第50卷第9期 中国科学技术大学学报 Vol. 50, No. 9
2020年9月 JOURNAL OF UNIVERSITY OF SCIENCE AND TECHNOLOGY OF CHINA Sep. 2020

文章编号:0253-2778(2020)09-1218-11

Magnetic islands in collisionless magnetic reconnection

LU Quanming[1,2], WANG Rongsheng[1,2], HUANG Kai[1,2], WANG Shui[1,2]

(1. *CAS Key Lab of Geospace Environment, School of Earth and Space Sciences, University of Science and Technology of China, Hefei 230026, China*

2. *CAS Center for Excellence in Comparative Planetology, Hefei 230026, China*)

Abstract: The roles of magnetic islands were reviewed in two essential aspects of collisionless magnetic reconnection: rapid dissipation from magnetic energy to plasma kinetic energy and generation of energetic electrons. The current sheet around the X line may be extended and unstable to the tearing mode instability. Secondary magnetic islands are generated and then consequentially interact each other in the extended current sheet. Such a nonstationary magnetic reconnection can maintain a large reconnection rate for a long time and efficiently dissipate magnetic energy. Electrons can be accelerated inside magnetic islands by Fermi and betatron mechanisms, as well as by reconnection electric field in the vicinity of the X line. The interaction of magnetic islands can result in further electron acceleration. These acceleration processes can make energetic electrons possess a power-law spectrum.

Key words: collisionless magnetic reconnection; magnetic islands; dissipate; energetic electrons

CLC number: P354 **Document code**: A doi:10.3969/j.issn.0253-2778.2020.09.002

Citation: LU Quanming, WANG Rongsheng, HUANG Kai, et al. Magnetic islands in collisionless magnetic reconnection[J]. Journal of University of Science and Technology of China, 2020,50(9):1218-1228.
陆全明,王荣生,黄楷,等. 无碰撞磁场重联中的磁岛[J]. 中国科学技术大学学报,2020,50(9):1218-1228.

特约评述

无碰撞磁场重联中的磁岛

陆全明[1,2],王荣生[1,2],黄 楷[1,2],王 水[1,2]

(1.中国科学技术大学地球和空间科学学院中国科学院近地空间环境重点实验室,安徽合肥 230026;
2.中国科学院比较行星学卓越创新中心,安徽合肥 230026)

摘要:在以下两个方面回顾了磁岛在无碰撞磁场重联中的作用:磁能到等离子体动能和热能的快速转化以及高能量电子的产生.重联的X点附近的电流片可能被拉伸并导致撕裂模不稳定性,并形成相互作用的次

Received: 2020-08-16; **Revised**: 2020-09-15

Foundation item: Supported by the NSFC of China (41774169, 41527804), Key Research Program of Frontier Sciences, CAS(QYZDJ-SSW-DQC010).

Biography: LU Quanming(corresponding author), male, born in 1969, PhD/Changjiang Distinguished Prof. He received his BS degree from Nanjing University in 1990, and his MS and PhD degrees from University of Science and Technology of China in 1993 and 1996, respectively. He had been a postdoctor from 1996 to 1998 at Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, and from 1998 to 2000 at Tsukuba University, Japan. He joined the faculty of University of Science and Technology of China as associate professor in the Department of Earth and Space Sciences in 2000. He was promoted to full professor in 2003. His research field has been focused on space plasma physics, and he has published more than 200 SCI papers in international high-level academic journals including *Nature Physics*, *Nature Communications* and *Physical Review Letters*. E-mail: qmlu@ustc.edu.cn

级磁岛.这种非稳态的磁场重联图像可以维持长时间的高重联率,进而有效地耗散磁能.电子可在磁岛内通过费米和 betatron 机制加速,也可在 X 点附近通过重联电场加速.磁岛间的相互作用可进一步加速电子.这些加速过程可导致高能量电子的幂律谱分布.

关键词:无碰撞磁场重联;磁岛;耗散;高能量电子

0 Introduction

Magnetic reconnection, which is accompanied by a topological change of magnetic field lines, provides a physical mechanism to convert magnetic energy to plasma kinetic energy[1-4]. It is generally accepted that magnetic reconnection is the fundament to explain the explosive phenomena in space plasma, including solar flare, substorm in the earth's magnetosphere, etc[5-8]. These explosive phenomena usually last several minutes, and it means that energy conversion provided by magnetic reconnection should be sufficiently fast to explain these explosive phenomena. Simultaneously, energetic particles are ubiquitously observed in these explosive phenomena[9-12]. Therefore, a successful reconnection model should have two indispensable ingredients: a high reconnection rate and generation of energetic particles.

The first quantitative reconnection model was proposed by Sweet and Parker independently, which is named as the Sweet-Parker model and based on the magnetohydrodynamic (MHD) theory[13-14]. In the Sweet-Parker model (as shown in Fig. 1), ions and electrons are coupled together, and they move toward the diffusion region from the inflow region. After these plasmas are accelerated in the diffusion region, they will enter the outflow region. The dissipation of magnetic energy is fulfilled via Ohmic heating in the diffusion region. The predicted reconnection rate is $R_0 \propto R_m^{-1}$, where R_m is magnetic Reynolds number. In space plasma, magnetic Reynolds number R_m is very large, and thus the reconnection rate is too small to explain quantitatively the explosive phenomena. Another drawback of Sweet-Parker model is that particle dynamics cannot be embedded in the model self-consistently. Therefore, a more promising model is necessary to describe these explosive phenomena in space plasma.

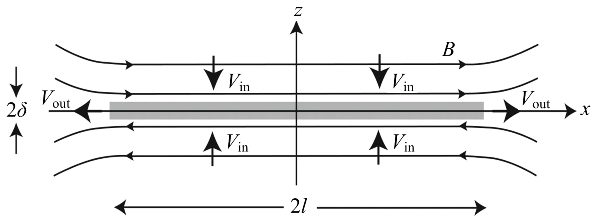

Fig. 1 Schematic drawing of Sweet-Parker model[4]

One appealing solution is collisionless magnetic reconnection model, where the motions between ions and electrons are decoupled[15-18]. The diffusion region consists of the ion diffusion and electron diffusion region (as shown in Fig. 2). In the ion diffusion region with its scale being about ion inertial length, electrons are frozen in the magnetic field, and ions are unmagnetized; in the electron diffusion region with its scale being about electron inertial length, both ions and electrons are unmagnetized. The predicted reconnection rate is around 0.1, which is sufficiently high to explain these explosive phenomena in space plasma[19-20]. Because in the ion diffusion region, electrons are frozen in the magnetic field, move toward the X line along the separatices, and then away from the X line along the magnetic field just below the separatrices after they are accelerated in the vicinity of the X line by the reconnection electric field. Such kind of electron motion will lead to the Hall current in the reconnection plane, and a quadrupolar structure of the out-of-plane magnetic field is then formed[21-24]. There is plenty of observational evidence to demonstrate the occurrence of collisionless magnetic reconnection in the earth's and planetary magnetosphere[25-30]. Particle dynamics can also be intrinsically embedded in

特约评述

collisionless magnetic reconnection[31-34].

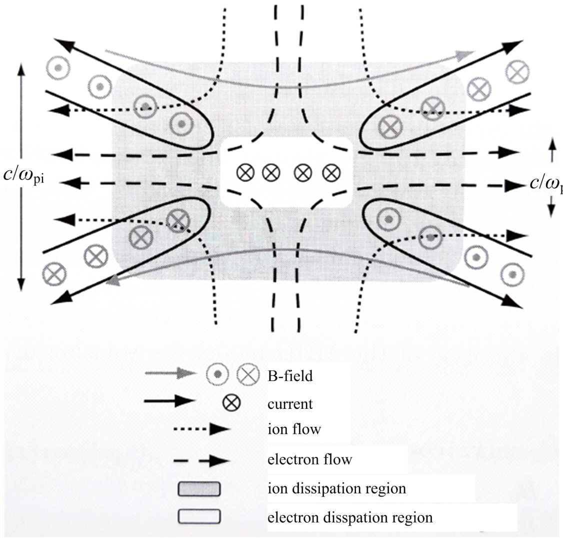

Fig. 2 Schematic drawing of collisionless magnetic reconnection model[2]

The reconnection models described above assume that reconnection is in a steady state. However, in reality, magnetic reconnection is usually non-stationary. Magnetic islands are usually generated during the topological change of magnetic field lines occurring in magnetic reconnection. These islands can undergo contracting and coalescence between islands, and then particles can be energized through these processes[35-38]. Therefore, magnetic islands play an important role in both dissipation of magnetic energy and particle acceleration. In recent years, satellite observations with a constellation of spacecraft in a small interspacecraft spacing can achieve fine spatial resolution and high temporal resolution for plasma data, providing a chance to study the roles of magnetic islands in collisionless magnetic reconnection[39-40]. We will review the observational and simulation progress of magnetic islands on energy dissipation and electron dynamics in collisionless magnetic reconnection, focuing on collisionless magnetic reconnection: if there is no explicit expression, magnetic reconnection described in the following is collisionless.

1 Magnetic islands and energy dissipation

Particle-in-cell simulations have shown that the current sheet around the X line of magnetic reconnection is not stationary, and it can be extended along the outflow direction slowly[41-44]. Then, the opening angle made by the upstream magnetic field becomes smaller, and the reconnection rate (or equivalently the reconnection electric field) decreases[45]. Therefore, the extension of the current sheet around the X line will lead to the decrease of reconnection rate, and it will also reduce the efficiency of both the dissipation from magnetic energy to plasma kinetic energy and electron acceleration[42,46]. However, Drake et al.[41] pointed out that magnetic islands can be generated in the extended current sheet around the X line due to tearing mode instability, and these islands are called secondary islands. The generation of secondary islands will separate the extended current sheet into several fragmented current sheets, and a new X line is then formed between two secondary islands. Around the new X line, a larger opening angle made by the upstream magnetic field is formed, and then the reconnection rate is increased. These secondary islands at last merge into the outflow region, thus enhancing the efficiency of energy dissipation. In Ref. [41], an ambient guide magnetic field is introduced, and it is considered as a prerequisite condition to generate secondary islands in an extended current sheet around the X line. Later, Daughton et al.[42] found that even in anti-parallel magnetic reconnection when open boundary conditions are used in their PIC simulations, the current sheet around the X line can also be extended, and then secondary magnetic islands are generated in the extended current sheet, just as in guide field reconnection.

Now we know that secondary islands can be ubiquitously observed in PIC simulations of anti-parallel and guide field reconnection. Several PIC simulations further found that secondary islands can be repetitively generated in the extended current sheet around the X line[47,48]. Fig. 3 shows the evolution of magnetic field lines and reconnection electric field in PIC simulations with an open outflow boundary condition. At $\Omega_i t=50$, the primary X line is around $x=85d_i$, where Ω_i is ion gyrofrequency and d_i is ion inertial length and there are two secondary islands moving toward the outflow boundaries. When the two islands move away from the outflow boundaries, at $\Omega_i t=76$, another secondary island appears at about $x=98d_i$. At $\Omega_i t=127$ and 200, secondary islands are repetitively generated in the extended current sheet. The electric field induced around the new X line and inside magnetic islands can increase the plasma kinetic energy in the current sheet, and lead to the enhancement of energy dissipation.

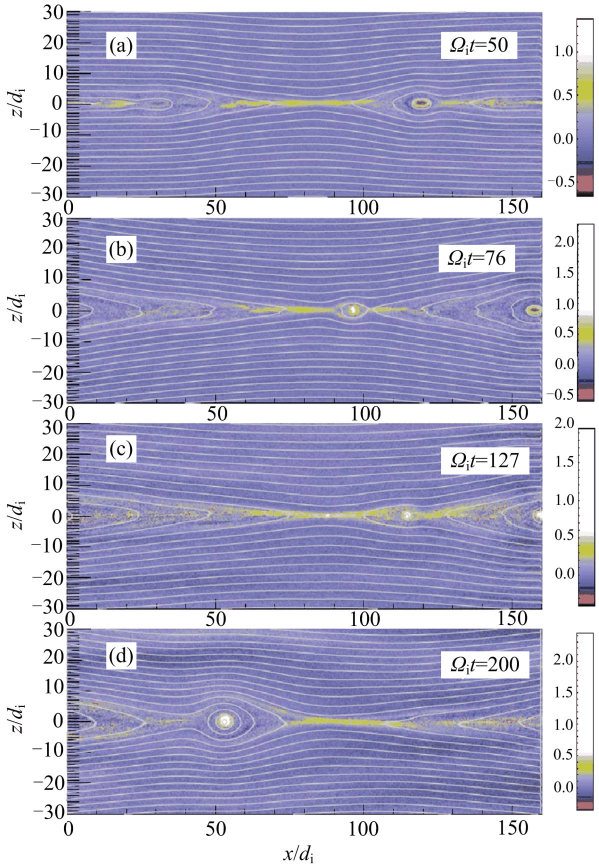

Fig. 3 The repetitive generation of secondary islands in the extended current sheet[47]

With Cluster spacecraft, Wang et al.[49] presented the first evidence for the existence of a secondary magnetic island in the vicinity of an ion diffusion region. The length of the island is about 3 ion inertial lengths, and there is more obvious enhancement of energetic electron fluxes inside the secondary island than the other regions as predicted in numerical simulations. The existence of secondary islands in the vicinity of the X line has then been identified by numerous satellite observations[50-53]. In 2016, Wang et al.[54] further identified a total of 19 secondary islands in the ion diffusion region of a magnetotail reconnection event with Cluster observations, and most of these secondary islands are suffering from coalescence. At last, they proposed a new picture of magnetic reconnection: the ion diffusion region is full of secondary islands interacting with each other. The reconnection rate can maintain a high value for a long time in such a nonstationary picture of magnetic reconnection.

In three-dimensional (3D) kinetic simulations of magnetic reconnection, the secondary islands (usually called flux ropes in three-dimension) generated in the vicinity of the X line are not homogeneous in the out-of-plane direction, and can interact in a variety of complex ways which are impossible in 2D models[55], as shown in Fig. 4. In 3D magnetic reconnection with a limited X-line extent, an internal X-line asymmetry along the out-of-plane direction develops because of the flux transport by electrons beneath the ion kinetic scale[56,57]. How these 3D structure of secondary islands will affect the dissipation of magnetic energy is still unknown and need further investigation.

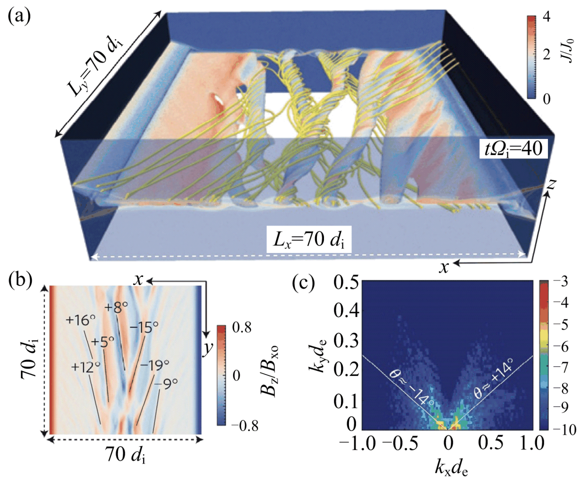

Fig. 4 3D structures of secondary islands[55]

特约评述

2 Magnetic islands and electron acceleration

After electrons are accelerated by the reconnection electric field in the vicinity of the X line, they will leave the acceleration region quickly. Therefore, it is difficult to accelerate an electron to very high energy. However, satellite observations associated with magnetic reconnection usually find that energetic electrons own a power law distribution[9-11], and it means that additional acceleration process is necessary.

By performing 2D particle-in-cell simulations, Fu et al.[58] studied electron acceleration in a magnetic island formed in anti-parallel magnetic reconnection. Fig. 5 plots the generation of magnetic island and a typical electron trajectory in the island. Because of the periodic boundary condition utilized in the simulation, the electrons are trapped in the magnetic island. Fig. 6 describes the time evolution of the energy and velocities of the electron trapped in the island(A2 to D2). The island is generated between two X lines, and is then compressed by the high-speed outflow from the two X lines. The electrons can be accelerated at the two ends of the island. Because in their simulations there is no initial guide field in the current sheet, the electron motions are non-adiabatic, although such an acceleration process is similar to that of Fermi acceleration in magnetic island, which has been studied by Drake et al.[59]. A strong guide field is introduced in Ref. [59], the trapped electron inside the magnetic island suffers from a classic Fermi acceleration. The electron acceleration inside a magnetic island has also been confirmed by satellite observations by identifying the enhancement of energetic electron fluxes inside the magnetic island[49, 60-63]. If there are several magnetic islands in the current sheet, these islands will merge with each other and eventually form a big island. Oka et al.[64] and others[65-67] further found that electrons can also be efficiently accelerated by the induced electric field during the merging of magnetic islands. The merging of magnetic islands have already been observed by satellites[54, 68-70].

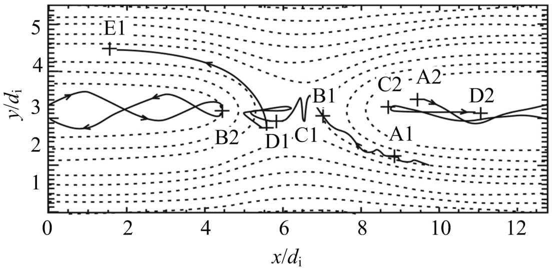

Fig. 5 Typical electron trajectories passing through the X line (A1 to E1) and trapped in a magnetic island(A2 to D2)[58]

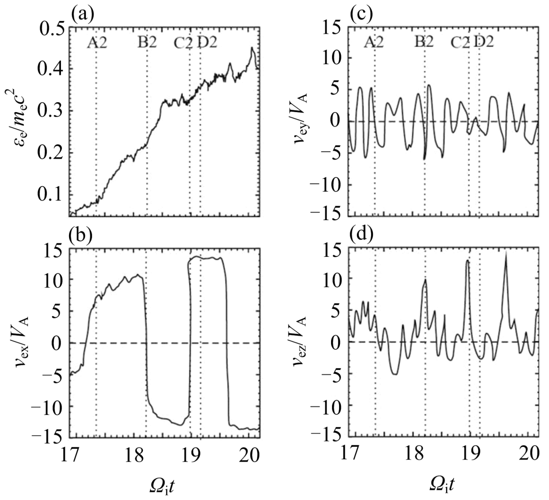

Fig. 6 The time evolution of the energy and velocities of the electron trapped in the island (A2 to D2)[58]

When the spatiotemporal scales for the variation of electromagnetic field are much larger than those of electron gyromotion, the electron motions are adiabatic because their trajectories can be well described at the lowest order by perpendicular gyration about the magnetic field and parallel propagation along the magnetic field. Besides the acceleration by the parallel electric field, electrons can also be accelerated through betatron and Fermi mechanisms if electron motions are adiabatic[71]. Betatron acceleration is associated with the perpendicular gyromotion and linked to conservation of the adiabatic invariant $\mu = mv_\perp^2/(2B)$. As a particle experiences temporal variation in the magnetic field, its energy evolution follows the equation $\varepsilon_\perp \propto mv_\perp^2 \propto B$. For an electron, the energy gain must ultimately be due to

特约评述

the electric field, which should be either opposite to the gyromotion or an induced electric field opposite to the grad-B drift. Huang et al.[72] found that that only the electrons trapped by the parallel electric field in the region with the enhancement of magnetic field can suffer betatron acceleration. In Fermi process of electron acceleration, the parallel action $\int v_{\parallel} dl$ along a field line is conserved, and the contraction of the field line results in energy gain. Equivalently, contracting of the magnetic field drives an induced electric field opposite to the direction of the curvature drift.

In magnetic reconnection with the generation of magnetic islands, in addition to the fact that electrons can be accelerated in the vicinity of X line by the reconnection electric field, electrons can still be accelerated in magnetic islands where they are compressed and contracted by the tension-drive flow from the X lines. With MMS observations in an earth's magnetotail reconnection event, Zhong et al.[73] found enhanced energetic electrons in a reconnection-generated magnetic island, which is identified to be caused due to the adiabatic processes of betatron and Fermi acceleration. Fig. 7 describes the schematic diagram of betatron and Fermi acceleration in an island.

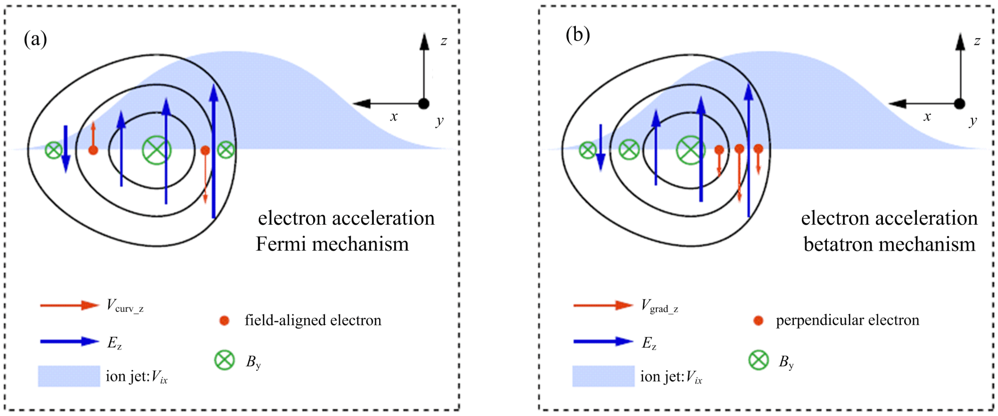

Fig. 7 Schematic diagram of betatron and Fermi acceleration in an island[73]

When there is a guide field in magnetic reconnection, the spatiotemporal scales of electron gyromotion becomes very small, and electron trajectories can be well described as adiabatic motions. Electron acceleration around the X line is caused due to the parallel electric field because of the existence of the guide field. Numerous kinetic simulations have analyzed the contributions of the parallel electric field, betatron and Fermi mechanisms in magnetic reconnection with a guide field, where several islands are generated and interact with each other[74-77]. Wang et al.[67] found that in multiple island reconnectionelectrons are firstly accelerated by both the parallel electric field in the vicinity of the X lines and the Fermi mechanism due to the contraction of magnetic islands, and then two magnetic islands begin to merge each other. In such a process, the electrons can be accelerated by both the parallel electric field and betatron mechanisms. During the betatron acceleration, the electrons are locally accelerated in the regions where the magnetic field is piled up by the high-speed flow from the X line. At last, when the coalescence of two islands into one big island finishes, the electrons can be further accelerated by the Fermi mechanism because of the contraction of the big island. Such a process is described in Fig. 8. With the increase of the guide field, the contributions of the Fermi and betatron mechanisms to electron acceleration become less and less important. When the guide field is sufficiently large, the contributions of the Fermi and betatron mechanisms are almost negligible. Such a process with generation and coalescence of magnetic islands can lead to a power-law distribution of energetic electrons, as presented in satellite observations. Li et al.[77] also investigated electron acceleration in magnetic reconnection, and found that a lower upstream plasma beta tends to form a smaller index of a power law spectrum. However, there is still a controversy on which is the dominant mechanism that results in the power-law spectra of energetic electrons. Guo et al.[48] thought that Fermi mechanism is the dominant mechanism. However, Lu et al.[78] analyzed the acceleration mechanisms for energetic electrons with a power law distribution, and found both the parallel electric field and Fermi mechanism work.

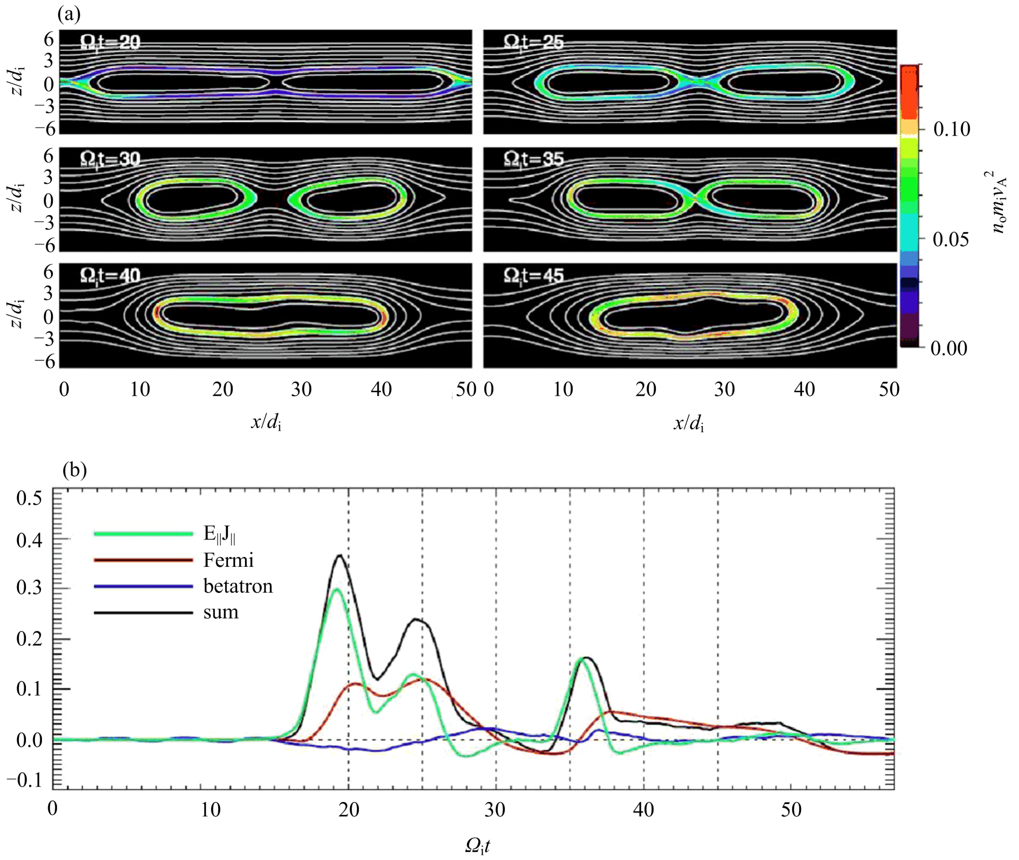

Fig. 8 The time evolution of (a) the magnetic field lines and electron energy in a defined flux tube, (b) the contributions of the parallel electric field, Fermi, and betatron mechanisms to electron acceleration in the flux tube[67]

Most of kinetic simulations on electron acceleration during magnetic reconnection used a two-dimensional model, which assumes an unlimited length in the out-of-plane direction. Dahlin et al.[75] used a 3D kinetic simulations to study electron acceleration. The results have shown that magnetic islands in 3D developed an axial structure. However it will not throttle the dominant Fermi mechanism responsible for efficient electron acceleration. Electron acceleration in 3D magnetic reconnection is still waiting for further investigation.

3 Conclusion

The generation of magnetic islands is usually observed in the topologic change of a magnetic field occurring during magnetic reconnection. In this paper, we described the roles of magnetic islands in the dissipation from magnetic to plasma kinetic energy and the production of energetic electrons. The generation of secondary magnetic islands and the consequential interactions between these islands in the extended current sheet around the X line can lead to the maintenance of large reconnection rates for a long time, and the efficiently dissipate magnetic energy to particle energy . Electrons can be accelerated in the vicinity of the X line by reconnection electric field, and inside magnetic islands by Fermi and betatron mechanisms. The interaction of magnetic islands can result in further electron acceleration, and the produced energetic electrons possess a power-law spectrum.

Please also note, in this paper, we only consider the dissipation of magnetic energy in the vicinity of X line during magnetic reconnection, while recently both simulations and observations have indicated that the dissipation can also occur inside magnetic islands[79-81]. Besides, there are still two factors which may influence magnetic reconnection. One is the inhomogeneity in the out-of-plane direction, and the other is plasma waves. 3D kinetic simulations have shown that both the X line and islands may be distorted along the out-of-plane direction. Numerous plasma waves are observed by spacecraft around the X line, the separatrix region and the outflow region, and they can effectively scatter and then heat particles[82-89]. How these factors influence the dissipation and electron acceleration is another frontier topic, which needs further investigation.

References

[1] BISKAMP D. Magnetic Reconnection in Plasmas[M]. Cambridge: Cambridge University Press, 2000.

[2] BIRN J, PRIEST E R. Reconnection of Magnetic Fields: Magnetohydrodynamics and Collisionless Theory and Observations[M]. Cambridge: Cambridge University Press, 2007.

[3] YAMADA M, KULSRUD R, JI H T. Magnetic reconnection[J]. Rev Mod Phys, 2010, 82: 603-664.

[4] WANG S, LU Q M. Collisionless Magnetic Reconnection[M]. Beijing: Science Press, 2019. (in Chinese)

[5] GIOVANELLI R G. A theory of chromospheric flares [J]. Nature, 1946, 158: 81-82.

[6] NISHIDA A. Geomagnetic Diagnostics of the Magnetosphere[M]. New York: Springer, 1978.

[7] TSUNETA S, HARA H, SHIMIZU T, et al. Observation of a solar flare at the limb with the Yohkoh Soft X-ray Telescope[J]. Publ Astron Soc Jpn, 1992, 44: L63-L69.

[8] ANGELOPOULOS V, MCFADDEN J P, LARSON D, et al. Tail reconnection triggering substorm onset [J]. Science, 2008, 321: 931-935.

[9] LIN R P, HUDSON H S. Nonthermal process in large solar flares[J]. Sol Phys, 1976, 50: 153-178.

[10] HOLMAN G D, SUI L H, SCHWARTZ R A, et al. Electron bremsstrahlung hard X-ray spectra, electron distributions, and energetics in the 2002 July 23 solar flare[J]. Astrophys J, 2003, 595(2): L97-L101.

[11] ØIEROSET M, LIN R P, PHAN T D, et al. Evidence for electron acceleration up to 300 keV in the magnetic reconnection diffusion region of Earth's magnetotail[J]. Phys Rev Lett, 2002, 89: 195001.

[12] WANG R S, LU Q M, LI X, et al. Observations of energetic electrons up to 200 keV associated with a secondary island near the center of an ion diffusion region: A Cluster case study[J]. J Geophys Res, 2010, 115: A11201.

[13] SWEET P A. The neutral point theory of solar flares [C]// Electromagnetic Phenomena in Cosmical Physics, Proceedings from IAU Symposium No. 6. Cambridge: Cambridge University Press, 1958: 123.

[14] PARKER E N. Sweet's mechanism for merging magnetic field in conducting fluids[J]. J Geophys Res, 1957, 62: 509-520.

[15] BIRN J, DRAKE J F, SHAY M A, et al. Geospace Environmental Modeling (GEM) magnetic reconnection challenge[J]. J Geophys Res, 2001, 106: 3715-3719.

[16] SHAY M A, DRAKE J F, ROGERS B N, et al. Alfvénic collisionless magnetic reconnection and the Hall term[J]. J Geophys Res, 2001, 106: 3759-3772.

[17] MA Z W, BHATTACHARJEE A. Hall magnetohydrodynamic reconnection: The Geospace Environment Modeling challenge[J]. J Geophys Res, 2001,106: 3773-3782.

[18] PRITCHETT P L. Geospace Environment Modeling magnetic reconnection challenge: Simulations with a full particle electromagnetic code[J]. J Geophys Res, 2001, 106: 3783-3798.

[19] SHAY M A, DRAKE J F, ROGERS B N, et al. The scaling of collisionless, magnetic reconnection for large systems[J]. Geophys Res Lett, 1999, 26: 2163-2166 .

[20] LIU Y H, HESSE M, GUO F, et al. Why does steady-state magnetic reconnection have a maximum local rate of order 0. 1? [J]. Phys Rev Lett, 2017, 118: 085101.

[21] HESSE M, SCHINDLER K, BIRN J, et al. The diffusion region in collisionless magnetic reconnection [J]. Physics of Plasmas, 1999, 6: 1781.

[22] ROGERS B N, DENTON R E, DRAKE J F. Signatures of collisionless magnetic reconnection[J]. J

特约评述

Geophys Res, 2003, 108(A3): 1111.
[23] LU Q M, HUANG C, XIE J L, et al. Features of separatrix regions in magnetic reconnection: Comparison of 2-D particle-in-cell simulations and Cluster observations [J]. J Geophys Res, 2010, 115: A11208.
[24] SANG L L, LU Q M, WANG R S, et al. Quadrupolar and hexapolar Hall magnetic field during asymmetric magnetic reconnection without a guide field [J]. Physics of Plasmas, 2018, 26: 062120.
[25] ØIEROSET M, PHAN T D, FUJIMOTO M, et al. In situ detection of collisionless reconnection in the Earth's magnetotail[J]. Nature, 2001, 412: 414-417.
[26] DENG X H, MATSUMOTO H. Rapid magnetic reconnection in the Earth's magnetosphere mediated by whistler waves[J]. Nature, 2001, 410: 557-560.
[27] NAGAI T, SHINOHARA I, FUJIMOTO M, et al. Geotail observations of the Hall current system: Evidence of magnetic reconnection in the magnetotail [J]. J Geophys Res, 2001,106: 25929-25949.
[28] VAIVADS A, KHOTYAINTSEV Y, ANDRÉ M, et al. Structure of the magnetic reconnection diffusion region from four-spacecraft observations[J]. Phys Rev Lett, 2004, 93: 105001.
[29] ZHANG H, ZONG Q Z, FRITZ T A, et al. Cluster observations of collisionless Hall reconnection at high-latitude magnetopause [J]. J Geophys Res, 2008, 113: A03204.
[30] WANG R S, LU Q M, HUANG C, et al. Multispacecraft observation of electron pitch angle distributions in magnetotail reconnection [J]. J Geophys Res, 2010, 115: A01209.
[31] DRAKE J F, SHAY M A, THONGTHAI W, et al. Production of energetic electrons during magnetic reconnection[J]. Phys Rev Lett, 2005, 94: 095001.
[32] PRITCHETT P L. Relativistic electron production during driven magnetic reconnection[J]. Geophys Res Lett, 2006, 33: L13104.
[33] PRITCHETT P L. Relativistic electron production during guide field magnetic reconnection[J]. J Geophys Res, 2006, 111: A10212.
[34] LU S, ANGELOPOULOS V, FU H. Suprathermal particle energization in dipolarization fronts: Particle-in-cell simulations[J]. J Geophys Res Space Physics, 2016, 121: 9483-9500.
[35] PRITCHETT P L. Kinetic properties of magnetic merging in the coasescence process [J]. Physics of Plasmas, 2007, 14: 052102.
[36] KARIMABADI H, DORELLI J, ROYTERSHEYN V, et al. Flux pileup in collisionless magnetic reconnection: Bursty interaction of large flux ropes[J]. Phys Rev Lett, 2011, 107: 025002.
[37] WANG X, HUANG C. The process of the coalescence of magnetic islands [J]. Chinese J Geophys, 2016, 59: 2356.
[38] LIU Y, LU Q M, WANG R S, et al. Electron acceleration and formation of power-law spectra of energetic electrons during the merging process of multiple magnetic islands: Particle-in-cell simulations [J]. Astrophys Space Sci, 2019, 364: 109.
[39] ESCOUBET C, FEHRINGER M, GOLDSTEIN M. The Cluster mission [J]. Ann Geophys, 2001, 19: 1197-1200.
[40] BURCH J L, MOORE T E, TORBERT R B, et al. Magnetospheric multiscale overview and science objectives [J]. Space Science Reviews, 2016, 199: 5-21.
[41] DRAKE J F, SWISDAK M, SCHOEFFLER K M, et al. Formation of secondary islands during magnetic reconnection [J]. Geophys Res Lett, 2006, 33: L13105.
[42] DAUGHTON W, SCUDDER J, KARIMABADI H. Fully kinetic simulations of undriven magnetic reconnection with open boundary conditions [J]. Physics of Plasmas, 2006, 13: 072101.
[43] KARIMABADI H, DAUGHTON W, SCUDDER J. Multi-scale structure of the electron diffusion region [J]. Geophys Res Lett, 2007, 34: L13104,
[44] HUANG C, LU Q M, WU M, et al. The evolution of electron current sheet and formation of secondary islands in guide field reconnection[J]. Nonlin Processes Geophys, 2011, 18: 727-733.
[45] CASSK P A, LIU Y H, SHAY M A. A review of the 0. 1 reconnection rate problem [J]. J Plasma Phys, 2017, 83: 715830501.
[46] FUJIMOTO K. Time evolution of the electron diffusion region and the reconnection rate in fully kinetic and large system [J]. Physics of Plasmas, 2006, 13: 072904.
[47] KLIMAS A, HESSE M, ZENITANI S. Particle-in-cell simulation of collisionless reconnection with open outflow boundaries [J]. Physics of Plasmas, 2008, 15: 082102.
[48] GUO F, LI X C, LI H, et al. Efficient production of high-energy nonthermal particles during magnetic reconnection in a magnetically dominated ion-electron plasma[J]. The Astrophysical Journal Letters, 2016, 818: L9.
[49] WANG R S, LU Q M, DU A M, et al. In situ observations of a secondary magnetic island in an ion

diffusion region and associated energetic electrons[J]. Phys Rev Lett, 2010,104: 175003.

[50] EASTWOOD J P, PHAN T D, MOZER F S, et al. Multi-point observations of the Hall electromagnetic field and secondary island formation during magnetic reconnection[J]. J Geophys Res, 2007, 112: A06235.

[51] TEH W L, NAKAMURA T, NAKAMURA R, et al. Oblique ion-scale magnetotail flux ropes generated by secondary tearing modes[J]. Journal of Geophysical Research: Space Physics, 2018, 123: 8122-8130.

[52] ZHONG Z H, TANG R X, ZHOU M, et al. Evidence for secondary flux rope generated by the electron Kelvin-Helmholtz instability in a magnetic reconnection diffusion region [J]. Phys Rev Lett, 2018, 120: 075101.

[53] STAWARZ J E, EASTWOOD J P, GENESTRETI K J, et al. Intense electric fieldsand electron-scale sub structure within magnetotail flux ropes as revealed by the Magnetospheric Multiscale mission [J]. Geophysical Research Letters, 2018, 45: 8783-8792.

[54] WANG R S, LU Q M, NAKAMURA R, et al. Coalescence of magnetic flux ropes in the ion diffusion region of magnetic reconnection[J]. Nature Physics, 2016, 12: 263-267.

[55] DAUGHTON W, ROYTERSHTEYN V, KARIMABADI H, et al. Role of electron physics in the development of turbulent magnetic reconnection in collisionless plasmas[J]. Nature Physics, 2011, 7: 539-542.

[56] LIU Y H, LI T C, HESSE M, et al. Three-dimensional magnetic reconnection with a spatially confined X-line extent: Implications for dipolarizing flux bundles and the dawn-dusk asymmetry [J]. Journal of Geophysical Research: Space Physics, 2019, 124: 2819-2830.

[57] HUANG K, LIU Y H, LU Q M, et al. Scaling of magnetic reconnection with a limited X-line [J]. Geophys Res Lett, 2020: e2020GL088147.

[58] FU X R, LU Q M, WANG S. The process of electron acceleration during collisionless magnetic reconnection [J]. Physics of Plasmas, 2006, 13: 012309.

[59] DRAKE J F, SWISDAK M, CHE H, et al. Electron acceleration from contracting magnetic islands during reconnection[J]. Nature, 2006, 443: 553-556.

[60] CHEN L J, BHATTACHARJEE A, PUHL-QUINN P A, et al. Observation of energetic electrons within magnetic islands[J]. Nature Physics, 2008, 4: 19-23.

[61] WANG R S, LU Q M, LI X, et al. Observations of energetic electrons up to 200 keV associated with a secondary island near the center of an ion diffusion region: A Cluster case study [J]. Journal of Geophysical Research, 2010, 115: A11201.

[62] LU S, ARTEMYEV A V, ANGELOPOULOS V, et al. Energetic electron acceleration by ion-scale magnetic islands in turbulent magnetic reconnection: Particle-in-cell simulations and ARTEMIS observations [J]. Astrophys J, 2020, 896: 105.

[63] FU H S, XU Y, VAIVADS A, et al. Super-efficient electron acceleration by an isolated magnetic reconnection[J]. Astrophys J Lett, 2019, 870: L22.

[64] OKA M, PHAN T D, KRUCHER S, et al. Electron acceleration by multi-island coalescence[J]. Astrophys J, 2010, 714: 915-926.

[65] TANAKA K G, YUMURA T, FUJIMOTO M, et al. Merging of magnetic islands as an efficient accelerator of electrons [J]. Physics of Plasmas, 2010, 17: 102902.

[66] TANAKA K G, FUJIMOTO M, BADMAN S V, et al. Dynamic magnetic island coalescence and associated electron acceleration[J]. Physics of Plasmas, 2011, 18: 022903.

[67] WANG H Y, LU Q M, HUANG C, et al. The mechanisms of electron acceleration during multiple X line magnetic reconnection with a guide field [J]. Astrophys J, 2016, 821(2): 84.

[68] ZHAO Y, WANG R S, LU Q M, et al. Coalescence of magnetic flux ropes observed in the tailward high-speed flows [J]. Journal of Geophysical Research: Space Physics, 2016, 121: 10898-10909.

[69] WANG R S, LU Q M, NAKAMURA R, et al. Interaction of magnetic flux ropes via magnetic reconnection observed at the magnetopause[J]. Journal of Geophysical Research: Space Physics, 2017, 122, 10436-10447.

[70] ZHOU M, BERCHEM J, WALKER R J, et al. Coalescence of macroscopic flux ropes at the subsolar magnetopause: Magnetospheric multiscale observations [J]. Physical Review Letters, 2017, 119(5): 55101.

[71] FU H S, KHOTYAINTSEV Y V, ANDR M, et al. Fermi and betatron acceleration of suprathermal electrons behind dipolarization fronts[J]. Geophysical Research Letters, 2011, 38: L16104.

[72] HUANG C, WU M Y, LU Q M, et al. Electron acceleration in the dipolarization front driven by magnetic reconnection [J]. Journal of Geophysical Research: Space Physics, 2015, 120: 1759-1765.

[73] ZHONG Z H, ZHOU M, TANG R X, et al. Direct evidence for electron acceleration within ion-scale flux rope [J]. Geophysical Research Letters, 2020, 47: e2019GL085141.

[74] DAHLIN J T, DRAKE J F, SWISDAK M. The mechanisms of electron heating and acceleration during magnetic reconnection[J]. Physics of Plasmas, 2014, 21: 092304.

[75] DAHLIN J T, DRAKE J F, SWISDAK M. Electron acceleration in three-dimensional magnetic reconnection with a guide field[J]. Physics of Plasmas, 2015, 22(10): 100704.

[76] DAHLIN J T, DRAKE J F, SWISDAK M. The role of three-dimensional transport in driving enhanced electron acceleration during magnetic reconnection[J]. Physics of Plasmas, 2017, 24(9): 092110.

[77] LI X C, GUO F, LI H, et al. Nonthermally dominated electron acceleration during magnetic reconnection in a low-β plasma[J]. Astrophys J, 2015, 811: L24.

[78] LU Q M, WANG H Y, HUANG K, et al. Formation of power law spectra of energetic electrons during multiple X line magnetic reconnection with a guide field[J]. Physics of Plasmas, 2018, 25: 072126.

[79] HUANG C, LU Q M, WANG R S, et al. Development of turbulent magnetic reconnection in a magnetic island[J]. Astrophys J, 2017, 835: 245.

[80] FU H S, VAIVADS A, KHOTYAINTSEV Y V, et al. Intermittent energy dissipation by turbulent reconnection[J]. Geophys Res Lett, 2017, 44: 37-43.

[81] WANG S M, WANG R S, LU Q M, et al. Direct evidence of secondary reconnection inside filamentary currents of magnetic flux ropes during magnetic reconnection[J]. Nature Communications, 2020, 11: Article number 3964.

[82] CATTELL C, DOMBECK J, WYGANT J, et al. Cluster observations of electron holes in association with magnetotail reconnection and comparison to simulations[J]. J Geophys Res, 2005, 110: A01211.

[83] WANG R S, LU Q M, KHOTYAINTSEV Y V, et al. Observation of double layer in the separatrix region during magnetic reconnection[J]. Geophys Res Lett, 2014, 41: 4851-4858.

[84] HUANG S Y, FU H S, YUAN Z G , et al. Two types of whistler waves in the Hall reconnection region [J]. J Geophys Res Space Physics, 2016, 121: 6639-6646.

[85] GRAHAM D B, VAIVADS A, KHOTYAINTSEV Y V, et al. Whistler emission in the separatrix regions of asymmetric magnetic reconnection[J]. J Geophys Res Space Physics, 2016, 121: 1934-1954.

[86] CAO D, FU H S, CAO J B, et al. MMS observations of whistler waves in electron diffusion region[J]. Geophys Res Lett, 2017, 44: 3954-3962.

[87] BURCH J L, DOKGO K, HWANG K J, et al. High-frequency wave generation in magnetotail reconnection: Linear dispersion analysis[J]. Geophys Res Lett, 2019, 46: 4089-4097.

[88] LI W Y, GRAMHAM D B, KHOTYAINTEV Y V, et al. Electron Bernstein waves driven by electron crescents near the electron diffusion region[J]. Nature Comm, 2020, 11: Article number 141.

[89] LI Z, LU Q M, WANG R S, et al. In situ evidence of resonant interactions between energetic electrons and whistler waves in magnetopause reconnection[J]. Earth and Planetary Physics, 2019, 3: 467-473.