Simulating the Ion-trapping Acceleration at Rippled Reconnection Fronts

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Abstract

Reconnection fronts (RFs) play a vital role in particle acceleration and energy transport in the terrestrial magnetosphere. It is widely believed that RFs have planar monotonic profiles that determine the particle dynamics. However, recent in situ studies have revealed that the front surface is not planar as expected but rather rippled. How the surface irregularities of RFs’ impact particle energization and transport is still an open issue. Using a particle-tracing technique, we traced the trajectories of ions near fronts with or without surface ripples at different scales to understand how ions are mediated by such rippled structures. We find that the ion relative energy gain increases considerably when the rippled surface of RFs appears. The main acceleration mechanism is ion-trapping acceleration, in which ions are confined at the RFs for a longer time by the rippled structure and are accelerated by the downward electric field. Moreover, ions can be accelerated effectively when their gyroradius is comparable to the size of the ripple. Formulas of relative energy gain as a function of the ripple size are presented.

Unified Astronomy Thesaurus concepts: Interplanetary particle acceleration (826); Space plasmas (1544); Particle physics (2088)

1. Introduction

Reconnection fronts (RFs), one of the most efficient accelerators of particles in the terrestrial magnetosphere, are characterized by an abrupt strong enhancement of magnetic field (Nakamura et al. 2002; Runov et al. 2009; Sergeev et al. 2009; Zhou et al. 2009; Liu et al. 2013, 2019a; Fu et al. 2020), normal to local current sheets. Such structures are thought to be followed by a strong magnetic field region called the dipolarizing flux bundle (DFB; Liu et al. 2013, 2014) or flux pileup region (FPR; Khotyaintsev et al. 2011) and usually preceded by a small magnetic dip structure (Pan et al. 2015; Yao et al. 2015; Schmid et al. 2019). They are usually embedded in the bursty bulk flows or high-speed plasma jets in the terrestrial magnetotail (Cao et al. 2013; Karlsson et al. 2015; Pritchett & Runov 2017), separating hot tenuous plasmas from ambient cold dense plasmas. The transient reconnection has been suggested as a possible mechanism responsible for the formation of RFs in both simulations (Sitnov et al. 2009) and observations (Fu et al. 2013).

Studies have suggested that RFs are crucial regions for particle acceleration, pitch angle evolution, wave–particle interactions and electromagnetic energy conversion in space plasma. For instance, rapid increases in energy fluxes of electrons and ions from tens to hundreds of keV are a typical feature of RF events (Zhou et al. 2010, 2011; Fu et al. 2011; Khotyaintsev et al. 2011; Liu et al. 2013; Zhou et al. 2018). Pitch angle distribution of suprathermal electrons can evolve dramatically around RFs (Runov et al. 2013; Liu & Fu 2019; Liu et al. 2020); strong particle and wave activity can occur in the vicinity of RFs during their Earthward propagation (Ono et al. 2009; Fu et al. 2014; Zhou et al. 2014, 2009; Greco et al. 2017; Breuillard et al. 2016; Yang et al. 2017; Liu et al. 2021a, 2019b) and RFs are associated with energy conversion from electromagnetic fields to particles (Zhong et al. 2019; Liu et al. 2021b, 2018b; Huang et al. 2015; Khotyaintsev et al. 2017; Sitnov et al. 2009). The energetic plasma in the vicinity of RFs plays a key role in connecting the magnetotail with the inner magnetosphere because they carry a large amount of energy and can be injected into the inner magnetosphere to affect the ring current and radiation belt (Gabrielse et al. 2012; Turner et al. 2014). Possible mechanisms responsible for the energization of particles around RFs have been widely investigated based on both spacecraft observations and numerical simulations during the last decade. The strong convection electric field induced by strong magnetic field gradient of RFs provides the significant adiabatic acceleration of the ambient particles (Birn et al. 2004, 2013, 2015; Gabrielse et al. 2012, 2014, 2016; Ganushkina et al. 2013; Liu et al. 2016; Turner et al. 2016). Nonadiabatic effects, caused by particle reflection ahead of the RFs (Zhou et al. 2010, 2018; Drake et al. 2014; Greco et al. 2014), resonance with RFs (Ukhorskiy et al. 2013, 2017), and scattering by wave emissions (Zhou et al. 2009; Greco et al. 2017) are also significant for particle energization.

The above studies typically assumed that the RFs’ surfaces have a planar boundary at typical thicknesses comparable to the ion gyroradius and below (Nakamura et al. 2002; Zhou et al. 2009; Sergeev et al. 2009; Schmid et al. 2011; Liu et al. 2013). However, it has recently been found that the RFs’ surfaces are not planar as expected but rather rippled. Low-frequency instabilities can be excited by pressure gradients around RFs at various scales, such as lower hybrid drift instabilities at electron scales (Davidson & Gladd 1975; Divin et al. 2015a, 2015b; Pan et al. 2015), kinetic interchange instabilities at ion scales (Pritchett & Coroniti 2010), and magnetohydrodynamic interchange instability at magnetohydrodynamic scales (Nakamura et al. 2002; Lu et al. 2020). With the in situ observations, Wu et al. (2018) reported a wavy RF event, where different magnetic structures and electron distributions exist around the RF at ion scale. Liu et al. (2018a) revealed for the first time that the RFs’
layer has electron-scale density gradients, currents, and electric fields by using Magnetospheric Multiscale mission measurements. Pan et al. (2018) further analyzed these electron-scale structures, and they indicated these rippled structures are generated by the lower hybrid drift instability. These studies suggest that the RFs are not uniform structures. How such a wavy front impacts the particle energization and transport remains unknown. In this paper, with a particle tracing technique, we examine the influence of rippled RFs on the ion dynamics and compare it to the other scenario with a smooth surface. Section 2 presents the methodology, Section 3 reports the simulation results, and Section 4 summarizes our conclusions.

2. Model Description

In this study, we focus on the RFs in the context of the Earth’s magnetotail. To numerically solve the particle motion and investigate the effects of the RFs’ rippled surfaces on the particle dynamics, we initialize the electromagnetic background with a two-dimensional plasma sheet, superposed by an RF profile with a rippled surface. The initial magnetotail magnetic field is obtained by an asymptotic magnetotail vector potential $A_0B_0$ given by Pritchett & Coroniti (1995),

$$A_0B_0 = LB_0 \ln \left( \cosh[F(x)(z/L)] / F(x) \right)$$

with $F(x)$ in the form introduced by Zhou et al. (2018),

$$\begin{align*}
F(x) &= \exp \left[ \frac{B_{\infty}(x - x_0)}{B_0L} \right. \\
&\quad + \left. \frac{(B_{0,0} - B_{\infty})(x^3 - x_0^3)}{3B_0Lx^3} \right],
\end{align*}$$

where $x_0$ is the boundary of the plasma sheet near the Earth’s side, $B_{\infty}$ is the equatorial $B_z$ at $x = -\infty$, $B_0$ is the lobe field strength at $x_0$, $L$ is the current sheet half thickness at $x = x_0$, and $B_{0,0}$ is the equatorial $B_z$ at $x_0$. In our simulations, we adopt the following parameters to represent a thick plasma sheet: $B_{\infty} = 5$ nT, $B_0 = 50$ nT, $B_{0,0} = 15$ nT, $L = 2 RE$, and $x_0 = -10 RE$. We further superpose an RF field on the plasma sheet field by first prescribing the RF density $n_0$ modified from Pan et al. (2018), which decreases from 0.6–0.25 cm$^{-3}$ across the RF, as

$$n_0(X, Y) = \begin{cases} 0.175 \tanh \left( \frac{(X^* + 0.1[Y])}{4RE} \right) \cdot \frac{[Y]}{D} \\ + 0.425 + A \cdot \exp \left( -\frac{(X^* + 0.1[Y])}{4RE} \right) \cdot \frac{Y^2}{a^2} \end{cases} \times \sin(2\pi/\lambda \cdot Y),$$

where $X^* = X - X_f - V_f(t - t_i)$ indicates the Earthward propagation of a coherent RF structure at the speed of $V_f = 400$ km s$^{-1}$. $X_f = -21 RE$ is the location of the RF center at $t = t_i$ (we chose $t_i = 100$ s for following simulations), $D$ is the half thickness of the RF, $A$ is the amplitude of perturbation, $\lambda$ is the disturbance wavelength, and $a$ is the characteristic width of the Gaussian envelope. The last term represents the density perturbation on the ripples. Although the sinusoidal function is an idealized model, it can well represent the observed ripple structure (Pan et al. 2018). Here we choose the following parameters based on previous studies (Nakamura et al. 2002; Zhou et al. 2009; Sergeev et al. 2009; Pritchett & Coroniti 2010; Schmid et al. 2011; Liu et al. 2013, 2018a; Pan et al. 2018; Wu et al. 2018; Lu et al. 2020) to represent a typical ion-scale RF and its rippled structure: $A = 0.05$ cm$^{-3}$, $D = 0.5$ RE, $\lambda = 0.25$ RE, $a = 0.25$ RE. The ion temperature is a planar hyperbolic-tangent profile between 5 and 7.5 keV, while the electron temperature change from 1.2–2 keV, and the temperature disturbance is anticorrelated with the density disturbance. By assuming pressure balance (Pritchett et al. 2012), we then obtain the magnetic field profile $\Delta B$ to represent the RF field. In our simulations, the electric field consists of the dawn–dusk convective electric field (Runov et al. 2009; Zhou et al. 2018) and Hall electric field (Runov et al. 2011; Pan et al. 2015), as

$$E = - V_f \times B + J \times B/jen.$$  

With the above settings, we carry out two types of simulations: one with a planar surface and the other with a rippled surface. For the RF with a planar boundary, most of the settings are the same with the rippled one, but $A = 0$.

To trace the energetic particle motion in the above prescribed electromagnetic environment, we solve the relativistic Lorentz equation:

$$\frac{d(\gamma v)}{dt} = \frac{q}{m} (E + \frac{v}{c} \times B),$$

where $v$ is the velocity of a particle with charge $q$ and mass $m$, $\gamma = \frac{1}{\sqrt{1 - v^2/c^2}}$ is the relativistic correction factor, and $c$ is the speed of light. Only those with 90° pitch angle at the neutral sheet are traced in the equatorial XY plane. Fast integration of Lorentz trajectories is integrated by using a fourth-order Runge–Kutta scheme for the particles.

3. Particle Tracing and Simulation Results

To demonstrate the effects of the RFs’ rippled structures on the motion of particles, we compare the spatial distribution of RFs without or with surface ripples and the corresponding trajectories of ions from two simulations. Figure 1 shows some example trajectories in the equatorial plane for ions interacting with RFs. RFs are initialized in the middle of the tail at $X = -14.75 RE$ and propagate Earthward. Ions are initially positioned at a given position shown as black dots in Figures 1(a) and (d) ($X = -13.6 RE$ and $Y = 1.5 RE$). The initial energy of these ions ranges from 1–19 keV with an even interval of 2 keV. The background color represents the $B_z$ field at time $t = 0$ s. The color of the curves represents the ion energy along its trajectory. The top row is the result of case 1 where the RF has a planar surface. The bottom row is the result of case 2 where the RF has a rippled surface. In case 1, the ions gyrate in the equatorial plane before the arrival of the RF. During this period, the energy of ions barely changes. When RFs arrive, the ions encounter a sharp enhancement of $B_z$, and then experience multiple reflections and reentries to the DFB space. In a full gyration, ions are accelerated by the duskward electric field during their duskward gyration and decelerated by the duskward electric field during their dawnward gyration. Moreover, the duskward electric field that ions experience during their duskward gyration is larger.
than that during their dawnward gyration (see a detailed discussion in Figure 2). As a result, each time they cross the RF surface and reenter the DFB, ions gain energy. Ions interact with the front and gain a variable amount of energy. After that, ions appear to resume the repetitive gyration motion with smaller gyroradius around the enhanced $B_z$ field. They experience periodic energy variations due to the DFB-associated electric field. The above behaviors also appear in case 2 where the RF has a rippled surface. However, in case 2, some ions are trapped by the front and have longer path as they drift in the duskward direction. As a result, these ions gain more energy by the RF associated duskward electric field.

To investigate the physical mechanism of this phenomenon in more detail, we choose the ion that has the largest energy gain. Figure 2 (from top to bottom) shows the $xy$ positions of the ion in case 1 as a function of time, the time series of the northward magnetic field $B_z$, the sunward electric field $E_s$, the duskward electric field $E_y$, the ion experiences, the work done by electric fields, and the corresponding energy gain and kinetic energy. The left column represents results from case 1 while the right column from case 2. As clearly seen in the top row of Figure 2, ions undergo a gyration motion and stay in a confined region, the size of which is determined by their gyroradius around the background $B_z$ before their encounter of RFs. During this period, the ions’ energy remains relatively constant before $t = 20$ s (Figure 2(a10), (b10)). After the ions encounter the RF, their trajectories become complicated. As the magnetic field of the RF changes with small scales, the ions no longer behave adiabatically. When ions move duskward, they are accelerated by the duskward electric field (Figure 2, the left shadowed area). Conversely, they are decelerated by the duskward electric field during their dawnward motion (Figure 2, the right shadowed area). The duskward electric field that ions experience during their duskward motion is larger than that during their dawnward motion (Figure 2(a5)). As a result, ions gain energy in each full gyration while they cross the RF surface and reenter the DFB with an enhanced magnetic field. Such process repeats until ions penetrate deep into the DFB where they fail to make another reflection. This mechanism is similar to the acceleration due to ions reflection at planar RF (Zhou et al. 2010, 2018). Moreover, ions in case 2 are reflected and reenter the DFB more frequently, and are trapped by the rippled structure to gain energy more efficiently. The energy of ion in case 1 (Figure 2(a10)) oscillates back and forth in a certain range because of the gyration motion after it reaches the DFB in about 40 s. In contrast, the energy of ion in case 2 (Figure 2(b10)) increases continually because of the trapping by the rippled surface. As a consequence, the ion gains more energy in case 2. This mechanism is consistent with the quasi-trapping effect (Ukhorskiy et al. 2013) with multi-reflection or surfiing acceleration (Hoshino 2005). The combination of reflection and trapping leads to a more efficient acceleration in case 2. During their interaction with RFs, ions

![Figure 1. Spatial distribution of RFs with different surfaces in color and the trajectories of ions in lines. Locations of ions is shown with black dots. Top row: the RF with a planar surface. Bottom row: the RF with a rippled surface.](image-url)
Figure 2. Ions' trajectories and related data chosen from case 1 (left) and case 2 (right). (a) Spatial distribution of the RF with planar surface in color at $t = 0$ s and the trajectory of ion in line chosen from case 1. (b) Spatial distribution of the RF with a rippled surface in color at $t = 0$ s and the trajectory of ion in line from case 2. (a1) X and (a2) Y components of the ion’s location. (a3) $B_z$, (a4) $E_x$, and (a5) $E_y$ that ion undergoes. (a6) work done by $E_x$. (a7) work done by $E_y$. (a8) work done by total electric field. (a9) ion’s energy gain. (a10) ion’s energy. (b1)–(b10) is the same format as in (a1)–(a10).
move Earthward due to $E \times B$ drift and are accelerated by the $E_x$ (Figure 2(a6), (b6)). Meanwhile, they drift downward because their gyroradii are larger in the ambient plasma sheet than inside the DFB due to the tailward gradient in the $B_z$ component at the vicinity of RFs. Furthermore, the ions’ energy gain (Figure 2(a9) and (b9)) are equal to the work done by the electric field (Figure 2(a8), (b8)), suggesting that they are mainly accelerated by the $E_x$ (Figure 2(a7), (b7)).

In order to further understand the energization under the effect of the RF structure, we distribute hundreds of ions in both cases with the initial location randomly specified in the same box $[x = (-14.2 R_E, -13.8 R_E), y = (0.6 R_E, 1.0 R_E)]$. These ions have random initial energies from 5–30 keV and random initial gyro-phases from $0°$–$360°$. Figure 3 shows the relative energy gain ($K$) of the ions after they cross the RFs with and without the rippled surface, represented by black dots and red dots, respectively. The relative energy gain is determined as $K = (W_m - W_0)/W_0$, where $W_m$ is the current energy of ions, and $W_0$ is the initial energy. For most of these ions, both kinds of RFs can accelerate them to achieve more than three times (relative energy gain equals two) of the initial energy. In the case without the rippled RF surface, the relative energy gain of these ions is nearly constant, with a factor of 2–5 regardless of their initial energy. However, in the case with a rippled RF surface, the relative energy gain spreads widely, ranging from a factor of 1–10, especially for those with an initial energy between 10 and 15 keV. The relative energy gain of these ions significantly exceeds the rest of ions. The above results suggest that the RF with a rippled structure can selectively accelerate some ions. Given the initial energy and the wavelength of the ripple on the RF boundary, the energization can be interpolated as a resonant effect as the ion gyroradius becomes close to the wavelength of the ripple.

To elucidate the effect of the wavelength of the ripple ($L$) on the RFs, we carry out several simulations with various wavelengths of the ripples and analyze the ion acceleration after they pass the rippled RFs. In each simulation, we distribute the same amount of ions (i.e., 500) randomly and specify their initially energies from 5–30 keV and gyro-phases from $0°$–$360°$ as before. The wavelength of the ripple changes from $0.2 R_E$ to $0.3 R_E$ among these simulations. From each simulation, we pick up those ions that achieve the most efficient energization by the rippled RF. That is, the relative energy gain of these ions are among the top 10% of all ions in that simulation. Figure 4 shows the average initial energy ($\langle W_0 \rangle$), the ratio of average gyration radius and wavelength ($\langle R_0 \rangle / L$), and the average relative energy gain ($\langle K \rangle$) of these ions as a function of the ripple’s wavelength ($L$). The average initial energy of these ions exhibits a linear relationship with the wavelength. That means, a more energetic particle could gain the most efficient energization with a larger wavelength at the rippled RFs. The ratio of average gyration radius and wavelength is about 1.3, suggesting that to obtain the energy most effectively, the gyroradius is nearly comparable to the wavelength. This is similar to resonant interaction. The above two relations are inherently equivalent because the gyroradius is related to the kinetic energy. On the other hand, the average relative energy gain of these ions with the most efficient energization decreases as the wavelength increases. When the wavelength of the ripple goes to infinity, the RF structure is equivalent to a planar surface and the relative energy gain of the ions become very small. According to these relations, we can easily fit with linear formulas, from which we can quickly determine what kind of ions can be effectively accelerated provided the length scale of the ripple, and obtain their relative energy gain after crossing the RF surface. The fitted formulas are provided below in Equations (6) and (7):

$$W_0[\text{keV}] = 84.8 \times L[\text{Re}] - 6.859, \quad (6)$$
$$K = -7.69 \times L[\text{Re}] + 8.622. \quad (7)$$

4. Conclusion and Discussion

RFs have been well recognized as being important to particle acceleration and transport (Zhou et al. 2009; Gabrielse et al. 2012; Liu et al. 2013; Turner et al. 2014; Fu et al. 2020). Recent studies investigating the RFs’ surfaces have suggested that they are not planar as commonly assumed but rather rippled (Liu et al. 2018a; Pan et al. 2018; Lu et al. 2020). The knowledge of how such structured RFs impact the particle energization and transport in the magnetotail remains elusive. In this study, we use a particle tracing code to study ion dynamics in association with the rippled RFs and compare the results to that with a planar RF surface. The trajectories of particles are traced, under a prescribed electromagnetic environment with a two-dimensional plasma sheet and the superposition of an RF magnetic profile with either a planar or rippled surface. The ions behave quite differently at the planar and rippled RFs. Major results are summarized as follows:

1. Ions are reflected and accelerated during their interaction with RFs. When the rippled surfaces of RFs appear, the ions gain energy more considerably.
2. The main acceleration mechanism is ion-trapping acceleration, in which ions are confined at the RFs by the rippled structure and are accelerated by the duskward electric field. The longer time ions are trapped in the rippled structure, the longer path they drift in the dusk direction and thus the more energy they gain. This is because the total energy gain of a particle is calculated as $\int E \cdot dL$.
3. We carry out a number of simulations with various sizes of the ripple at the RF surface. Linear relations are found between the relative energy gain of the ion and the wavelength of the ripple, suggesting that the ion can be accelerated effectively when the gyration radius of the ion is comparable to the wavelength of the ripple. From these
formulas, we can quickly determine what kind of ions can be effectively accelerated provided the length scale of the ripple, and find their relative energy gain after crossing the RF surface.

The above experiments were initiated with the same ions but under different kinds of RFs. The vastly different energization and transport of these ions indicated that rippled structure of RFs can play an important role in regulating the behavior of the ions. The above numerical experiments investigated the effects of the wavelength scale of RFs with rippled surfaces and may shed light on their complicated roles in transporting and energizing ions. Future studies will utilize a more realistic and dynamic magnetic field configuration and self-consistent inductive electric field to better understand ion accelerations and use distribution functions of particles to compare with observational results.

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Figure 4. Three relevant parameters and correlation analysis of the top 10% relative energy gain of ions as functions of the wavelength: the ratio of the average gyration radius and wavelength (red), the average initial energy (green), and the average energy gain (black).

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