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Energetic ion acceleration during magnetic reconnection in the Earth's magnetotail

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Abstract

In this paper, we present a comprehensive study of the energetic ion acceleration during magnetic reconnection in the Earth's magnetosphere using the Geotail data. A clear example of the energetic ion acceleration up to 1 MeV around an *X*-type neutral line is shown. We find that the energetic ions are localized at far downstream of reconnection outflow. The time variation of energetic ion and electron is almost the same. We observe ∼100 keV ions over the entire observation period. We study ten events in which the Geotail satellite observed in the vicinity of diffusion region in order to understand the reconnection characteristics that determine the energetic ion acceleration efficiency. We find that the reconnection electric field, total amount of reduced magnetic energy, reconnection rate, satellite location in the Earth's magnetosphere (both X_{GSM} and Y_{GSM}) show high correlation with energetic ion acceleration efficiency. Also, ion temperature, electron temperature, ion/electron temperature ratio, current sheet thickness, and electric field normal to the neutral sheet show low correlation. We do not find any correlation with absolute value of outflow velocity and current density parallel to magnetic field. The energetic ion acceleration efficiency is well correlated with large-scale parameters (e.g., total amount of reduced magnetic energy and satellite location), whereas the energetic electron acceleration efficiency is correlated with small-scale parameters (e.g., current sheet thickness and electric field normal to the neutral sheet). We conclude that the spatial size of magnetic reconnection is important for energetic ion acceleration in the Earth's magnetotail.

Keywords: Magnetosphere, Magnetic reconnection, Energetic particles

Introduction

The origin of energetic particles is a long-standing problem in space physics spanning over several decades. So far, two major acceleration processes have been proposed. One is the diffusive shock acceleration based on Fermi mechanism at the collisionless shock (Blandford and Ostriker 1978). This acceleration mechanism explains the power-law energy distribution function with an index of 2, which is often observed in the high energy range (e.g., cosmic rays). Therefore, the collisionless shock is widely believed to be one of the sources of energetic particles. The other process is magnetic reconnection through which particles are accelerated by the interaction with a strong inductive electric field (Zelenyi et al. 1990). The stored magnetic field energy can be rapidly released to the particles during the magnetic reconnection. Numerical simulations have tested energetic particle acceleration during magnetic reconnection in various plasma environments, such as solar corona, Earth's magnetosphere, and pulsar magnetosphere (Drake et al. 2006; Hoshino et al. 2001; Oka et al. 2010; Pritchett 2008; Zenitani and Hoshino 2001), and various mechanisms have been proposed for energetic particle acceleration during reconnection.

The Earth's magnetosphere has been regarded as a space laboratory for particle acceleration during magnetic reconnection, since precise information on plasma and electromagnetic fields is available through in situ spacecraft observations. At the start of the satellite observations, it was reported that the energetic particles with several 100 keV to 1 MeV are often observed in magnetotail (Fan et al. 1975; Hones et al. 1976; Sarris et al. 1976). The relationship between these energetic particles and magnetic reconnection has been examined since the early stage of space research. Terasawa and

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Nishida (1976) claimed that energetic electron bursts (0.3–1.0 MeV) occurred close to a magnetic reconnection region, because the southward turning of magnetic field was simultaneously observed with the burst. Baker and Stone (1977) also studied an energetic electron burst (>1 MeV) and concluded that the observed energetic electron bursts are usually associated with neutral sheet crossing. Energetic ion bursts in the magnetotail have also been studied by many authors (Fan et al. 1975; Sarris et al. 1976). The energy spectrum of high-energy ions can be described by the power-law distribution ($\gamma \sim 4 - 6$), and the typical upper ion energy is $\sim$ 300 keV during geomagnetic activity (Baker et al. 1979; Fan et al. 1975; Sarris et al. 1976). Moebius et al. (1983) reported energetic protons in the energy range 30 to 500 keV and energetic electrons >75 keV obtained by ISEE-1. They presented combined thermal plasma, magnetic field, and energetic particle observations for energetic particle bursts in the plasma sheet. The localized sources of energetic ions up to 500 keV have been observed during the passage of the neutral line. They conclude that the energetic ion acceleration took place in the vicinity of an X-type neutral line. Many observations suggest that energetic particle bursts might be related to magnetic reconnection.

Modern satellite observations reveal more precise acceleration sites of energetic electrons during magnetic reconnection. Øieroset et al. (2002) showed the significant electron acceleration up to 300 keV at an X-type neutral line based on a Wind satellite observation. On the other hand, some studies show that the energetic electrons are generated not only at the X-type neutral line but also in the wider region surrounding an X-type neutral line (Asano et al. 2008; Imada et al. 2007). A statistical study by Imada et al. (2005) discussed plasma heating and acceleration in and around magnetic reconnection region. They conclude that the electrons are first energized at an X-type neutral line and further accelerated in the magnetic flux pileup region. Another important finding for energetic electron acceleration is the relationship to small magnetic islands. Chen et al. (2008) showed that energetic electron fluxes peak at sites of compressed density within islands. Retino et al. (2008) also found the energetic electron flux enhancement within a small-scale flux rope that may be associated with flux rope coalescence. Recent spacecraft observations claim that the energetic electrons can be further accelerated at the dipolarization front which locates far downstream of reconnection flow (Fu et al. 2011).

There are some detailed studies of energetic ion acceleration in the magnetotail, using the modern satellite observations (Artemyev et al. 2014; Haaland et al. 2010). These studies indicate the relationship between energetic ion bursts and the geomagnetic activity and/or thin current sheet formation (Luo et al. 2014; Sarafopoulos 2008). However, the precise position of energetic ion acceleration during magnetotail reconnection and acceleration mechanism is still not certain. Further, energetic electron and ion acceleration seems to be different in some cases (Moebius et al. 1983; Øieroset et al. 2002). Imada et al. (2011) studied the favorable conditions for energetic electron acceleration during magnetic reconnection in the Earth's magnetotail by using ten Geotail magnetic reconnection observations. Their finding is that the energetic electrons are efficiently accelerated in a thin current sheet during fast reconnection events. The aim of this paper is to understand the favorable conditions for energetic ion acceleration by using ten magnetic reconnection events discussed in Imada et al. (2011). We will also reveal the difference between energetic ion and electron acceleration.

Instrumentation

We have used the data from comprehensive measurements onboard the Geotail satellite, including the low-energy particles (LEP/EAi, EAe) (Mukai et al. 1994), the energetic particles and ion composition instrument (EPIC/ICS) (Williams et al. 1994), and the magnetic fields (MGF) (Kokubun et al. 1994). We calculated the ion and electron temperature, density, and the three components of the velocity from the distribution functions obtained by the LEP instrument. To obtain ion moments, 12-s time-resolution data are used. We averaged the 12-s time-resolution electron moments into 60-s time resolution to reduce the statistical uncertainty. As for the energetic ions, we used energy spectra with angular distributions of energetic protons with the energy range of 58 keV to 3 MeV obtained every 96 s by EPIC. To investigate the energetic electrons acceleration, we used the integrated electron flux of > 38 (keV) measured by the EPIC instrument with 12-s time resolution. Although EPIC electron observation has two energy channels with energies higher than 38 and 110 keV, we only used the lower-energy channel which can result in enough particle counts during magnetic reconnection. The energetic particle data were integrated over pitch angle by assuming an isotropic velocity distribution function.

Observations of energetic ions: case study

We show a clear example of a Geotail observation of the energetic ion acceleration around an X-type neutral line. The reconnection event on 28 January 1997 observed at $X = -29R_E$ is one of the strongest electron acceleration event observed by Geotail. An overview of this reconnection event is shown in Fig. 1. Three components of the magnetic field, ion (red thick), and electron (blue thin) density and three components of the velocity, temperature, energetic electron integrated flux, and energetic ion differential flux are presented from top to bottom, respectively. Fast (> 1000 km s^{-1}) and tenuous (< 0.1 m^{-3}) tailward flows were observed from 1614 UT. Simultaneously,

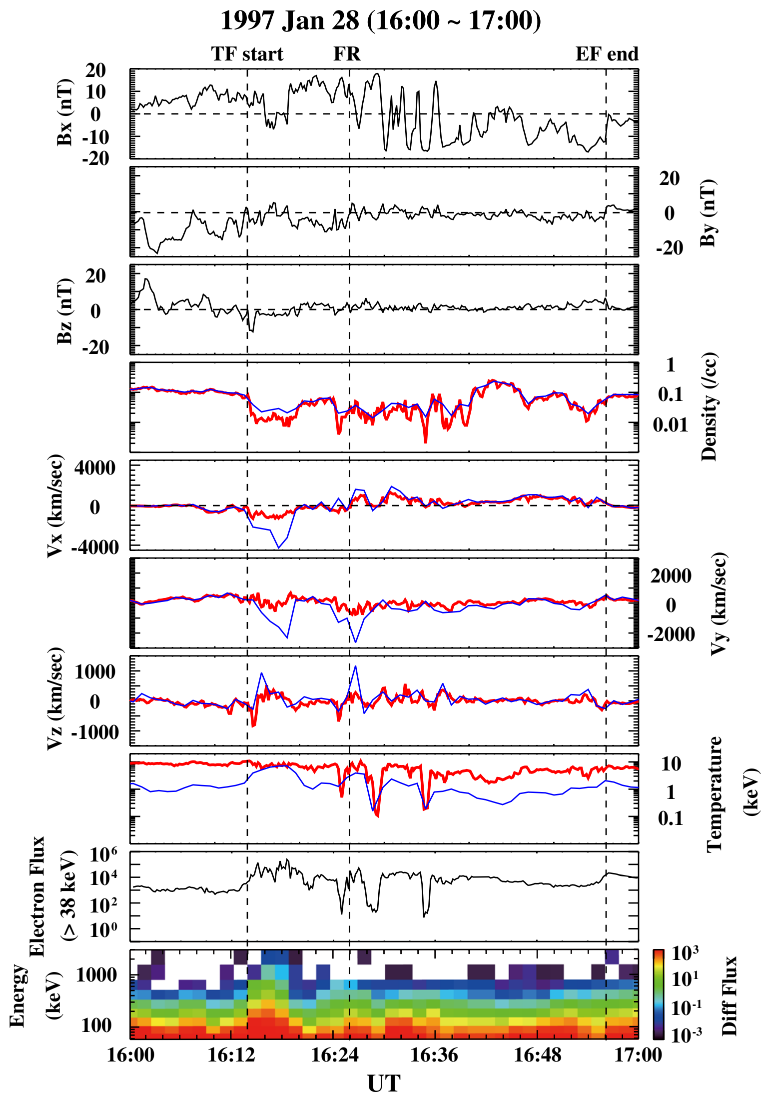

Fig. 1 Overview of the reconnection event on 28 January 1997. Three components of the magnetic field, ion (*red thick*), and electron (*blue thin*) density and three components of the velocity, temperature, energetic electron integrated flux, and energetic ion differential flux are presented from top to bottom, respectively. The *three vertical dotted lines* show the starting tailward flow (correspond to the downstream of reconnection out flow), the flow reversal (upstream), and earthward flow end time (downstream)

large negative Bz up to −13 nT was also observed. This is the typical signature at the tailward side of a reconnection outflow region. Because the main component of the ions is beyond the observational range of the LEP instrument, the ion moment data, such as ion temperature, velocity, and density, might be systematically underestimated from 1614 UT to 1620 UT (Asano et al. 2004). This is the reason why the ion density is largely less than that of electron, i.e., ion density is seriously underestimated. Both the electron temperature and energetic electrons flux are enhanced inside the tailward flow. The energetic ion acceleration up to 1 MeV have also been clearly observed. Once the tailward flows are terminated from 1620 to 1624, the flow direction has been changed from tailward to earthward at 1626 indicating the passage of an X-type neutral line. The event on 28 January 1997 is well studied concerning the fine reconnection structure such as Hall current system by Asano et al. (2004). According to their analysis, Geotail was located near the magnetic diffusion region at 1626 UT, because the inward Hall current toward the X-type neutral line in the central plasma sheet and the outward field aligned current from the X-line near the plasma sheet-lobe boundary (16:24 and 16:28) are clearly observed at that time. The sign of Hall magnetic field (By) has been also changed at this moment, and the thickness of the estimated current sheet is less than the ion inertia length. The energetic electrons and ions in the vicinity of X-type neutral line show slightly smaller value (∼ten times) than that in the tailward flow. The thin current sheet condition might continue until 1640 UT, because Bx rapidly changes several times. Earthward fast flows were observed intermittently and terminated at 1656 UT. Differential flux of energetic ions (a few hundred kiloelectron volt) and energetic electron flux (>38 keV) show similar value during the earthward flow. The energetic ions up to 1 MeV seems to be localized inside the tailward flow. A time variation of energetic ions and electrons is almost the same during the event. We cannot observe clear difference in energetic ion and electron acceleration. We can observe ∼100 keV ions over the entire observation period (16:00–17:00 UT).

Figure 2a shows the ion energy spectra obtained before (dotted line, 16:05:54) and during (solid line, 16:15:36) the reconnection outflow. The ion energy spectrum obtained at the time when the fast tailward flow start (16:15:36) is shown. This spectrum is the hardest one during the event. We also show the energy spectrum without any reconnection signatures (16:05:54). The spectra are fitted by power-law distribution function from 100 keV to 1 MeV. The energy spectra of the event clearly shows the strong ion acceleration with a significant hardening of the energy spectra from $\gamma = 5.4$ to 2.5. The estimated value of γ is in good agreement with the past study. Note that γ is derived from differential flux. The anisotropy of energetic ions might give an important information to understand the acceleration processes during magnetic reconnection. Figure 2b shows the anisotropy of energetic protons in the X-Y (2D) plane observed during the tailward flow. The energetic protons up to ∼1 MeV have a significant flux enhancement in the tailward ($-X$) (slightly duskward $+Y$) direction. Although it is difficult to discuss the anisotropy of energetic ion for north-south direction with EPIC data, these energetic ions are traveling directly from the source region. The Geotail spacecraft might locate close to the energetic ion acceleration region. The energetic ions are accelerated up to 1 MeV far from the X-type neutral line toward the downstream region.

Statistical property of energetic ion acceleration

In the previous section we showed a clear example of the energetic ion acceleration around an X-type neutral line in order to understand where the energetic ion can be accelerated. We also discuss the difference between energetic ion and electron acceleration. The results indicate that the source of energetic ion up to 1 MeV seems to be located at the downstream of reconnection outflow. However, we do not find clear difference between energetic ion and electron acceleration. In this section, we will present the favorable conditions for energetic ion acceleration using ten reconnection events discussed in Imada et al. (2011). In their study, they surveyed the reconnection events where the Geotail satellite observed the vicinity of diffusion region and identified events satisfying the following conditions: (1) $X_{\rm GSM} < -15R_E$, (2) the presence of fast bulk flow ($Vx > 500$ km s^{-1}), and (3) the presence of hot electron (>2 keV) Nagai et al.2001. The characteristics of each reconnection event (e.g., reconnection rate, current sheet thickness, and outflow velocity) have been already determined by Imada et al. (2011). They also confirm the consistency of their reconnection characteristics with other in situ observations. They transformed the coordinate into the current sheet normal system using the minimum variance analysis (MVA) (Sonnerup and Cahill 1967), where N is the estimated current sheet normal, L is in the direction of maximum variation ($\sim X_{\rm GSM}$), and M completes a right-hand system. The current density $\mathbf{j}$ is calculated directly from the ion and electron velocity difference, $\mathbf{j} = ne(\mathbf{v_i} - \mathbf{v_e})$. With pressure balance between the tail lobe and plasma sheet, magnetic field intensity in the tail lobe is derived as $B_{\rm lobe} = (B^2 + 2\mu_0 n k_B (T_i + T_e))^{1/2}$, where B, n, T_i, and T_e are local magnetic field intensity, plasma density, ion, and electron temperatures observed by Geotail in the current sheet, respectively. Using j_M and $B_{\rm lobe}$, a half thickness

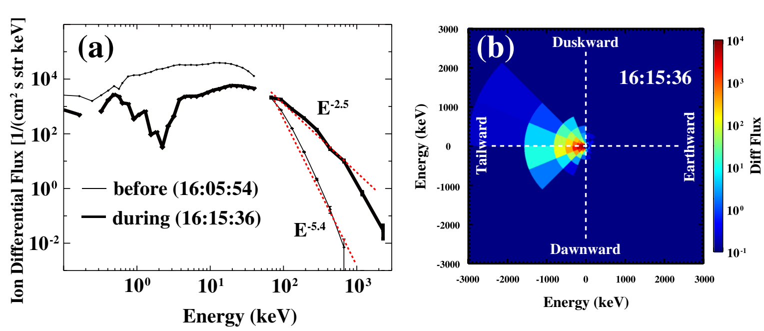

Fig. 2 a Ion energy spectra obtained before (dotted line, 16:05:54) and during (solid line, 16:15:36) the reconnection outflow. **b** Anisotropy of energetic protons in the X-Y (2D) plane observed during the tailward flow of current sheet δ is calculated from the Ampere's law assuming the homogeneity of current density in a current sheet, $\delta = B_{\mathrm{lobe}}/\mu_0 j_M$. The electric fields are calculated from $\mathbf{v} \times \mathbf{B}$ with frozen-in assumption. Reconnection rate can be estimate from the lobe Alfven velocity, the lobe magnetic field, and the reconnection electric field (E_M). They calculated ΔB^2 which is proportional to the total amount of reduced magnetic energy during reconnection by using B_{lobe} before and after the reconnection. In this paper, we use their values for reconnection characteristic parameters (for details, see Imada et al. (2011)). The index of kappa distribution for energetic electron is also determined from Imada et al. (2011). The indexes of power-law distributions for energetic ion in each event are newly estimated. The spectra are fitted by power-law distribution functions from 100 keV to 1 MeV. We have selected the hardest spectrum to decide the typical γ of each event. We also check the similarity of energetic ions and electrons enhancement by checking their time variation in the same way discussed in the previous section. The list for the ten reconnection events is shown in Table 1.

First, we compare γ (energetic ion) and κ (energetic electron) to clarify the relationship between the energetic ion and electron acceleration. Figure 3 shows the relationship between energetic electron and ion (κ-γ). Although the correlation coefficient is low ($\sim$0.15), the solid line shows the result of linear fitting. The event that shows hard spectrum in energetic electrons (small κ) also shows hard energetic ion energy spectrum (small γ) and vice versa. If we ignore the two events (event C and I in Table 1) which are far from linear fitting, the correlation coefficient becomes better (0.84; dotted line). Therefore, the energetic ion and electron acceleration seem to have a similar time variation except for the two events. We also checked the similarity of energetic ions and electrons enhancement in each event. Two events (A and G) show the different time variations for energetic electrons and ions (not shown here). Although these two events show the different time variations for energetic electrons and ions, a time variation of energetic ions and electrons is similar in most events.

Next, to clarify the relationship between the energetic ion acceleration efficiency and the reconnection characteristics, we carried out correlation analysis among them. We use the following parameters for reconnection characteristics: ion temperature (Ti), electron temperature (Te), ion/electron temperature ratio (Ti/Te), current sheet thickness (δ), reconnection electric field (E_M), electric field normal to the neutral sheet (E_N), total amount of reduced magnetic energy (ΔB^2), reconnection rate (R), absolute value of outflow velocity ($|V|$), current density parallel to magnetic field ($j_{\parallel}$), and satellite location in the Earth's magnetosphere (X, Y). Figure 4 shows the relationship between the energetic ion parameter (γ) and the reconnection characteristics. All vertical axes show γ, while the horizontal axes show each of the parameters. The squares/diamonds show the result of 1 min/12 s average results, respectively. The fitted results for squares/diamonds are presented by solid/dashed lines, respectively. The correlation coefficients are also shown in the figure.

We have classified the relationship between reconnection characteristics and energetic ion acceleration into three types: (1) good correlation (absolute value of correlation coefficient $|r| > 0.6$); (2) ambiguous correlation ($0.6 > |r| > 0.3$); and (3) no correlation ($|r| \sim 0$). We found that E_M, ΔB^2, R, X_{GSM}, and Y_{GSM} can be categorized into good correlation with energetic ion acceleration efficoency. The strong reconnection electric field and the large amount of reduced magnetic energy cause strong ion acceleration. The magnetic reconnection location in X_{GSM} also affect the energetic ion acceleration. Note that we do not include the distant tail reconnection event A in the analysis of satellite location. Ion acceleration also

Table 1 List of ten reconnection events observed by Geotail

Event	Date	Time	[X, Y]	Electron (κ)	Ion (γ)	Similarity
A	940115	18:00–20:00	[−96, 7]	4.3	5.5	Different
B	960127	13:45–15:45	[−29, 5]	4.2	5.1	Similar
C	961113	10:00–12:00	[−18, 2]	3.2	6.9	Similar
D	961210	17:00–19:00	[−26, 1]	3.6	4.3	Similar
E	970128a	13:30–15:30	[−29, 10]	3.0	2.8	Similar
F	970128b	15:30–17:30	[−29, 9]	3.1	2.5	Similar
G	970225a	09:20–11:20	[−27, 6]	4.2	5.7	Different
H	970225b	14:00–16:00	[−26, 3]	3.8	5.7	Similar
I	970313	15:00–17:00	[−24, 7]	4.5	4.1	Similar
J	970420	08:00–10:00	[−17, 9]	4.3	5.4	Similar

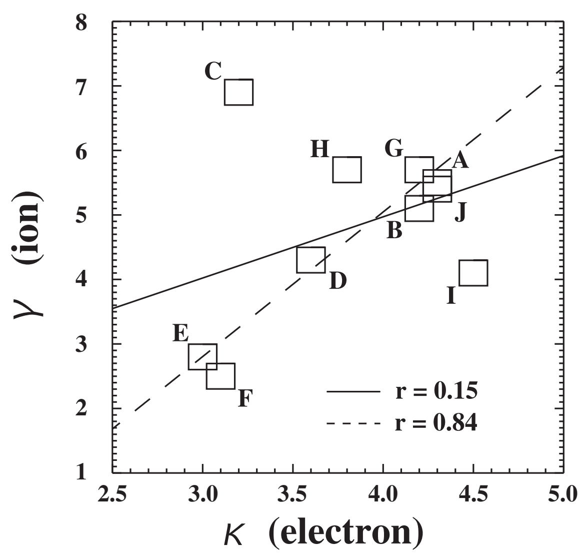

Fig. 3 Relationship between energetic electrons (κ) and ions (γ)

depends on the reconnection location in Y_{GSM}. The duskside reconnection strongly accelerates energetic ions. Ti, Te, Ti/Te, δ, and E_M are classified in ambiguous correlation. We cannot find any correlation with absolute |V| and $j_{\|}$. Table 2 shows the correlation coefficients between energetic electron/ion and reconnection parameters. In the last line of Table 2, E/I represents good correlation with energetic electron/ion acceleration, respectively. Both of energetic ions and electrons show good correlation with reconnection electric field. Only energetic ions show good correlation with total amount of reduced magnetic energy, reconnection rate, and satellite location in the Earth's magnetosphere (both X_{GSM} and Y_{GSM}). On the other hand, only energetic electrons show good correlation with ion temperature, electron temperature, ion/electron temperature ratio, current sheet thickness, and electric field normal to the neutral sheet.

Summary and discussion

The energetic ion acceleration during magnetic reconnection in the Earth's magnetosphere has been studied using Geotail data. We showed a clear example of energetic ion acceleration up to 1 MeV around an X-type neutral line. The energetic ions are localized at far downstream of reconnection outflow. We also found that a time variation of energetic ion ($\sim$1 MeV) enhancement is almost the same as that of energetic electron (>38 keV). We can observe $\sim$100 keV ions over the entire observation period. The ten events in which the Geotail satellite observed the vicinity of diffusion region have also been studied to infer what reconnection characteristics determine the energetic ion acceleration efficiency. We found that reconnection electric field, total amount of reduced magnetic energy, reconnection rate, satellite location in the Earth's magnetosphere (both X_{GSM} and Y_{GSM}) can be categorized into good correlation with energetic ion acceleration efficiency. Ion temperature, electron temperature, ion/electron temperature ratio, current sheet thickness, and electric field normal to the neutral sheet are classified in ambiguous correlation. We cannot find any correlation with absolute value of outflow velocity and current density parallel to the magnetic field. We find that the energetic ions seem to be well correlated with the large-scale parameters (e.g., total amount of reduced magnetic energy and satellite location), although the energetic electron acceleration efficiency seems to be correlated with the small-scale parameters (e.g., current sheet thickness and electric field normal to the neutral sheet).

Let us discuss the plausible scenario of the energetic ion acceleration up to 1 MeV is from the result of our observation. Our observations show that the energetic ions ($\sim$1 MeV) and electrons (>38 keV) seem to be accelerated at the same place. The standard energetic electron acceleration mechanism is that the unmagnetized electrons in the vicinity of the X-type diffusion region can be accelerated by strong inductive electric field during the meandering/Speiser motion. The polarization electric field in a thin current sheet can also contribute to electron pre-acceleration. Furthermore, accelerated electrons, which have a large gyroradius, are then transported outward from the diffusion region and are further accelerated around the piled-up magnetic field region because of ∇B drift and/or curvature drift under the nonadiabatic motion (Hoshino 2005). The reconnection electric field is important for energetic ion and electron acceleration, because ions and electrons get energy from it. For energetic electron acceleration, the pre-acceleration/heating is crucial to get large gyroradius for second-step acceleration. The electron pre-acceleration and/or heating are generally defined by the small-scale plasma condition. This is the reason why the energetic electron acceleration efficiency is well correlated with small-scale parameter of magnetic reconnection. On the other hand, for energetic ion acceleration, the gyroradius is large enough for second-step acceleration. Hot ions at the piled-up magnetic field region can be accelerated without any pre-acceleration. However, the spatial scale size of the acceleration region is conclusive for energetic ion acceleration up to 1 MeV. In the case of reconnection electric field of 10 mV m^{-1}, the spatial scale needs to be at least 10^5 km ($\sim$magnetosphere width) to accelerate ions up to 1 MeV. Energetic ion acceleration efficiency clearly depends on the satellite location Y_{GSM}. This result indicates the importance of the spatial size of the magnetic reconnection in Y_{GSM}. Energetic ion acceleration efficiency also depends on the satellite location X_{GSM}. The scale length in Y_{GSM} direction might be different with location of

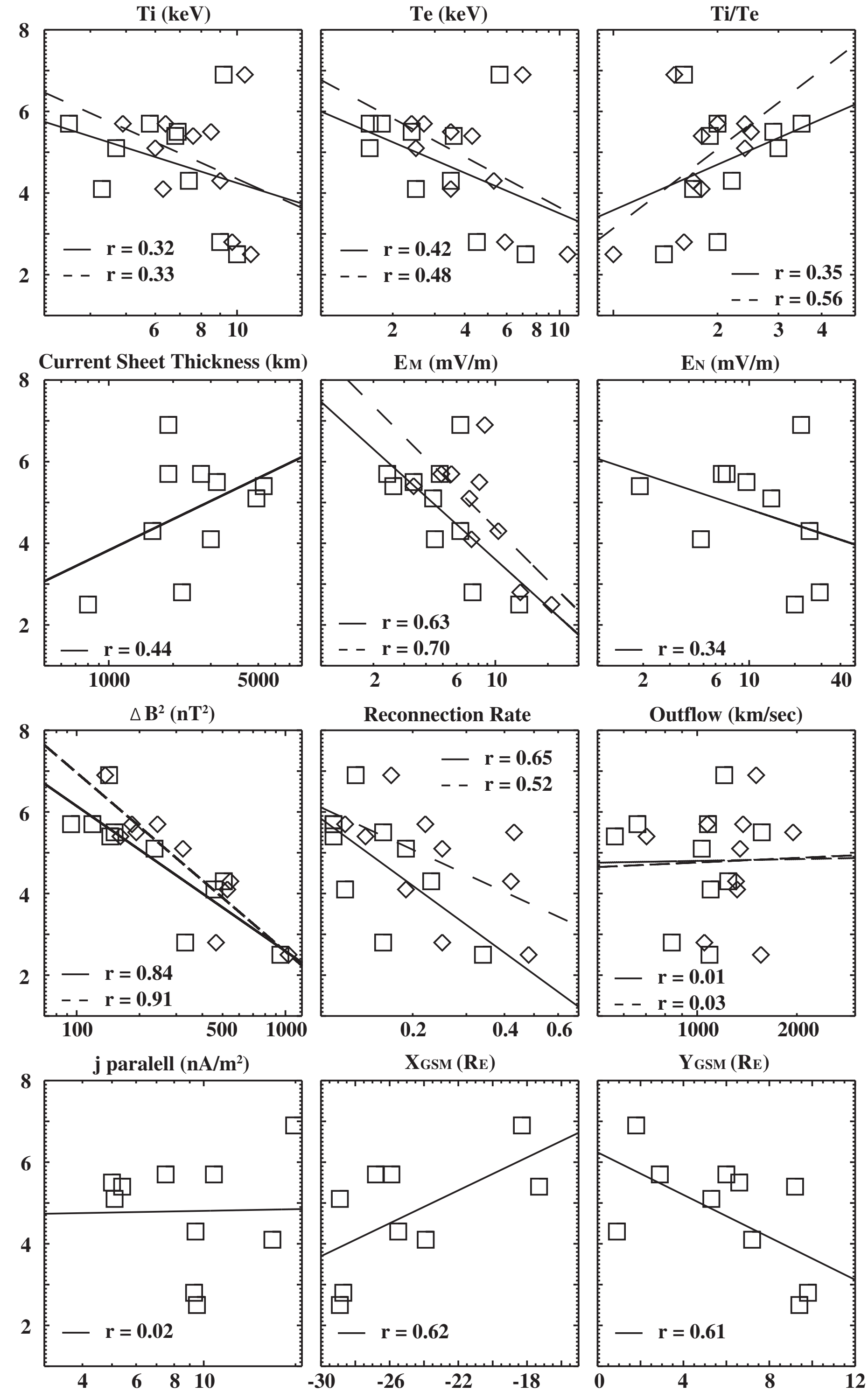

Fig. 4 Relationship between the energetic ions (γ) and the reconnection characteristics. The *squares/diamonds* show the result of 1 min/12 s average results, respectively. The fitted results for squares/diamonds are presented by *solid/dashed lines*, respectively

Table 2 Correlation coefficients between energetic particle acceleration efficiency and reconnection characteristics

	Ti	Te	Ti/Te	δ	E_M	E_N	ΔB^2	R	$\lvert V \rvert$	$j_{//}$	X	Y
Electron	0.68	0.75	0.52	0.69	0.82	0.78	0.39	0.50	0.02	0.40	0.26	0.03
Ion	0.32	0.42	0.35	0.44	0.63	0.34	0.84	0.65	0.01	0.02	0.62	0.61
Good correlation	*E*	*E*	–	*E*	*E*, *I*	*E*	*I*	*I*	–	–	*I*	*I*

magnetic reconnection in X_{GSM}. Imada et al. (2008) studied the dawn-dusk asymmetry of energetic particles and claimed the importnace of the spatial diffusion of energetic particles to explain the observed asymmetry. The energetic particles in magnetotail can gain energy larger than the available potential energy by spatial diffusion. Therefore, we conclude that the spatial size of magnetic reconnection is important for energetic ion acceleration in the Earth's magnetosphere. To strengthen our conclusion, we need to examine more reconnection events. It is also important to compare our results with recent magnetic reconnection observations by *Time History of Events and Macroscale Interactions during Substorms* (THEMIS). Especially, this is useful for understanding the relationship between the energetic ion acceleration and reconnection location in X_{GSM}, because THEMIS has a large coverage in X_{GSM}. The magnetospheric multiscale (MMS) mission reveals more precise plasma conditions during magnetic reconnection. We expect that MMS observations clarify the relationship between energetic particle acceleration and reconnection conditions thoroughly. This is crucial for understanding the energetic particle acceleration mechanisms during magnetic reconnection.

Before closing, we emphasize that studying magnetic reconnection in various plasma conditions is important in order to understand the universal plasma physics lying behind the individual phenomenon (Terasawa et al. 2000). There are similarities between the plasma parameters in Earth's magnetotail and the solar corona. Table 3 shows the typical parameters of magnetic reconnection in the Earth's magnetotail and the solar corona. In the Earth's magnetotail, we sometimes observe energetic ion acceleration up to a few megaelectron volts. Therefore, the maximum energy observed in the magnetotail reconnection seems to exceed the available potential energy. This means that the energetic ion acceleration process in the magnetotail might be affected by the large-scale conditions. On the other hand, during the solar flare, we rarely observe >500 MeV proton by the ground-based neutron monitors, the so-called ground level enhancements (Andriopoulou et al. 2011). Therefore, the maximum energy observed in the solar corona seems to be lower than the available potential energy. The effect of large-scale conditions to the energetic ion acceleration process in the solar corona might be limited. The Earth's magnetosphere and the solar corona are similar in some respects but very different in many other respects. The detailed comparison between the Earth's magnetosphere and the solar corona might open a new window of opportunity in understanding the particle acceleration better, and in our future work, we intend to study this comparison.

Table 3 Typical values for energetic particle acceleration in Earth's magnetotail and solar corona

	L (m)	V_A (m s^{-1})	B (T)	R	E_R (V/m)	eϕ (eV)
Earth's magnetotail	10^8	10^6	10^{-8}	0.1	10^{-3}	10^5
Solar corona	10^8	10^6	10^{-2}	0.1	10^3	10^{11}

The typical scale length (L), Alfven velocity (V_A), magnetic field strength (B), reconnection rate (R), the expected reconnection electric field (E_R), and available potential energy (eϕ) in the Earth's magnetotail and the solar corona

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
SI analyzed the Geotail data and drafted the manuscript. MH also analyzed the observation, especially the energetic ion data. All authors contributed to the interpretations of the data and the writing of the paper. All authors read and approved the final manuscript.

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