Abstract

Cosmological hydrodynamic simulations have demonstrated that shock waves could be produced in the intergalactic medium by supersonic flow motions during the course of hierarchical clustering of the large-scale-structure in the Universe. Similar to interplanetary shocks and supernova remnants (SNRs), these structure formation shocks can accelerate cosmic ray (CR) protons and electrons via diffusive shock acceleration. External accretion shocks, which form in the outermost surfaces of nonlinear structures, are as strong as SNR shocks and could be potential accelerations sites for high energy CR protons up to \(10^{18}\) eV. But it could be difficult to detect their signatures due to extremely low kinetic energy flux associated with those accretion shocks. On the other hand, radiative features of internal shocks in the hot intracluster medium have been identified as temperature and density discontinuities in X-ray observations and diffuse radio emission from accelerated CR electrons. However, the non-detection of gamma-ray emission from galaxy clusters due to \(\pi^0\) decay still remains to be an outstanding problem.

Keywords: acceleration of particles, cosmic rays, shock waves

1. Introduction

In [1] shocks in the intracluster medium (ICM) appeared as candidate acceleration sites for ultra-high-energy cosmic rays (CRs) in the so-called ‘Hillas diagram’, in which the maximum energy of CR nuclei achievable by a cosmic accelerator was estimated from the confinement condition:

\[
E_{\text{max}}(\text{GeV}) \sim z \cdot \beta_a \cdot B_{\mu G} \cdot L_{\text{Mpc}},
\]

where \(E_{\text{max}}\) is given in units of \(10^{21}\) eV, \(z\) is the charge of CR nuclei, and \(\beta_a = v_a/c\), \(B_{\mu G}\), and \(L_{\text{Mpc}}\) are the characteristic speed, the magnetic field strength in units of microgauss, and the size in units of Mpc of the accelerator, respectively. For shocks associated with galaxy clusters with \(\beta_a \sim 0.01\), \(B_{\mu G} \sim 1\), \(L_{\text{Mpc}} \sim 1\), CR protons could be accelerated up to \(\sim 10^{19}\) eV.

[2] first suggested that cosmic shocks induced by the structure formation can accelerate CR protons up to \(10^{19.5}\) eV via diffusive shock acceleration (DSA). Independently and more or less simultaneously, [3] showed, using cosmological hydrodynamic simulations, that accretion shocks around galaxy clusters have \(v_s \sim 3 \times 10^3\) km s\(^{-1}\), and suggested that, for the Bohm diffusion with microgauss magnetic fields, the maximum energy of protons achieved via DSA by cluster accretion shocks is limited to \(\sim 60\) EeV \(\left(\tau_{\text{acc}} = \tau_{\text{pion}}\right)\), due to the energy loss via photo-pion interactions with the cosmic background radiation (see Figure 1). Adopting simple models for magnetic field strength and DSA, and an analytic relation between the cluster temperature and the spherical accretion shock, [4] showed that the CR protons from a cosmological ensemble of cluster accretion shocks could make a significant contribution to the observed CR flux near \(10^{19}\) eV.

Observational evidence for the electron acceleration by a cluster accretion shock was first suggested by [5] who proposed that diffuse radio relics detected in the outskirts of several clusters could be diffuse synchrotron emission from fossil electrons re-energized by...
accretion shocks. Since the discovery of a shock in the Bullet cluster (1E 0657-56) [6], about a dozen of shocks have been detected as sharp discontinuities in X-ray temperature or surface brightness in mainly merging clusters [7, 8]. Moreover, giant radio relics such as the Sausage relic in CIZA J2242.8+5301 and the Toothbrush relic in 1RXS J0603.3+4214 are thought to result from merger-driven shocks, since most of observed properties can be explained by synchrotron emission from shock-accelerated electrons cooling behind the shock [9, 10]. So the presence of cosmic shocks in the ICM within a few Mpc from the cluster center has been established, although shocks in lower density filaments await to be detected by future observational facilities [11, 12].

In this contribution, we review the properties of structure formation shocks, the physical processes involved in the acceleration of CR ions and electrons at collisionless shocks, and observational signatures of shocks and nonthermal particles in the ICM.

2. Properties of Structure Formation Shocks

The properties and energetics of cosmological shocks have been studied extensively, using numerical simulations for the large-scale-structure (LSS) formation [e.g., 13, 14, 15, 16, 17, 18]. The average spatial frequency between shock surfaces is \( \sim 1 \text{ Mpc}^{-1} \) inside nonlinear structures of clusters, filaments, and sheets. These shocks can be classified mainly into two categories: (1) external accretion shocks with the Mach number, \( 3 \lesssim M_s \lesssim 100 \), that form around the outermost surfaces of nonlinear structures, and (2) internal shocks mostly with \( M_s \lesssim 5 \) that form in the hot ICM inside nonlinear structures [14]. In Figure 2, external accretion shocks encompassing the cluster coincide with the region with sharp temperature discontinuities, indicating high Mach number shocks. On the other hand, weak internal shocks within a few Mpc from the cluster center are associated with mild temperature variations. The presence of internal shocks has been confirmed in many merging clusters, while radiative signature of external accretion shocks have not been detected so far due to very low surface brightness.

Weak internal shocks with \( 2 \lesssim M_s \lesssim 3 \) have high kinetic energy flux and are responsible for most of the shock energy dissipation into heat and nonthermal components of the ICM such as CRs, magnetic fields, and turbulence. By adopting a DSA model of CR proton acceleration, [14] predicted that the ratio of the CR proton to gas thermal energies dissipated at all cosmological shocks through the history of the Universe could be substantial, perhaps up to 50%. However, this estimate has to be revised to significantly lower values as we will...
discuss in Section 5.

3. Turbulence and Magnetic Fields in Large-Scale Structure

Magnetic field is one of the key elements that govern the plasma processes at collisionless shocks and radiative signatures of accelerated particles. The intergalactic space is observed to be permeated with magnetic fields and filled with turbulence and CRs, similar to the interstellar medium within our Galaxy [15] [19] [20] [11] [12]. Analysis of the rotation measure data for Abell clusters indicates that the mean magnetic field strength ranges up to several $\mu$G in the ICM [21, 22].

Using hydrodynamic and magneto-hydrodynamic (MHD) simulations for the structure formation, it has been suggested that turbulence could be produced in the ICM by cascade of the vorticity generated behind cosmological shocks or by merger-driven flow motions, and that the intergalactic magnetic fields could be amplified via turbulence dynamo [10] [23] [24] [25]. The seed fields might have been injected into the ICM via galactic winds and AGN jets or originate from some primordial processes [20] [11] [12]. This turbulence dynamo scenario typically predicts that the energy budget among different components in the ICM could be $E_{\text{el}} \sim 0.1 E_{\text{th}}$ and $E_B \sim 0.01 E_{\text{th}}$, where $E_{\text{th}}$ is the thermal energy density [19]. As shown in Figure 3, the volume-averaged magnetic field strength ranges 0.1 – 1 $\mu$G in the ICM ($T > 10^7$ K) and 0.01 – 0.1 $\mu$G in filaments ($10^5 < T < 10^7$ K), which seems to be consistent with observations [22] [21]. In the peripheral regions ~ 5 Mpc away from the cluster center where external accretions are expected to form, the magnetic field strength should be similar to that of filaments, i.e., ~ 0.01 – 0.1 $\mu$G. The magnetic fields should be much weaker in sheet-like structures and voids, but neither theoretical nor observational estimates are well defined in such low density regions.

Relativistic protons and electrons with the same rigidity ($R = p c / e \gamma$) are accelerated in the same way in DSA regime. But for the particle injection to the DSA process, the obliquity angle, $\Theta_{\text{Bn}}$, becomes an important factor. At quasi-parallel shocks ($\Theta_{\text{Bn}} \lesssim 45^\circ$), where the magnetic field direction is roughly parallel to the flow velocity, MHD waves are self-generated due to streaming of CR protons upstream of the shock, and protons are injected/accelerated efficiently to high energies via DSA [26] [27] [28]. At quasi-perpendicular shocks ($\Theta_{\text{Bn}} > 45^\circ$), the modified two stream instability could generate oblique whistler waves, which results in the pre-heating of thermal electrons to a $kT > 4.3$ keV.

Fermi I acceleration process, if they are scattered by plasma waves excited in the preshock region [29]. In addition to $\Theta_{\text{Bn}}$, excitation of MHD/kinetic waves by plasma instabilities and wave-particle interactions at collisionless shocks depend on the shock parameters such as the plasma beta, $\beta_p = P_{\text{gas}} / P_B$, and the Alfvén Mach number, $M_A \approx \sqrt{B_0 / \rho_c}$. For the internal ICM shocks, $\beta_p \sim 50$, $M_A \lesssim 3$, and $M_A \lesssim 20$. So they are super-critical, i.e., $M_A > M_{\text{crit}}$, where the critical Mach Number is $M_{\text{crit}} \sim 1 – 1.5$ for high beta plasma, and some ions are reflected specularly at the shock ramp, independent of the obliquity angle [30]. In the preshock region, some of incoming ions and electrons are reflected upstream, and the drift between incoming and reflected particles may excite plasma waves via various micro-instabilities, depending on the shock parameters. For low beta plasma ($\beta_p \lesssim 1$), at high $M_A$ quasi-perpendicular shocks ($M_A \gtrsim \sqrt{\beta_p m_p / m_e}$) the Buneman instability is known to excite electrostatic waves, leading to the shock-surfing-acceleration of electrons in the shock foot [31]. For low $M_A$ quasi-perpendicular shocks ($M_A \lesssim \sqrt{m_p / m_e}$), on the other hand, the modified two stream instability could generate oblique whistler waves, which result in the pre-heating of thermal electrons to a $kT > 4.3$ keV.

4. Electron Acceleration at Cosmological Shocks

Plasma kinetic processes govern the preacceleration of electrons in the shock transition zone, which leads to the injection of CR electrons to the Fermi I process. Figure 4 shows thermal and suprathermal distributions of electrons and protons for the gas with $kT \approx 4.3$ keV.
The particle momentum should be greater than a few times the postshock thermal proton momentum \( (p_{\text{th},p}^0) \) to cross the shock transition. So thermal electrons with \( p_{\text{th},e} = p_{\text{th},p} \sqrt{m_e/m_p} \) need to be pre-accelerated to the injection momentum, \( p_{\text{inj}} \sim 3.5 p_{\text{th},p} \), before they can start participating to the full DSA process \([33]\). Such injection from the thermal Maxwellian pool is expected to be very inefficient, especially at low Mach number shocks, and depend very sensitively on the shock Mach number. But if there are suprathermal electrons with the \( \kappa \)-like power-law tail, instead of the Maxwellian distribution, the injection and acceleration of electrons can be enhanced greatly even at weak cluster shocks \([33]\). As illustrated in Figure 4, the particle injection flux at \( p_{\text{inj}} \) is larger for a \( \kappa \)-distribution with a smaller value of \( \kappa \). So the development of a \( \kappa \)-like suprathermal distribution is critical in the electron acceleration via DSA.

In the case of low \( M_X \) quasi-perpendicular shocks in the high beta ICM plasma, some incoming electrons are mirror reflected at the shock ramp and gain energy via multiple cycles of SDA, while protons can go through a few SDA cycles with only minimal energy gains \([29]\). In the foreshock of such weak shocks, the electron firehose instability induces oblique magnetic waves, which in turn provide efficient scattering necessary to energize the thermal electrons to suprathermal energies, leading to efficient injection to the DSA process. This picture is consistent with the observational fact that the magnetic field obliquity is typically quasi-perpendicular at giant radio relics such as the Sausage relic \([9]\), and the double relic in the cluster PSZ1 G108.18 \([35]\).

Radio relics are diffuse radio structures detected in the outskirts of merging galaxy clusters. Their observed properties can be best understood by synchrotron emission from relativistic electrons accelerated at merger-driven shocks: elongated morphologies over \( \sim 2 \) Mpc, spectral aging across the relic width (behind the putative shock), integrated radio spectra of a power-law form with gradual steepening above \( \sim 2 \) GHz, and high polarization levels \([10, 11, 35]\).

The sonic Mach number of a relic shock can be estimated from either radio or X-ray observations, using the radio spectral index relation, \( \alpha_{\text{th}} = (M_{\text{rad}}^2 + 3)/2(M_{\text{rad}}^2 - 1) \), or the X-ray temperature jump condition, \( T_2/T_1 = \left( M_X^2 + 3 \right)(5M_X^2 - 1)/16M_X^2 \), respectively. In some radio relics, the two estimates are different, i.e., \( M_X < M_{\text{rad}} \), indicating that the simple DSA origin of radio relics might not explain the observed properties \([37]\). For example, \( M_X \approx 1.2 - 1.5 \) and \( M_{\text{rad}} \approx 3.0 \) for the Toothbrush relic \([38]\), while \( M_X \approx 2.7 \) and \( M_{\text{rad}} \approx 4.6 \) for the Sausage relic \([9, 39]\). Such discrepancy could be explained by the two following scenarios based on DSA: (1) injection-dominated model in which \( M_X \approx M_{\text{rad}} \) and \( M_X \) is under-estimated due to projection effects, and (2) reacceleration-dominated model in which preexisting electrons with a flat energy spectrum is reaccelerated by a weak shock with \( M_X \approx M_{\text{rad}} \)\([41, 42]\). Figure 5 illustrates that such two viable scenarios, albeit with different sets of model parameters, could reproduce the observed surface brightness and spectral index profiles of the Toothbrush relic \([38]\).

Using structure formation simulations, \([40]\) carried out mock observations of radio relic shocks detected in simulated clusters and showed that X-ray observations are inclined to detect weaker shocks due to projection effects, while radio observations tend to observe stronger shocks with flatter radio spectra. This naturally supports the injection-dominated model, in which \( M_X \) tends to be smaller than \( M_{\text{rad}} \) for a given radio relic.

The ICM is thought to contain fossil relativistic electrons left over from tails and lobes of extinct AGNs. Mildly relativistic electrons with \( \gamma_e \lesssim 10^2 \) survive for long periods of time, since the cooling time scale of electrons in \( B \sim 1 \) \( \mu \)G is \( t_{\text{rad}} \approx 10^{10} \) yr \( \cdot \) \( 10^2 / \gamma_e \). They could provide seed electrons to the DSA process, which alleviates the low injection/acceleration efficiency problem at weak cluster shocks in the case of the injection-dominated model. If we conjecture that radio relics form when the ICM shocks encounter fossil mildly relativistic electrons with \( \gamma_e \lesssim 10^2 \), then the model may explain why only about 10% of merging clusters contain radio relics \([42]\).

The so-called infall shocks form in the cluster outskirts when the WHIM from adjacent filaments pene-

Figure 4: Momentum distribution, \( p^2 f(p) \), of electrons and protons for the gas with \( kT = 4.3 \) keV in the case of the \( \kappa \)-distributions with \( \kappa = 2, 3, 5, \) and 10. The Maxwellian distributions are shown in black solid lines. The vertical lines indicate the range of the injection momentum of \( p_{\text{inj}} = (3.5 - 4) p_{\text{th},p} \) above which particles can be injected into the DSA process \([33]\).
energy is transferred to CR proton energy for shocks dominated model with a $M_A$ shock kinetic energy flux, and the volume-averaged ratio of the CR to thermal pressure in the ICM, $\langle \rho_{\text{CR}} \rangle / \langle \rho_{\text{th}} \rangle$ \cite{15}. Adopting the DSA efficiency model in which $\eta \sim 0.1$ for $M_s \geq 3$ given in \cite{51}, for example, \cite{48} estimated that $\langle \rho_{\text{CR}} \rangle = 0.02$ for Coma-like clusters. In \cite{50}, in which a thermal-leakage injection model was implemented to DSA simulations, the efficiency is estimated to be $\eta \approx 0.01$ for $M_s = 3 - 5$ shocks. Note that in this DSA model the efficiency depends sensitively on the assumed injection model as well as $M_s$.

The key parameters in predicting the $\nu^0$ decay $\gamma$-ray emission are the CR proton acceleration efficiency, $\eta(M_s)$, defined as the ratio of the CR energy flux to the shock kinetic energy flux, and the volume-averaged ratio of the CR to thermal pressure in the ICM, $\langle \rho_{\text{CR}} \rangle / \langle \rho_{\text{th}} \rangle$ \cite{15}. Adopting the DSA efficiency model in which $\eta \sim 0.1$ for $M_s \geq 3$ given in \cite{51}, for example, \cite{48} estimated that $\langle \rho_{\text{CR}} \rangle = 0.02$ for Coma-like clusters. In \cite{50}, in which a thermal-leakage injection model was implemented to DSA simulations, the efficiency is estimated to be $\eta \approx 0.01$ for $M_s = 3 - 5$ shocks. Note that in this DSA model the efficiency depends sensitively on the assumed injection model as well as $M_s$.

Recently, \cite{45} tested several different prescriptions for the DSA efficiency by comparing the $\gamma$-ray flux from simulated clusters with the Fermi-LAT upper-limit flux levels of observed clusters. Even with the relatively less efficient model based on the hybrid simulation results of \cite{22}, in which $\eta \approx 0.05$ for $M_s = 5$ quasi-parallel shocks, and the consideration of the random magnetic field directions, they find that about 10-20% of simu-
lated clusters have the predicted $\gamma$-ray flux levels above the Fermi-LAT upper limits. So the authors suggested that only if $\eta \leq 10^{-3}$ for all Mach number shocks, which results in the average value of $\langle X_{\text{CR}} \rangle \lesssim 0.01$ in the ICM, the predicted $\gamma$-ray fluxes from simulated clusters can stay below the Fermi-LAT upper limits. This agrees with the conclusion of [52], which predicted $\langle X_{\text{CR}} \rangle \lesssim 0.0125 \pm 0.014$ based on the analysis of four year Fermi-LAT data.

Non-detection of $\gamma$-ray emission from galaxy clusters might be explained, if the CR proton acceleration is much less efficient than expected in the current DSA theory (i.e. $\eta \lesssim 10^{-3}$ for $M_{s} \sim 3$). In that regard, the proton acceleration at weak shocks in the low density, high beta ICM plasma needs to be investigated further, since so far most of hybrid/PIC plasma simulations have focused on strong shocks in $\beta_{p} \lesssim 1$ ISM and solar wind plasma.

Finally, armed with our new understandings based on the recent plasma hybrid simulations [27][28], it is worth examining if strong accretions shock can accelerate CR protons to ultra-high energies. The protons are expected to be accelerated efficiently via DSA only in the quasi-parallel portion of the outermost surfaces encompassed with accretion shocks. There magnetic fields could be amplified via Bell’s non-resonant hybrid instability by a factor of $B(B_{0}) \propto \sqrt{M_{A}}$ [28], where $B_{0} \sim 0.1 \mu$G and $M_{A} \sim 300$. So it is reasonable to assume the magnetic field strength at external accretion shocks is $B \sim 0.1 \mu$G, about one order of magnitude smaller than that typically adopted in the previous studies [e.g., 2][3]. Considering the photo-pair energy losses, protons can be accelerated up to $E_{p,\text{max}} \sim 10^{18}$ eV at quasi-parallel accretion shocks (see Figure 1).

### 6. Summary

1. Astrophysical plasmas consist of both thermal and CR particles that are closely coupled with permeating magnetic fields and underlying turbulent flows. So understanding the complex network of physical interactions among these components, especially in the high beta collisionless ICM plasma, is crucial to the study of the particle acceleration at structure formation shocks (see Figure 6).

2. Gravitational energy associated with hierarchical clustering of the large-scale-structures must be dissipated at structure formation shocks into several different forms: heat, CRs, turbulence and magnetic fields [14].

3. The vorticity generated by curved shocks decays into turbulence behind the shock, which in turn cascades into MHD/plasma waves in a wide range of scales and amplify magnetic field via turbulence dynamo [19].

4. There is growing observational evidence indicating the presence of weak shocks, relativistic electrons,
References

[1] A. M. Hillas, The Origin of Ultra-High-Energy Cosmic Rays, ARA&A22 (1984) 425–444. doi:10.1146/annurev.aa.22.080184.002333

[2] C. A. Norman, D. B. Melrose, A. Achterberg, The Origin of Cosmic Rays above 10 18.5 eV, ApJ454 (1995) 60. doi:10.1086/176666

[3] H. Kang, D. Ryu, T. W. Jones, Cluster Accretion Shocks as Possible Acceleration Sites for Ultra-High-Energy Protons below the Greisen Cutoff, ApJ456 (1996) 422. arXiv:astro-ph/9507113 doi:10.1086/176666

[4] H. Kang, J. P. Rachen, P. L. Biermann, Contributions to the Cosmic Ray Flux above the Ankle: Clusters of Galaxies, MNRS286 (1997) 257–267. arXiv:astro-ph/9608071 doi:10.1093/mnras/286.2.257

[5] T. A. Ensslin, P. L. Biermann, U. Klein, S. Kohle, Cluster radio relics as a tracer of shock waves of the large-scale structure formation, A&A332 (1998) 395–409. arXiv:astro-ph/9712293

[6] M. Markovitch, A. H. Gonzalez, L. David, A. Vikhlinin, S. Murray, W. Forman, C. Jones, W. Tucker, A Textbook Example of a Bow Shock in the Merging Galaxy Cluster 1E 0657-56, ApJ567 (2002) L27–L31. arXiv:astro-ph/0106468 doi:10.1086/339619

[7] M. Markovitch, A. Vikhlinin, Shocked and cold fronts in galaxy clusters, Phys. Rev.443 (2007) 1–53. doi:10.1103/physreps.2007.01.001

[8] H. R. Russell, J. S. Sanders, A. C. Fabian, S. A. Baum, M. Donahue, A. C. Edge, B. R. McNamara, C. P. O’Dea, Chandra observation of two shock fronts in the merging galaxy cluster Abell 2146, MNRS406 (2010) 1721–1733. arXiv:1004.1659 doi:10.1111/j.1365-2966.2010.16822.x

[9] R. J. van Weeren, H. J. A. Röttgering, M. Brüggen, M. Hoeft, Particle Acceleration on Megaparsec Scales in a Merging Galaxy Cluster, Science 330 (2010) 347–. doi:10.1126/science.1194293

[10] R. J. van Weeren, H. J. A. Röttgering, H. T. Interna, L. Rudnick, M. Brüggen, M. Hoeft, J. B. R. Oonk, The "toothbrush-relic": evidence for a coherent linear 2-Mpc scale shock wave in a massive merging galaxy cluster?, A&A546 (2012) A124. arXiv:1209.2196 doi:10.1051/0004-6361/201219000

[11] M. Brüggen, A. Bykov, D. Ryu, H. Röttgering, Magnetic Fields, Relativistic Particles, and Shock Waves in Cluster Outskirts, Space Sci. Rev.166 (2012) 187–213. arXiv:1107.5223 doi:10.1007/s11214-011-9785-9

[12] G. Brunetti, T. W. Jones, Cosmic Rays in Galaxy Clusters and Their Nonthermal Emission, International Journal of Modern Physics D23 (2014) 1430007–98. doi:10.1142/S0218271814300079

[13] F. Miniati, D. Ryu, H. Kang, T. W. Jones, R. Cen, J. P. Ostriker, Properties of Cosmic Shock Waves in Large-Scale Structure Formation, ApJ542 (2000) 608–621. arXiv:astro-ph/0008444 doi:10.1086/371027

[14] D. Ryu, H. Kang, E. Hallman, T. W. Jones, Cosmological Shock Waves and Their Role in the Large-Scale Structure of the Universe, ApJ593 (2008) 599–610. arXiv:astro-ph/0805164 doi:10.1086/376723

[15] H. Kang, D. Ryu, C. P. Ostriker, Cosmological Shock Waves in the Large-Scale Structure of the Universe: Nongravitational Effects, ApJ669 (2007) 729–740. doi:10.1086/521717

[16] S. W. Skillman, B. W. O’Shea, E. J. Hallman, J. O. Burns, M. L. Norman, Cosmological Shocks in Adaptive Mesh Refinement Simulations and the Acceleration of Cosmic Rays, ApJ689 (2008) 1063–1077. arXiv:0806.1522 doi:10.1086/592496

[17] M. Hoeft, M. Brüggen, G. Yepes, S. Gottlöber, A. Schwope, Diffuse radio emission from clusters in the MareNostrum universe simulation, MNRA391 (2008) 1511–1526. arXiv:0807.1266 doi:10.1111/j.1365-2966.2008.1355.x

[18] F. Vazza, G. Brunetti, C. Gheller, Shock waves in Eulerian cosmological simulations: main properties and acceleration of cosmic rays, MNRS395 (2009) 1333–1354. arXiv:0808.0609 doi:10.1111/j.1365-2966.2009.14691.x

[19] D. Ryu, H. Kang, J. Cho, S. Das, Turbulence and Magnetic Fields in the Large-Scale Structure of the Universe, Science 320 (2008) 909–. doi:10.1126/science.1159923

[20] K. Dolag, A. M. Bykov, A.Diaferio, Non-Thermal Processes in Cosmological Simulations, Space Sci. Rev.134 (2008) 311–335.

microgauss level magnetic fields, and turbulence in the
ICM of galaxy clusters [12].

5. CR protons are expected to be accelerated mainly at quasi-parallel shocks. For weak internal shocks ($M_s \lesssim 3$) with high kinetic energy fluxes that form in the ICM, the CR proton acceleration efficiency is likely to be $\eta < 0.01$ in order to explain the non-detection of $\gamma$-ray emission from galaxy clusters due to inelastic $p-p$ collisions in the ICM [45].

6. At quasi-parallel portion of strong external accretion shocks, CR protons could be accelerated to ~ $10^{18}$ eV, if the preshock magnetic fields can be amplified to ~ 0.1$\mu$G via CR streaming instabilities [13,47].

7. CR electrons are expected to be accelerated preferentially at quasi-perpendicular shocks. [29]. Radio relics detected in the outskirts of merging clusters seem to reveal radiative signatures of relativistic electrons accelerated at merger-driven shocks mostly with $M_s \sim 2 - 3$ [41].

8. The injection of protons and electrons from thermal or suprathermal populations to the DSA process at collisionless shocks involves plasma kinetic processes such as excitation of waves by microinstabilities as well as shock surficing and shock surcencing acceleration [33]. During the last decade significant progress been made in that front through PIC/hybrid plasma simulations of non-relativistic shocks [27,29].

7. Acknowledgements

This work was supported by the National Research Foundation of Korea through grants NRF-2014R1A1A2057940 and NRF-2016R1A5A1013277. The author would like to thank D. Ryu for helpful comments on the paper.

References
