THE GENERATION OF NONTHERMAL PARTICLES IN THE RELATIVISTIC MAGNETIC RECONNECTION OF PAIR PLASMAS

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ABSTRACT

Particle acceleration in the magnetic reconnection of electron-positron plasmas is studied by using a particle-in-cell simulation. It is found that a significantly large number of nonthermal particles are generated by the inductive electric fields around an X-type neutral line when the reconnection outflow velocity, which is known to be an Alfvén velocity, is on the order of the speed of light. In such a relativistic reconnection regime, we also find that electrons and positrons form a power-law–like energy distribution through their drift along the reconnection electric field under the relativistic Speiser motion. A brief discussion of the relevance of these results to the current sheet structure, which has an antiparallel magnetic field in astrophysical sources of synchrotron radiation, is presented.

Subject headings: acceleration of particles — magnetic fields — plasmas — pulsars: individual (Crab Nebula) — relativity — stars: winds, outflows

1. INTRODUCTION

The nonthermal particles in space plasmas have attracted our attention for a long time. Their origins remain central problems, and many kinds of acceleration processes have been studied, such as double-layer and shock acceleration mechanisms.

Magnetic reconnection is one of the fundamental processes in plasmas. It is well accepted that it plays a crucial role in the Earth’s magnetotail, the solar corona, and astronomical accretion disks. Since the stored magnetic energy is rapidly released to particle kinetic energy, a reconnection process is also important as one of the acceleration mechanisms in plasmas. In astronomical high-energy situations, several radio observations (Lesch & Reich 1992; De Jager 1994) have suggested that magnetic reconnection may be the source of nonthermal radiation. Magnetic reconnection in pair plasmas is also discussed for the energetics of a striped wind of the Crab pulsar (Michel 1982, 1994; Coroniti 1990; Lyubarsky & Kirk 2001).

According to studies on reconnection of the Earth’s magnetotail, particle acceleration in reconnection takes place mainly around the X-type neutral region, where the amplitudes of magnetic fields are weak and charged particles become unmagnetized. They are accelerated by an inductive electric field perpendicular to the two-dimensional reconnection magnetic fields. Based on the studies on particle behavior around the X-type region (Speiser 1965; Sonnerup 1971), many authors (Zelenyi, Lominadze, & Taktakishvili 1990; Deeg, Borovsky, & Duric 1991) have investigated the particle energization by test-particle simulations in the time–stationary/dependent electrodynamic and magnetic fields obtained by MHD simulations. They have demonstrated that accelerated particles form power-law–like energy spectra.

In order to study the acceleration in reconnection fields more precisely, we should consider self-consistency between particle motion and electromagnetic fields. Thus, a full-particle simulation that follows the kinetic plasma equations is required. However, many of the full-particle studies of reconnection have focused on field structure or energy conversion. The acceleration of energetic particles in reconnection is not discussed enough, in spite of its importance. Hoshino et al. (2001) have discussed suprathermal electrons accelerated near the magnetic pile-up region in addition to the X-type region.

In this Letter, we study particle acceleration in magnetic reconnection of astronomical pair plasmas, using the particle-in-cell (PIC) code. We choose the condition that typical Alfvén velocity of plasma is on the order of light speed. From our simulation results, we find a remarkable amount of nonthermal components in the energy spectrum, and we find that this is a sign of acceleration by the strong inductive electric field near the X-type region. The high-energy particles are accelerated through a Speiser/meandering-like orbit around there, and their maximum energy has increased to $mc^2\Omega/\gamma$, where $\Omega$ is the cyclotron frequency and $T$ is the typical reconnection time, which may be defined by $L/c$, where $L$ is the size of the reconnection region. Moreover, the spectra around the X-type region seem to be power-law distribution with a power-law index of 1. We consider that the feedback effect of relativistic inertia plays an important role in formation of the spectra and propose a new process for the formation of this spectrum.

This Letter is organized as follows: In §2 we present our simulation conditions. In §3 we show several results and findings of our run. In §4 we study the acceleration in the vicinity of the X-type neutral point and introduce a basic idea for the formation of the power-law spectrum. In §5 we summarize and conclude our study.

2. SIMULATION MODEL

We use a high-resolution relativistic electromagnetic PIC code. The evolution of two-dimensional electromagnetic configuration is considered. We calculate all three components of the particle positions and velocities and observe the field structure in the (X-Z) simulation plane. All quantities are uniform in the Y-direction. For simplicity, we neglect any collisions, pair production, and pair annihilation of pair plasmas.

We study slab geometry of the plasma sheet, starting from a Harris equilibrium model (Harris 1962), which is commonly used for the reconnection problem. Since the standard Harris equilibrium is applicable only to nonrelativistic plasma sheets, we extended it into the relativistic plasmas by replacing the velocity $\gamma$ to the four-velocity $u = \gamma v = \gamma [1 - (v/c)^2]^{1/2}$, where $c$ is the speed of light.

The simulation region consists of $1024 \times 512$ numerical meshes, and the thickness of the plasma sheet $\lambda$ is set to 10
grids. The magnetic field, plasma density, and distribution function of plasmas are described by \( \mathbf{B}(z) = B_0 \tanh(z/l) \cdot \mathbf{x} \), \( n(z) = n_0 \cosh^2(z/l), \) and \( j = n(z) \exp \{-m|u_z^2 + (u_x - U)^2 + u_y^2)/2\}, \) respectively. The typical particle kinetic energy is \( 0.25 mc^2 \) in our condition. The total number of particles is \( 6.7 \times 10^7 \). The particle density in the plasma sheet is \( n_{ps} \sim 7.7 \times 10^7 \) pairs per grid, while \( n_{lobe} \sim 6-7 \) pairs in the lobe. We use the double periodic boundary condition; therefore, the system size of each plasma sheet is \( -51.2 \leq X/\lambda \leq 51.2 \) and \( -12.8 \leq Z/\lambda \leq 12.8 \). We assume a thin plasma sheet, where the thickness is comparable with the typical Larmor radius of particles, \( \lambda = 2\lambda_i \).

We assume that the cyclotron frequency in the lobe is equal to the plasma frequency in the current sheet, \( \Omega_c = \omega_{pe} \), where \( \Omega_c = eB_0/\lambda mc \) and \( \omega_{pe} = (4\pi n_0e^2/m)^{1/2} \). Thus, the reconnection outflow, whose speed is known to be an Alfvén velocity of the system \( V_a \sim c(1 + 2(\omega_{pe}/\Omega_c)^2)^{1/2} \), is expected to be on the order of the speed of light.

In the very early stage of reconnection, we drive small external electric fields localized on the outside of the plasma sheet in order to trigger an X-type neutral line around the center of the simulation box. The system slightly gains energy from these additional fields. After the electric fields were eliminated, we confirmed that the total energy is conserved within 0.1% error throughout the simulation run.

3. RESULTS

Figure 1 shows a snapshot of the magnetic field lines and the density at \( \tau_\lambda = 80.6 \), where \( \tau_\lambda = \lambda/V_a \) (Alfvén transit time). An X-type neutral line is formed at the center of the simulation box, and plasmas are streaming out from the X-type region toward the \( \pm X \)-directions. The maximum outflow speed reaches up to \( 0.91c \), which exceeds the typical Alfvén speed in the system. The basic behavior of the nonlinear evolution of the plasma sheet is the same as that of other MHD, hybrid, and particle simulation results performed in a nonrelativistic regime. The magnetic reconnection rate \( (cE_z/B_0)/V_a \) is about 0.33. As time goes on, the thickness of the plasma jet becomes \( \sim 2\lambda \), which is on the order of the meandering width of accelerated particles, while the meandering width before reconnection was \( (\lambda_{re})^{1/2} \sim 0.7 \lambda \).

Let us study plasma heating and acceleration during the relativistic magnetic reconnection. Figure 2a shows the energy spectra in the whole simulation box at two different stages of our simulation. In the initial growth phase \( \tau_\lambda = 11.5 \), the spectrum is well described by a Maxwellian, \( f(e) \propto \exp(-e/T) \), where \( T \sim 0.4mc^2 \) is the effective temperature. As time goes on, we can observe not only hot plasma but also a nonthermal high-energy tail in the spectrum. The dashed line shows the energy spectrum at \( \tau_\lambda = 80.8 \). One can observe a significant enhancement in the high-energy part, and the maximum energy reaches up to \( \sim 27mc^2 \). To analyze the acceleration site of the nonthermal particle, we show the energy spectra integrated particles only around the X-type region of \( -16.0 \leq X/\lambda \leq 16.0 \) and \( -6.4 \leq Z/\lambda \leq 6.4 \). The dotted line in Figure 2a indicates the above partial energy spectrum. We find that most of the high-energy particles in the system are produced around the X-type region.

Figure 2b shows two energy spectra around the X-type region in the log-log scales at \( \tau_\lambda = 80.8 \) and 92.4. This non-
the particles stay for a longer time around the cyclotron radius becomes larger with increasing time. Thus, the particles gain more and more energy.

The electric field during a Speiser/meandering orbit \( (\text{Speiser } 1965) \) is almost uniform around the X-type region, respectively. The reconnection electric field \( E_\text{r} \) is also found to be almost constant during the nonlinear evolution of reconnection, and \( E_\text{r} \) is about \( 0.3 B_\text{r} \). The parameter \( t_\gamma \) is the onset time of reconnection, which is controlled by the driven electric field in the outer plasma sheet. In this case, \( t_\gamma /\tau_\gamma \approx 40 \). We stop the simulation at when the outflow plasma starts to collide in the periodic boundary. Owing to this plasma compression effect, the growth of the electric field \( E_\text{r} \) is almost uniform around the X-type region and finally reaches up to \( 3 \lambda c / 4 \) in the typical run.

In order to study how the particles gain their energy, we first picked up some typical high-energy particles in the outflow region and traced their positions backward in time. As a result, we found that most of the nonthermal particles come through the X-type region. The particles are initially situated on both sides of the plasma sheet, and they are successively transported into the X-type region as the reconnection evolves. Once they come into the X-type region, they are strongly accelerated along the reconnection electric field \( E_\text{r} \), and their motions are basically described by the so-called Speiser/meandering orbit. Owing to the reconnecting magnetic field \( B_\text{r} \), the particle momentum \( P_\gamma \) is transformed to \( P_\gamma \), then the particles are ejected toward the \( \pm X \)-directions.

4. ACCELERATION AROUND THE X-TYPE REGION

Next, let us study the acceleration process around the X-type region in more detail. In the case of nonrelativistic reconnection, particles are accelerated by drifting toward the reconnection electric field \( E_\gamma \) during a Speiser/meandering orbit \( (\text{Speiser } 1965) \) around the X-type region. The typical acceleration timescale is described by the reciprocal of the cyclotron frequency determined by the reconnection magnetic field \( B_\text{r} \), i.e., \( mc/eB_\gamma \).

However, in our relativistic reconnection case, the electric field \( E_\gamma \) is strong enough to drive the particles into the Y-direction, and the particle energy reaches up to \( mc^2 \). In this regime, the cyclotron frequency is a function of the particle energy \( e \) and the cyclotron radius becomes larger with increasing time. Thus, the particles stay for a longer time around the X-type acceleration region and gain more and more energy.

Figure 3 shows the ratio of the inductive electric field \( |E_\gamma| \) to the magnetic field \( |B_\text{total}| \) to the ratio of the electric field to the magnetic field \( (|E_\gamma|/|B_\text{total}|) \) in the simulation plane \((-25.6 \leq X\lambda \leq 25.6 \text{ and } -9.6 \leq Z\lambda \leq 9.6) \) at \( t/\tau_\gamma = 80.8 \). The vectors and solid lines represent the plasma flow and magnetic field lines, respectively.

thermal part may be approximated by power-law distribution \( f(e) \propto e^{-z} \) with \( z \approx 1 \). We also find that the maximum energy \( e_\text{max} \) in the simulation box constantly grows in time, and the growth is well described by \( e_\text{max} \approx e_0 c(t - t_0) \), where \( c, e_0, \) and \( E_0 \) are the electric charge, speed of light, and electric field around the X-type region, respectively. The reconnection electric field \( E_\gamma \) is also found to be almost constant during the nonlinear evolution of reconnection, and \( E_\gamma \) is about \( 0.3 B_\gamma \). The parameter \( t_\gamma \) is the onset time of reconnection, which is controlled by the driven electric field in the outer plasma sheet. In this case, \( t_\gamma /\tau_\gamma \approx 40 \). We stop the simulation at when the outflow plasma starts to collide in the periodic boundary. Owing to this plasma compression effect, the growth of the electric field \( E_\gamma \) is almost uniform around the X-type region and finally reaches up to \( 3 \lambda c / 4 \) in the typical run.

We shall call the region satisfying the condition \( |E_\gamma| \geq |B_\text{total}| \) in cgs units as the acceleration region (AR). This region plays a very important role in particle acceleration, and the strength of acceleration is related to the size of the AR.

In the AR, there is no local frame that can remove \( V_\text{in} \) by Lorentz transformation, and a particle is accelerated toward the \( Y \)-direction. As the outflow velocity \( V_\text{out} \) becomes on the order of the speed of light, the frozen-in condition \( |E_\gamma| = V_\text{out}/c |B_\text{total}| \) in the outer edge of outflow region requires stronger \( |E_\gamma| \), and the AR grows larger. In our case, the size of the AR is about \( 25 \lambda \times 10 \lambda \). It is larger than the plasma sheet thickness and the typical spatial scale of Speiser/meandering motion. Note that the standard ion-electron reconnection in nonrelativistic reconnection such as seen in the Earth’s magnetotail may have a small region of size \( |E_\gamma| \geq |B_\text{total}| \) that is much less than the electron inertia scale. The size of AR is controlled by \( V_\gamma \sim V_\text{out} \).

Now we discuss the formation of the power-law energy spectrum in the AR. First, we assume that the reconnection electric field \( E_\gamma \) is almost uniform around the X-type region and that particles are running very fast with the speed of light toward the \( Y \)-direction. They are continually accelerated by the strong electric field \( E_\gamma \) until they are ejected from the AR. Therefore, the acceleration efficiency may be given by

\[
\frac{de}{dt} = eEc. \tag{1}
\]

We ignore particles running toward other directions because they are quickly ejected from the AR and are not accelerated enough to contribute to the high-energy part.

Second, we roughly assume that their typical lifetime \( \tau \) around the AR is estimated by the quarter gyration of a Speiser orbit in the neutral \((X, Y)\)-plane. Taking into account that the Lorentz factor \( \gamma = 1/\sqrt{1 - (v/c)^2} \) affects the cyclotron frequency in the relativistic regime, the loss rate with which the accelerated particles escape from the X-type acceleration region
can be given by
\[
\frac{1}{N} \frac{dN}{dt} = -\frac{1}{\tau(\gamma)} = -\frac{4\Omega_z}{2\pi} = -\frac{mc^2}{e}\frac{2\Omega_z}{\pi} \quad (2)
\]

where \( N \) is the particle number and \( \Omega_z \) is a cyclotron frequency by a typical value of the reconnection magnetic field \( B_z \).

From these two relations, we can easily find \( N \propto e^{-s} \), where \( s = 2\Omega_z/\pi e \) becomes on the order of 1.

5. SUMMARY AND DISCUSSION

We have carried out simulations of magnetic reconnection in astronomical pair plasmas, and we found that a significantly large number of nonthermal particles are generated owing to the strong inductive electric field in the AR. Our simulation shows that particle acceleration by magnetic reconnection can work effectively in the universe. Moreover, the energy spectrum around the AR resembles power-law distribution with a power-law index of 1. This is a quite hard spectrum, which we have never yet seen.

It is highly expected that reconnection in relativistic pair plasmas may occur in high-energy astronomical objects, such as a striped wind of pulsars and active galactic nuclei. The acceleration by reconnection occurs in relatively short timescale, several tens of the Alfven transit time \( \tau_a = \lambda/V_A \sim \lambda/c \), this acceleration may be a good candidate for the origin of nonthermal particles.

In our simulation code, we neglect any Coulomb collisions for simplicity. This treatment is acceptable since the mean free path of particles is generally quite long in space plasmas. They are virtually collisionless; thus, pair annihilation is also neglected. Considering the fact that reconnection occurs on a relatively short timescale of \( \sim 10^3 \lambda/c \), our assumptions may be acceptable. Note that this code does not include any radiation losses, such as the synchrotron and inverse Compton losses. In their test-particle study, Schopper, Lesch, & Birk (1998) have noted that the effect of synchrotron loss is not negligible in their high-energy situation \( \sim (10^4 - 10^6)mc^2 \). The effects of pair production and pair annihilation are also neglected in our study. More precise simulation should include them, but this cannot be achieved using the PIC code.

We have also discussed the formation of a power-law spectrum around the X-type region, and our simulation result is well described by \( N \propto e^{-s} \), where the index \( s \) is about the unity. Strictly speaking, we are unable to discuss the classical Speiser/meandering orbit in the vicinity of the X-type region where \( |E_y| \gtrsim |B_{total}| \) due to the characteristics of Lorentz transformation changes. Particle orbits are still similar to Speiser/meandering orbits, but they are driven by and resonant with \( E_y \).

We are still in the process of searching for analytical solutions for the acceleration orbit, but the essential point of our model is as follows: the more strongly particles are accelerated in the \( Y \)-direction, the longer they stay in the AR owing to the relativistic effect of cyclotron motion.

In our run, the growth of the maximum energy \( e_{\text{max}} \) seems to be confined by the periodic boundary. Simulations run with a larger simulation box may produce energy greater than \( 38mc^2 \). The multiple reconnections may be also important for producing high-energy particles. If two or more reconnection regions are formed in the plasma sheet, ejected particles travel into another AR so that they can be more accelerated.

We have also performed simulation runs with different Alfven speed parameters. We have recognized a remarkable number of nonthermal particles in every case. Together with the dependence of reconnection behavior on the plasma sheet thickness, we will report the full story in a coming paper.

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