can transfer rotational energy to a low-density periphery of the central engine, thus forming a purely baryonic outflow with the energy per particle appreciably exceeding the rest mass energy. Such outflows are potentially capable of reaching relativistic velocities. Since the energy is transported, at least initially, in the form of Poynting flux, the question arises of how and where the electromagnetic energy is eventually transformed to plasma energy. In the scope of ideal magnetohydrodynamics, the energy could in principle be transferred to the plasma via gradual acceleration by electromagnetic stresses. However, a systematic study (Komissarov et al. 2009; Tchekhovskoy et al. 2009, 2010; Lyubarsky 2009) showed that even though externally confined flows could in principle be accelerated until there is equipartition of the kinetic and magnetic energy, the conditions would be rather restrictive. Moreover, the truly matter-dominated stage could in any case be achieved only at exponentially large distances (Lyubarsky 2010a). Therefore, magnetic dissipation (reconnection) is necessary to use the electromagnetic energy of the flow. The reconnection implies switched magnetic polarity within the flow (i.e., striped wind, see Fig. 1c). Such a structure naturally forms in outflows from obliquely rotating sources, such as pulsars or magnetars (Michel 1971; Usov 1994). Accreting systems are axisymmetric; however, one can speculate that in the accretion disk, dynamo action and magnetorotational instability generate magnetic fields of alternating polarity (Spruit et al. 2001). Thus, independent of the exact field configuration at the launch site, the flow expansion ensures that in the far zone, the overall magnetic structure is that of the striped wind with stripes of oppositely directed azimuthal fields separated by current sheets. The width of the stripes is small relative to all characteristic scales, and therefore, the structure of the flow is locally simple; i.e., plane current sheets separate domains with oppositely directed magnetic fields.

When applying the reconnection theory to relativistic winds and jets, one has to take into account an important point that is sometimes ignored. In the standard approach, a steady-state regime is assumed; the reconnection rate is then determined by the rate of evacuation of the plasma from the current sheet because the reconnecting magnetic field lines are loaded with the plasma and, for the reconnection process to proceed, this plasma should be continuously removed from the current sheet. In classical reconnection models, the plasma is ejected from the sides of the reconnection box; such an exhaust forms in Alfvén propagation time $\sim L/c$ and the classical reconnection regime is therefore established on the time scale $t \gg L/c$. This condition may not be easily fulfilled in relativistic flows because of the relativistic dilation of time. In striped winds, the size of the current sheets is of the order of the transverse size of the flow, and the steady reconnection regime can therefore be established only if the Alfvén propagation time across the flow, $\Theta r/c$, where Θ is the opening angle of the flow and r the distance from the origin, is less than the proper propagation time, $r/(\gamma c)$, where γ is the bulk Lorentz factor of the flow. This implies that the classical Sweet–Parker or Petschek reconnection regimes can develop only if $\Theta\gamma < 1$. This condition is obviously violated in pulsar winds, but even in narrow jets it is not always fulfilled; for example, in gamma-ray bursts, $\Theta\gamma$ typically exceeds unity and could reach a few dozen (e.g., Tchekhovskoy et al. 2010). In this case, the steady-state reconnection models outlined above become irrelevant because the plasma is not ejected from the sides of the current sheet.

In principle, plasma accumulation within the sheet could be compensated for by the lateral expansion of the flow. In pulsar winds, the particle density is so small that the alternating magnetic fields cannot be maintained beyond some distance from the center because of charge starvation. That is to say, the amplitude of the magnetic oscillations, which is proportional to the current flowing in the sheets, decays only as $1/r$, whereas the column density of the particles in the sheet decreases as $1/r^2$. At some radius, therefore, there ceases to be enough particles to carry the required current and the current sheet then begins to recruit additional charge carriers from the surrounding magnetized plasma, which annihilates the magnetic flux that originally threaded the newly recruited charge carriers. This hinges on the existence of anomalous resistivity, and the rate at which it can proceed depends on the details of the microphysics of this mechanism. In any case, one can expect that the process comes into play when the thickness of the current sheet becomes comparable to the gyroradius of the sheet particles or, equivalently, when the drift velocity of the current-carrying charges approaches the speed of light. Dissipation causes the supersonic flow to accelerate, thus effectively converting Poynting flux into kinetic energy. An inescapable side effect of this acceleration is therefore the relativistic dilation of the dissipation time scale. Taking this into account, it has been found that the alternating magnetic fields are annihilated completely only at distances comparable to the radius of the termination shocks (Lyubarsky and Kirk 2001; Kirk and Skjæraasen 2003; Zenitani and Hoshino 2007). Whether the dissipation process is complete before the wind arrives at the shock or the wind enters the shock still being Poynting-dominated depends on the parameters of the wind and uncertainties in the resistivity mechanism. However, even if the alternating fields survive, they dissipate completely at the shock front via the compression-driven reconnection (Lyubarsky 2003; Pétri and Lyubarsky 2007; Nagata et al. 2008; Sironi and Spitkovsky 2011). Therefore, in pulsar winds, the Poynting flux is transferred to the plasma via magnetic dissipation.

The charge starvation mechanism operates in pulsar winds because the plasma density is extraordinarily low. Even though the content of jets in active galactic nuclei and gamma ray bursts is uncertain, one can expect that these outflows are typically heavily loaded by plasma from the accretion disk, and therefore, the charge starvation conditions are achieved only at unreasonably large distances. This notwithstanding, the magnetic reconnection in relativistic jets is widely invoked in models of the active galactic nuclei (Romanova and Lovelace 1992; Giannios et al. 2009, 2010) and gamma ray bursts (Thompson 1994, 2006; Usov 1994; Spruit et al. 2001; Drenkhahn 2002; Drenkhahn and Spruit 2002; Giannios 2008. An efficient mechanism for the dissipation of alternating fields in the Poynting-dominated outflows was proposed by Lyubarsky (2010b).

If the flow is accelerated, an effective gravity force appears in the proper plasma frame so that the hot plasma within the current sheet is supported against the gravity force by the magnetic pressure. Such a configuration is known to be unstable with respect to the Kruskal–Schwarzschild instability, which is a magnetic counterpart of the Rayleigh–Taylor instability. Under the influence of the effective gravity force, the plasma could drip down between the magnetic field lines so that bridges between trickles thin out until the current sheet tears. Thus, the instability facilitates the reconnection. An important point is that the magnetic dissipation forces the flow to accelerate and the process is thus self-sustaining; i.e., the acceleration is an aid to reconnection whereas the reconnection promotes acceleration. Owing to the interplay between the reconnection and acceleration, the flow slowly accelerates at the expense of the magnetic energy until the alternating fields annihilate completely. Note that the proposed mechanism is based on an MHD instability of the current sheet and is independent of anomalous resistivity and the mechanism is therefore universal; it is seen that alternating fields inevitably dissipate in Poynting-dominated outflows.

3 Particle Acceleration and Kinetic Aspects of Magnetic Reconnection

In high-energy astrophysical settings, there are many cases where the Coulomb mean-free path is many orders of magnitude larger than the system size of interest. In these cases, not only the heated thermal plasma, but also nonthermal high-energy particles deviating from the Maxwellian velocity distribution function can be generated by magnetic reconnection.

Recently, particle acceleration in the course of relativistic reconnection has been intensively studied. A simple model of the acceleration of suprathermal particles in the vicinity of an X-point was presented by Romanova and Lovelace (1992) and Larrabee et al. (2003). The plasma converges to the reconnection site and thus generates the motional electric field

$\mathbf{v} \times \mathbf{B}$, which does not vanish even at the X-point where the magnetic field goes to zero because of the inertia resistivity. Therefore, a region in which $E > B$ arises, where the particles are accelerated almost along the zero magnetic field line. Since the particles are deviated from the zero line by the Lorentz force, they eventually leave the acceleration zone, the final energy being dependent on how close the particle approaches the X-point.

This X-point acceleration mechanism can be simply formulated when the electric field E is stronger than the reconnecting magnetic field B (Zenitani and Hoshino 2001a). For simplicity, we assume that the reconnecting magnetic field structure is modeled by $B = B_{0x} \tanh(z/\lambda) e_x + B_n \tanh(|x/L|^s (x/|x|)) e_z$ in two-dimensional space of x and z, where the index s represents the structure parameter characterizing the reconnecting magnetic field topology around the X-type region. The particle quickly gains relativistic energy in the region of $E_y > B_z = B_n \tanh(|x/L|^s (x/|x|))$, and the total energy gain of the particle ε may then be estimated as

$$\varepsilon \approx \int ecE_y dt = \int_{x_{in}}^{x_{out}} ecE_y \frac{dx}{v_x}, \tag{6}$$

where x_{in} and x_{out} show the position of a particle that enters the acceleration region and the position of its exit from the acceleration region, respectively. We have assumed that the velocity v_y of the accelerated particle is of the order of the speed of light. The velocity v_x in the acceleration with $E_y > B_z$ may be evaluated as

$$v_x = c\frac{B_z}{E_y} \simeq c\frac{B_n}{E_y}\left(\frac{x}{L}\right)^s \ll c. \tag{7}$$

Combining the above equations, we obtain the total energy gain as a function of the injection potion of the particle:

$$\varepsilon \simeq \begin{cases} \varepsilon_0 (\frac{1}{s-1})(\frac{L}{x_{in}})^{s-1} & \text{for } s > 1 \\ -\varepsilon_0 \log(\frac{x_{in}}{L}) & \text{for } s = 1, \end{cases} \tag{8}$$

where $\varepsilon_0 = eE_y^2 L/B_n$. We have assumed that $x_{in} \ll L$ and $x_{out} \sim L$. Since the number density of the energetic particle accelerated in the vicinity of the X-type neutral line, $N(\varepsilon)d\varepsilon$, is proportional to $|\, dx_{in}/d\varepsilon \,|$, we can calculate the energy spectrum as

$$N(\varepsilon) \propto \begin{cases} (\frac{\varepsilon}{\varepsilon_0})^{\frac{s}{1-s}} & \text{for } s > 1 \\ \exp(-\frac{\varepsilon}{\varepsilon_0}) & \text{for } s = 1. \end{cases} \tag{9}$$

We find that the relativistic X-type acceleration can produce a power-law energy spectrum, but the energy spectrum depends on the magnetic field structure around the X-type region. If the structure parameter $s = 1$, the accelerated particles form a Maxwellian-like spectrum, while for $s > 1$, the spectrum can be approximated by the power-law spectrum with an index of $s/(1-s)$.

The above simple theory can be confirmed by a test particle simulation under the prescribed X-type magnetic field and uniform electric field. We assume $B_n/B_{0x} = 1/10$ and $\lambda/L = 10$, because the reconnection rate of B_n/B_{0x} is thought to be of the order of 10^{-1} (Petschek 1964; Blackman and Field 1994). The charged particles are injected from outside

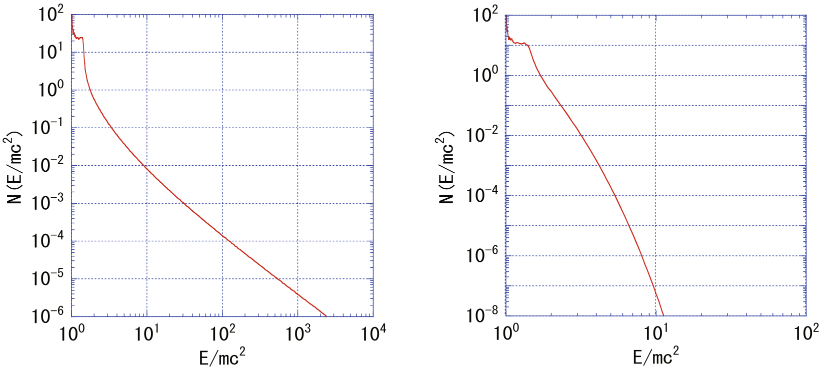

Fig. 2 Energy spectra of a test particle simulation for $B_z = B_n \tanh((x/L)^s)$ with (**a**) $s = 2$ and (**b**) $s = 1$

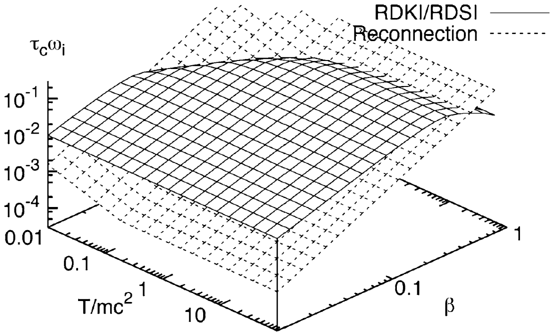

Fig. 3 Linear growth rates ω_i for drift-kink mode (*solid surface*) and reconnection/tearing mode (*dashed surface*) as functions of plasma temperature T/mc^2 and drift velocity $\beta = v_c/c$. The linear growth rate ω_i is normalized by the light transit time of the plasma sheet. Adapted from Zenitani and Hoshino (2007)

the current sheet. Figure 2 shows the energy spectra for two different magnetic field structures of $s = 2$ and $s = 1$. Except for the magnetic field topology, the other parameters are the same. We find a power-law energy spectrum for the case of $s = 2$.

We would like to mention that particle-in-cell (PIC) simulations, where the Lorentz equations and a set of Maxwell equations are self-consistently solved, have demonstrated that reconnection can proceed quickly and that a large number of nonthermal particles can be generated in and around the X-type neutral region (Zenitani and Hoshino 2001b; Jaroschek et al. 2004). The energy spectra obtained by the simulation can be approximated by $N \propto \epsilon^{-s}$ with $s = 1 \sim 2$. The energy spectra with $N \propto \epsilon^{-1}$ are also obtained in PIC simulations of driven reconnection (Lyubarsky and Liverts 2008), when the regions with reversing magnetic polarity are compressed; the current sheet is then split into magnetic islands separated by X-points so that the particles are accelerated by the Romanova–Lovelace mechanism. Under some conditions, similar particle spectra are generated at the termination shock in the striped wind (Sironi and Spitkovsky 2011).

The magnetic reconnection is an important magnetic field energy-dissipation process in the current sheet, but it should be noted that in addition to the reconnection mode, the drift-kink mode is known to be unstable for the relativistic current sheet. If the plasma consists of electron–positron-pair plasmas without a guid magnetic field, which is parallel to the initial electric current, the drift-kink mode often dominates the nonlinear evolution of the current sheet (Zenitani and Hoshino 2005a, 2008). The drift-kink mode can be excited along the electric current direction, while the reconnection mode occurs in the plane perpendicular to the initial electric current direction. Figure 3 shows the linear growth rates of two modes

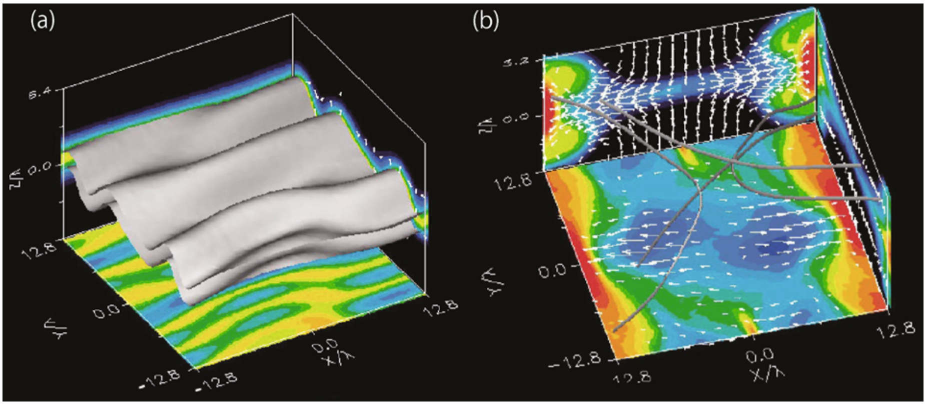

Fig. 4 Three-dimensional PIC simulation for a relativistic current sheet: (**a**) drift-kink mode without a guide magnetic field, (**b**) reconnection mode with a guide magnetic field, which suppresses the drift-kink mode. Adapted from Zenitani and Hoshino (2005b)

as functions of the pair plasma temperature normalized by the rest mass energy (T/mc^2) and the drift velocity carrying the electric current in the plasma sheet ($\beta = v_c/c$). One can see that the drift-kink mode overcomes the reconnection/tearing mode except at the drift velocity $\sim c$, the speed of light. In fact, Zenitani and Hoshino (2005b) demonstrated in a three-dimensional PIC simulation that the drift-kink mode dominates the nonlinear evolution shown in Fig. 4a. They also found that the energy spectrum obtained by the drift-kink mode shows nonthermal behavior, but the spectrum is much softer than that of the reconnection/tearing mode, and the magnetic field energy goes mostly into the heating of the thermal plasmas.

The drift-kink mode, however, can be stabilized by the guide magnetic field along the electric current, because the magnetic tension force can suppress the kinking plasma motion in the current sheet. Roughly speaking, if the magnitude of the guide field becomes comparable to the antiparallel magnetic field, the reconnection/tearing mode grows faster than the drift-kink mode. Figure 4b shows the nonlinear evolution of a three-dimensional PIC simulation with the guide magnetic field, and one can see the reconnection happens before the drift-kink mode evolution. The topology of the magnetic field structure in the current sheet is an important agent to control the particle acceleration in the relativistic current sheet.

In typical cases, the reconnection just triggers the magnetic energy release, permitting field lines to shrink so that only a small fraction of the total energy is released at the reconnection site. As we have already mentioned, in the general case of the reconnection with a guide field in magnetically dominated plasma, the magnetic energy is not dissipated, but simply transferred to magnetized outflows, which excite MHD turbulence. The turbulent cascade brings the energy to the dissipation scale eventually (Thompson and Blaes 1998; Cho 2005; Luo and Melrose 2006). In the collisionless plasma, one can expect efficient particle acceleration via absorption or scattering of small-scale waves; these processes still await systematic study.

The typical occurrence of regions with $E > B$ in the course of relativistic reconnection makes relativistic current sheets extremely efficient particle accelerators (Kirk 2004). The particle acceleration due to the reconnection-induced electric field may also be presented as first-order Fermi acceleration in the converging plasma flows because particles are reflected from the magnetized plasma of reversing polarity that is advected into the dissipation layer (de Gouveia dal Pino and Lazarian 2005; Giannios 2010). In the relativistic reconnection, the magnetized plasma converges with velocity as high as $0.1c$, which implies a very high acceleration rate, higher than that in the case of diffuse shock acceleration. Therefore, this mechanism is invoked if especially fast acceleration is necessary. Giannios (2010) proposed that ultra-high-energy cosmic rays (10^{19}–10^{20} eV) are produced in the course of magnetic reconnection in highly magnetized jets of an active galactic nucleus and gamma ray burst. The relativistic reconnection offers an ideal trap for particles to be accelerated to the highest observed energies because the strong magnetic field does not permit the particles to escape on the one hand and the acceleration rate is high enough to overcome severe synchrotron losses on the other hand.

Efficient particle acceleration on a time scale of the order of the gyration period makes the relativistic reconnection a plausible candidate for an extreme electron acceleration mechanism. The electron acceleration is generally limited by synchrotron losses. Balancing the acceleration force, eE, with the synchrotron radiation reaction drag force, one finds that under the standard condition $E < B$, the energy of synchrotron photons cannot exceed 100 MeV (Guilbert et al. 1983; de Jager et al. 1996). The synchrotron spectrum of the Crab Nebula extends to this limit, which already presents a strong challenge to particle acceleration models. The recent discovery of daylong gamma ray flares in the band of a few hundred megaelectron volts (Tavani et al. 2011; Abdo et al. 2011) demonstrated that this limit could be exceeded, at least occasionally. Uzdensky et al. (2011) proposed that such extreme acceleration occurs within the reconnecting layer, where $E > B$. They showed that even though the Larmor radius of the particle exceeds the thickness of the current sheet, the orbit shrinks towards the midplane so that the population of energetic particles, even if isotropic initially, eventually becomes focused into a tight beam along the current sheet where E could exceed B.

So far we have mainly discussed the particle acceleration for a single X-line reconnection, and the maximum attainable energy ε_{max} due to the single X-line acceleration can be roughly estimated by $\varepsilon_{max} \sim eBL$, where B is the magnetic field and L is the size of the reconnecting region. Using a detailed model taking account of the magnetic and electric field structure of reconnection, Larrabee et al. (2003) obtained the energy spectrum approximated by $\varepsilon^{-1}\exp(-\varepsilon/\varepsilon_0)$, where $\varepsilon_0 \sim \kappa\varepsilon_{max}$ with $\kappa \sim 12$. However, this maximum attainable energy may not necessarily be large enough to explain the high-energy cosmic rays. On the other hand, we can expect many magnetic reconnection regions generated from the nonlinear evolution of the large current sheet. Moreover, if we consider the reconnection acceleration in the pulsar wind nebula with striped wind structure and many current sheets, multiple reconnection regions are strongly expected.

The particle acceleration under the environment having multiple reconnection sites is an active research topic (Drake et al. 2006; Onofri et al. 2006; Oka et al. 2010). Drake et al. (2006) conjectures that the accelerated particles undergo first-order Fermi acceleration during the contraction within the magnetic island. If the gyroradius of the accelerated particle exceeds the size of the magnetic island, the particles escape the islands and their acceleration may cease. For those energetic particles, Hoshino (2012) proposed an idea shown in Fig. 5 for the acceleration of particles in a multi-island environment. In the original Fermi acceleration model (Fermi 1949), particles gain energy stochastically during head-on and head–tail collisions of particles with magnetic clouds as the scattering objects, and the increase in particle energy is known to be second order of V_c/c, where V_c and c are the velocity of the random motion of the magnetic cloud and the speed of light, respectively. However, when the magnetic reconnection regions are taken into consideration instead of magnetic clouds, it is shown that the energetic particles have a tendency to be distributed outside the magnetic islands, and they mainly interact with reconnection outflow jets. As a result, the increase in

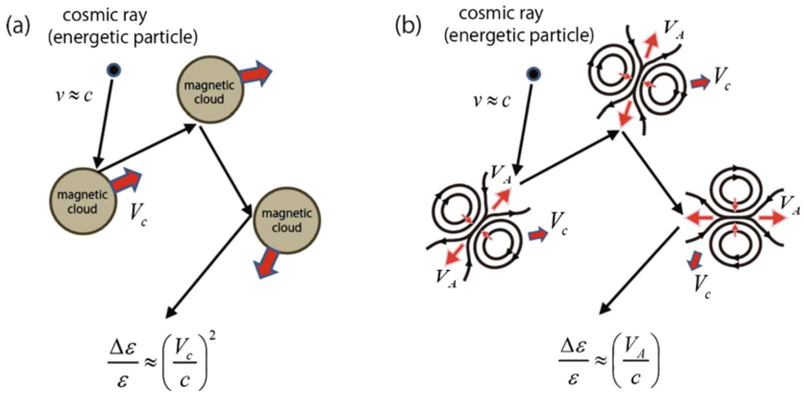

Fig. 5 Illustration of (**a**) the original Fermi acceleration model, which assumes randomly distributed magnetic clouds moving at random velocity V_c, and (**b**) the interaction of an energetic particle with magnetic islands instead of magnetic clouds. *Black lines* show magnetic field lines

particle energy becomes first order of V_A/c, where V_A is the Alfvén velocity. In general, the magnetic reconnection may have potentially rich turbulent structure at many scales, and it is important to investigate particle acceleration in such a turbulent reconnection region.

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