Properties of Merger Shocks in Merging Galaxy Clusters

Ji-Hoon Ha1, Dongsu Ryu1, and Hyesung Kang2

1 Department of Physics, School of Natural Sciences UNIST, Ulsan 44919, Republic of Korea; rya@sirius.unist.ac.kr
2 Department of Earth Sciences, Pusan National University, Busan 46241, Republic of Korea

Abstract

X-ray shocks and radio relics detected in the cluster outskirts are commonly interpreted as shocks induced by mergers of subclumps. We study the properties of merger shocks in merging galaxy clusters, using a set of cosmological simulations for the large-scale structure formation of the universe. As a representative case, we focus on the simulated clusters that undergo almost head-on collisions with mass ratio ~2. Due to the turbulent nature of the intracluster medium, shock surfaces are not smooth, but composed of shocks with different Mach numbers. As the merger shocks expand outward from the core to the outskirts, the average Mach number, ⟨M⟩, increases in time. We suggest that the shocks propagating along the merger axis could be manifested as X-ray shocks and/or radio relics. The kinetic energy through the shocks, $F_{\text{sh}}$, peaks at ~1 Gyr after their initial launching, or at ~1–2 Mpc from the core. Because of the Mach number dependent model adopted here for the cosmic-ray (CR) acceleration efficiency, their CR-energy-weighted Mach number is higher with $⟨M⟩_{\text{CR}} ~ 3–4$, compared to the kinetic-energy-weighted Mach number, $⟨M⟩_{\text{KE}} ~ 2–3$. Most energetic shocks are to be found ahead of the lighter dark matter (DM) clump, while the heavier DM clump is located on the opposite side of clusters. Although our study is limited to the merger case considered, the results such as the means and variations of shock properties and their time evolution could be compared with the observed characteristics of merger shocks, constraining interpretations of relevant observations.

Key words: acceleration of particles – galaxies: clusters: general – methods: numerical – shock waves

1. Introduction

The current ΛCDM cosmology favors the hierarchical structure formation, where small clumps first formed and continuously merged to become galaxy clusters. Shock waves are naturally induced in the intracluster medium (ICM) during the hierarchical structure formation. Since the gas in clusters is in the form of hot tenuous plasma, these shocks are collisionless as in other astrophysical environments. They heat the gas and, at the same time, accelerate cosmic rays (CRs) via diffusive shock acceleration (DSA; see, e.g., Bell 1978; Blandford & Ostriker 1978; Drury 1983). Using cosmological hydrodynamic simulations for the large-scale structure (LSS) formation of the universe, the properties and roles of shocks in the ICM as well as around clusters have been extensively studied (Miniati et al. 2000; Ryu et al. 2003; Pfommer et al. 2006; Kang et al. 2007; Hoeft et al. 2008; Skillman et al. 2008; Vazza et al. 2009; Schaal & Volker 2015).

Such studies have shown that external accretion shocks form around clusters, when the void gas of $T \sim 10^4$ K accretes onto them. With the accretion velocity of $\sim 10^3$ km s$^{-1}$ and the sound speed of $c_s \sim 10$ km s$^{-1}$, their Mach number is very high, of the order of $M_s \sim 100$. However, due to the low density, the kinetic energy flux through the shock surface, $F_{\text{sh}} = (1/2) \rho_1 v_1^2$, is small (where $\rho_1$ is the preshock gas density and $v_1$ is the shock speed), and hence external shocks are not energetically important. Inside clusters, internal shocks are induced by mergers of clumps and infall of the warm–hot intergalactic medium (WHIM) along filaments, as well as turbulent flow motions (see, e.g., Ryu et al. 2003). They form in the hot ICM that was heated by previous shock passages, and hence have lower Mach numbers. However, due to the higher gas density, internal shocks have larger $f_{\text{sh}}$, and thus play more important roles in heating ICMs and producing CRs, compared to external shocks.

Among internal shocks, turbulent shocks, produced by turbulent flow motions, are mostly weak with at most $M_s \lesssim 2$ (Porter et al. 2015), since ICM flow motions are subsonic with turbulent Mach number $M_t \sim 0.5$ (see, e.g., Ryu et al. 2008; Vazza et al. 2011a, 2017; Brunetti & Jones 2014; Miniati 2014). Infall shocks are formed by continuous infall of the WHIM of $T \sim 10^6$–$10^9$ K, often with streams of minor mergers, into the hot ICM of $T \sim 10^7$–$10^8$ K (see, e.g., Brown & Rudnick 2011; Pfommer & Jones 2011; Ogrean & Brüggen 2013a, for observations of infall shocks). They can have higher Mach numbers of up to $M_s \sim 10$ (Hong et al. 2014). With relatively high Mach numbers, infall shocks could be sites for efficient CR acceleration. However, they form mostly in the cluster outskirts, since the gas accretion from filaments normally halts around the virial radius and does not penetrate into the core. Moreover, they have small cross sections.

The shocks induced as a consequence of “major mergers” are called merger shocks. A merger of $M \sim 10^{13}M_\odot$ clumps with speed $\sim 10^3$ km s$^{-1}$ involves the kinetic energy of $E_{\text{merg}} \sim 10^{62}$ erg, and a substantial fraction of it is dissipated at merger shocks in the timescale of $\sim 1$–$2$ Gyr (see, e.g., Markovich & Vikhlinin 2007). Such merger shocks should be energetic enough to result in observable phenomena; thus, most shocks observed in X-ray and/or radio, usually in the outskirts of merging clusters, are interpreted as merger shocks.

The best known example of merger shock from X-ray observation is the one in the so-called Bullet Cluster (1E 0657-56; Markevitch et al. 2002). So far, dozens of shocks have been observed with Chandra, XMM-Newton, and Suzaku (see, e.g., Markovich et al. 2005; Ogrean et al. 2014; Itahana et al. 2015; Dasadia et al. 2016). They are found
typically at distance $d_s \gtrsim 1 \text{ Mpc}$ from the cluster center, and mostly weak with $M_s \sim 1.5$–3.

“Radio relics” are known to be the radio manifestation of ICM shocks. Their emission is interpreted as synchrotron radiation from CR electrons accelerated at shocks associated with them. Well studied radio relics include the so-called Sausage relic in the cluster CIZA J2242.8+5301 (e.g., van Weeren et al. 2010; Stroe et al. 2013), double relics in ZwCl 0008.8+5215 (e.g., van Waerebeek et al. 2011b) and PLCK G287.0+32.9 (e.g., Bagchi et al. 2011; Bobonoff et al. 2014), and the so-called Toothbrush relic in RX J0603.3+4214 (e.g., van Weeren et al. 2012; van Waerebeek et al. 2016). In addition, about 100 radio relics have been observed so far (see, e.g., Feretti et al. 2012; Brüggen et al. 2012a; Brunetti & Jones 2014, for reviews). They are also found at $d_s \gtrsim 1 \text{ Mpc}$, but the associated shocks are, on average, stronger than X-ray shocks, with $M_s$ as high as $\sim 4.5$.

A notable point is that the shock parameters inferred from X-ray and radio observations for the same object do not always agree with each other. In the case of the Sausage relic, for instance, the Mach number estimated with the radio spectral index near the edge (shock surface) is $M_{\text{radio}} \approx 4.6$ (van Weeren et al. 2010), while the value estimated with the discontinuity in X-ray observations is smaller with $M_X \approx 2.5$–3.1 (Ogurean et al. 2014; Akamatsu et al. 2015). In the case of the Toothbrush relic, the radio spectral index indicates $M_{\text{radio}} \approx 2.8$ (van Waerebeek et al. 2016), but X-ray observations reveal $M_X \lesssim 2$ (Itoh et al. 2015; van Waerebeek et al. 2016).

It was argued that the discrepancy between $M_X$ and $M_{\text{radio}}$ could be resolved by the reacceleration model in which a shock with $\sim M_X$ sweeps through and reaccelerates pre-existing “fossil CR electrons” of a flat energy spectrum consistent with the observed radio spectrum (e.g., Kang & Ryu 2015). However, Kang et al. (2017) recently suggested that, considering short cooling timescales of GeV electrons, it might be unrealistic to generate and/or maintain such flat-spectrum fossil CR electrons, so a shock with $\sim M_{\text{radio}}$ is required to reproduce the aforementioned radio observations. On the other hand, from mock X-ray and radio observations of relic shocks in clusters from LSS formation simulations, Hong et al. (2015) showed that the surfaces of ICM shocks are inhomogeneous with different $M_s$’s at different parts, and X-ray observations pick up the parts with higher shock energy flux but lower $M_s$, while radio emissions come preferentially from the parts with higher $M_s$ and so higher electron acceleration. As a result, $M_s$ inferred from X-ray discontinuities tends to be lower than that from radio spectral indices, explaining the discrepancy of $M_s$ in X-ray and radio observations.

The reacceleration scenario was partly motivated by the scarcity of radio relics. It is expected that most merger shocks would appear as radio relics, yet the fraction of X-ray luminous merging clusters with observed radio relics is on the order of $\sim 10\%$ (see, e.g., Feretti et al. 2012). In addition, some X-ray shocks do not exhibit radio relics (see, e.g., Russell et al. 2011). In the reacceleration scenario, merger shocks light up as radio relics only when they encounter clouds of fossil electrons left over, for instance, from either radio jets or previous episodes of shock/turbulence accelerations (see, e.g., Bonafede et al. 2014; Shimwell et al. 2015; van Waerebeek et al. 2017, for observations interpreted to reveal the reacceleration scenario).

Weak lensing observations have enabled the reconstruction of mass distribution in clusters. The technique has been applied to several merging clusters, imposing constraints on the interpretation and modeling of observed shocks. A weak lensing study of the Bullet Cluster, for instance, found dark matter (DM) clumps behind shocks, whose peaks are offset from the X-ray peaks (Clowe et al. 2004). A weak lensing mass reconstruction of CIZA J2242.8+5301 by Jee et al. (2015) revealed two DM clumps of almost equal masses, whose distributions are offset from the galaxy distribution as well as the X-ray emission. Okabe et al. (2015), on the other hand, argued that the clump behind the Sausage relic is less massive, and the one on the other side of the cluster and close to the peak of X-ray emission is about twice more massive. In addition, mass reconstructions identified, for instance, two DM clumps of mass ratio $\sim 5$ in ZwCl 0008.8+5215 (Golovich et al. 2017), two dominant DM clumps of mass ratio $\sim 3$ and a few smaller clumps in RX J0603.3+4214 (Jee et al. 2016), and one dominant DM clump and several smaller clumps in PLCK G287.0+32.9 (see Finner et al. 2017). In these clusters, heavy clumps are located behind the main relics.

Along with shocks, “cold fronts” are commonly observed in merging clusters. Cold fronts refer to the structures with opposite gradients of density and temperature, or contact discontinuities in fluid dynamics. Since the early reports in Markevitch et al. (2000) and Vikhlinin et al. (2001), a number of cold fronts have been observed (see, e.g., Markevitch et al. 2002; Markevitch & Vikhlinin 2007). They are often modeled as the borders of cool clumps (see, e.g., Bourdin et al. 2013), or in some cases, they are thought to be produced as a result of sloshing motions of clumps (see, e.g., Zuhone et al. 2010). Some of them appear behind merger shocks in merging clusters, typically about half way from the cluster core to shocks (see, e.g., Markevitch et al. 2002; Emery et al. 2017). Weak lensing observations indicate that in some cases, their locations are close to the peak of the DM distribution (see, e.g., Clowe et al. 2006; Okabe & Umetsu 2008).

All of the above observations tell us that the nature of merger shocks need to be understood and described in the context of the LSS formation, along with other observables such as X-ray and DM distributions.

Previous studies about shock waves inside and around clusters (see, e.g., Ryu et al. 2003, and the references mentioned above) mainly concerned the overall statistics of all cluster shocks, and thus did not particularly highlight merging clusters. Paul et al. (2011) and Schmidt et al. (2017) studied merging clusters in the context of the LSS formation, but did not analyze the properties of merger shocks in detail. Springel & Farrar (2007), van Waerebeek et al. (2011a), and Molnar & Broadhurst (2017a, 2017b), on the other hand, simulated and studied idealized binary mergers, but in a controlled-box, modeling specific objects, i.e., merger shocks in 1E 0657-56, CIZA J2242.8+5301, or ZwCl 0008.8+5215. In this paper, we study merger shocks in cosmological environments, reproduced with a set of hydrodynamic simulations for the LSS formation of the universe. As far as we know, this is the first attempt to simulate cluster merger shocks and analyze their properties in the context of the LSS formation, as opposed to the idealized binary merger simulations cited above. Observed merger events have a wide range of values for clump number, cluster mass, and impact parameter (see, e.g., Clowe et al. 2004; Okabe et al. 2015; Jee et al. 2016;
Golovich et al. 2017), and each shows distinctive features. We here focus on major merger events involving “almost head-on collisions” (with small impact parameters) of clumps with “mass ratio ∼2,” because they are the most likely to be observed with giant radio relics such as the Sausage relic associated with CIZA J2242.8+5301 (see, e.g., Okabe et al. 2015). We leave the exploration of mergers with different mass ratios and impact parameters as future works. By examining the spatial distributions of gas, X-ray emission, and DM, we identify merger-driven shocks and describe their properties. In particular, we quantify their properties in the realistic turbulent ICM, which could be done only with full LSS formation simulations. The quantities, such as the means and variations of \(\nu_c\) and \(M_*\) at shock surfaces and their time evolution, should provide inputs for detailed modeling of synchrotron emissions (see, e.g., Kang & Ryu 2015; Kang et al. 2017) and also constrain \(M_X\) and \(M_{\text{radio}}\) inferred from X-ray and radio observations of radio relics (see, e.g., Hong et al. 2015).

The paper is organized as follows. In Section 2, details of numerical simulations and the compilation of sample merging clusters are described. In Section 3, the identification of merging shocks is described, and then the properties of merger shocks and their time evolution are presented. A summary follows in Section 4.

2. Numerics

2.1. Simulations and Cluster Sample

To generate a sample of merging clusters used in this study, we performed numerical simulations of the LSS formation of the universe for a ΛCDM cosmology model with baryon density \(\Omega_B = 0.044\), DM density \(\Omega_{DM} = 0.236\), cosmological constant \(\Omega_\Lambda = 0.72\), rms density fluctuation \(\sigma_8 = 1.05\), Hubble parameter \(h = H_0/(100 \text{ km s}^{-1} \text{Mpc}^{-1}) = 0.7\), and primordial spectral index \(n = 0.96\). Except for \(\sigma_8\), the parameters are consistent with the WMAP7 data (Komatsu et al. 2011). While \(\sigma_8 \approx 0.82\) is the value best fitted to the WMAP7 data, we adopted a slightly larger \(\sigma_8\) to enhance the number of massive clusters formed in the simulations. Previously, larger \(\sigma_8\)’s were often used for cluster simulations, arguing that the properties of individual clusters and shock waves there are not very sensitive to \(\sigma_8\) (see, e.g., Thomas et al. 1998; Vazza et al. 2009).

Simulations were performed using a PM/Eularian hydrodynamic cosmology code (Ryu et al. 1993). A cubic box of comoving size of 50 \(h^{-1}\) Mpc with periodic boundaries was employed. A grid of 1024\(^3\) uniform zones was used, so the spatial resolution is \(\Delta l = 48.8 h^{-1}\) kpc. Nongravitational effects such as radiative and feedback processes were not included.

Sample clusters were compiled from a number of simulations with different realizations of the initial condition. As noted in the Introduction, we here focus on mergers with clump mass ratios \(\sim 2\), going through almost head-on collisions (specifically, the impact parameter \(\lesssim 2\Delta l = 140\) kpc). In addition, we constrained the epoch of the launching of axial shocks to the redshift range of 0.23 \(\lesssim z \lesssim 0.36\), ensuing the shocks have the best chance to be observed in X-ray and radio at 0.14 \(\lesssim z \lesssim 0.25\) \((\sim 1\) Gyr after the shock launching, see Section 3.2). The latter \(z\)’s match the redshift range of most of the giant radio relics; for instance, CIZA J2242.8+5301 and RX J0603.3+4214 have \(z = 0.188\) and 0.225, respectively (see the references in the Introduction). Finally, for the uniformity of the sample, we chose clusters with the X-ray weighted temperature \(T_X \sim 5\) keV after merger. CIZA J2242.8+5301 and RX J0603.3+4214, on the other hand, are observed to have \(T_X \sim 7-10\) keV (see, e.g., Ogrean et al. 2013b; Akamatsu et al. 2015), higher than those of sample clusters. Even with \(\sigma_8 = 1.05\), the box size of our simulations is not large enough to produce such massive clusters. In the end, five sample clusters were compiled from 10 simulations with different initialization, and their characteristic parameters are listed in Table 1. The average virial masses of 10 simulations (with different initialization, and also constrain \(M_X\) and \(M_{\text{radio}}\)) inferred from X-ray and radio observations of radio relics (see, e.g., Hong et al. 2015).

Table 1. The average virial masses of merging clumps, estimated at 0.174 Gyr before the axial shock launching time.

| Cluster | \(M_{\text{heavy}}/M_{\text{light}}\) | \(T_X^{\text{heavy}}\) (keV) | \(T_X^{\text{light}}\) (keV) | \(T_X\) (keV) | \(\sigma_8\) |
|---------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Cluster 1 | 1.84 | 4.26 | 2.99 | 5.12 | 0.36 |
| Cluster 2 | 1.97 | 3.88 | 2.20 | 4.65 | 0.35 |
| Cluster 3 | 1.96 | 4.08 | 2.33 | 4.92 | 0.23 |
| Cluster 4 | 2.00 | 3.79 | 2.15 | 4.55 | 0.30 |
| Cluster 5 | 1.99 | 3.83 | 2.18 | 4.60 | 0.25 |

Notes.

\(^a\) Ratio of total (baryons and DM) virial masses of two merging clumps, estimated at 0.174 Gyr before the axial shock launching time. \(^b\) X-ray weighted temperatures of two merging clumps, estimated at 0.174 Gyr before the axial shock launching time. \(^c\) X-ray weighted temperature of merged clusters, estimated at 1 Gyr after the axial shock launching time. \(^d\) Redshift of axial shock launching time (see Section 3.2).

2.2. Shock Identification and Energy Flux Calculation

In sample clusters, shocks (actually grid zones containing shocks) were identified with the algorithm described in Ryu et al. (2003) and Hong et al. (2014; see Vazza et al. 2011b for comparisons of different shock identification algorithms). Shocked grid zones were tagged if they satisfied the following three conditions: (1) \(\nabla \cdot v < 0\), i.e., converging local flow; (2) \(\Delta T \times \Delta \rho > 0\), i.e., same temperature and density gradient signs; and (3) \(|\Delta \log T| > 0.11\), i.e., the Mach number greater than 1.3. In numerical simulations, shocks are represented by jumps typically spread over two to three zones, and “shock zones” were defined as the minima of \(\nabla \cdot v\). The sonic Mach number can be estimated from the temperature jump across the shock jump, \(T_2/T_1 = (5M_s^2 - 1)(M_s^2 + 3)/(16M_s^2)\). Here, the subscripts 1 and 2 denote the preshock and postshock...
quantities, respectively. The Mach number of shock zones was defined as \( M_s = \max (M_{s,x}, M_{s,y}, M_{s,z}) \). Very weak shocks are not energetically important, yet are easily confused with sonic waves, so only shocks with \( M_s \geq 1.5 \) were considered. Note that a shock surface consists of a number of shock zones.

At shock zones, the shock kinetic energy flux was calculated as

\[
f_\phi = (1/2) \rho_1 v^2_s,
\]

where \( v_s = M_s c_s (\gamma P_{b,1}/\rho)^{1/2} \). A part of the shock kinetic energy is dissipated to accelerate CRs via DSA as well as to heat the gas, since ICM shocks are collisionless, as noted in the Introduction. The energy flux of CRs emerging from shock zones was estimated as

\[
f_{\text{CR}} = \eta(M_s) f_\phi
\]

(see, e.g., Ryu et al. 2003). Here, \( \eta(M_s) \) is the CR acceleration efficiency as a function of Mach number, and we employed the model presented in Kang & Ryu (2013). While our model \( \eta \) converges to \( \sim 0.23 \) for strong shocks with \( M_s \gg 1 \), it is much smaller with \( 7 \times 10^{-5} \lesssim \eta \lesssim 4 \times 10^{-2} \) for \( 3 \lesssim M_s \lesssim 4 \), and almost negligible for \( M_s \lesssim 2 \) (see Figure 2 of Hong et al. 2014). Such behavior of \( \eta \) is consistent with the recent hybrid plasma simulations by Caprioli & Spitkovsky (2014), although the magnitudes of two model \( \eta \)'s differ by up to a factor of two in the shock parameter range where a comparison can be made. This difference is not important here since we are mainly concerned with the relative importance of shocks with different Mach numbers, rather than the absolute amount of CR generation at these shocks.

The integrated kinetic and CR energies through shock surfaces were also calculated as

\[
F_{\phi, \text{CR}} = \sum_{\text{shocks}} f_{\phi, \text{CR}} \Delta S,
\]

where \( \Delta S \) is the surface area of the shock zone.

In the following section, we will present the quantitative properties of merger shocks averaged over the entire population in our sample clusters of relatively uniform characteristics.

3. Results

3.1. Overview of the Merging Process

To set the stage for describing the merging process, we begin with a general overview of an idealized binary merger (e.g., van Waerfen et al. 2011a; Molnar & Broadhurst 2017a), as illustrated in Figure 1. As two clumps are approaching and being compressed, shocks form and first move outward in the equatorial plane, perpendicular to the merger axis. We name these shocks equatorial shocks. Later, two axial shocks launch in opposite directions along the merger axis. The core passage of DM clumps and the formation of a single gas core occur after the shock launch.

Mergers in our structure formation simulations are, of course, much more complex. They excite turbulent flow motions and are often accompanied by multiple minor mergers and secondary infall along connecting filaments. As a consequence, the formation of merger shocks proceeds in a way that is more complex than in idealized binary mergers.

Figure 2 shows the merging process in a representative cluster, Cluster 1 (see Table 1). Two clumps, composed of baryons and DM, are approaching in an almost head-on collision, and for the sake of convenience, we refer to the four epochs in Figure 2 as the following terms: (a) the compression phase \( (z = 0.38) \) during which the two clumps are approaching, (2) the shock launching phase \( (z = 0.36) \) when the first axial shocks launch, (3) the DM core passage phase \( (z = 0.34) \) when the two DM cores pass each other and two gas clumps merge to form a single core, and (4) the time of the radio relic observation \( (z = 0.25) \) at \( \sim 1 \text{ Gyr} \) after the first axial shocks launch (see Section 3.2).

The middle column of Figure 2 demonstrates the presence of complex networks of shock surfaces in the ICM, even before the two clumps begin to contact and get compressed. Shock surfaces formed during the merger are patchy and highly intermittent with filamentary structures of high Mach number regions.

Figure 3 shows the one-dimensional (1D) distributions of the gas temperature (black), gas density (blue), and DM density (red) along the merger axis of Cluster 1 at the same four epochs as those of Figure 2. We define the zero point of distance, \( d \), along the merger axis as the position of maximum X-ray peak at a given time, except at earlier epochs \((z = 0.38 \text{ and } 0.36)\); at
$z = 0.36, d = 0$ corresponds to the X-ray peak that appeared during the compression, and at $z = 0.38$, the same zero point as that at $z = 0.36$ is adopted. The panel for $z = 0.38$ shows that the heavy (light) gas and DM clumps are approaching from the left-hand side (right-hand side). The gas clumps are being compressed, and a temperature peak appears between them. In the panel for $z = 0.36$, while the density peaks of gas clumps are still getting close to each other, axial shocks start to form at $d = 0$. The panel for $z = 0.34$ shows a single DM peak around the zero point, indicating that it is close to the DM core passage epoch. At that time, both the gas density and temperature distributions have a single peak at $d = 0$, indicating the formation of a merged core. Two axial shocks in the both sides of the peak are apparent.

The last epoch at $z = 0.25$ represents the time, around when the axial shocks have the “best chance” to be observed as a
radio relic or double radio relics (see Section 3.2). This corresponds to \(\sim 1\) Gyr after the axial shock launching. The axial shocks are identified at \(d_s \sim 1-2\) Mpc from the X-ray peak. The Mach number of the axial shock traveling ahead of the light DM clump (LDMC, hereafter) is \(M_s \approx 3.5\) (the red arrow), while that of the shock traveling ahead of the heavy DM clump (HDMC, hereafter) is \(M_s \approx 4\) (the blue arrow). Earlier studies for idealized binary mergers also found that the shock ahead of HDMC is stronger than that ahead of LDMC (van Waeeren et al. 2011a; Molnar & Broadhurst 2017a).

Figure 4 shows the two-dimensional (2D) slices of the gas density (top panels) and temperature (bottom panels), passing through X-ray peaks in the first three clusters of Table 1 at the times of radio relic observation. In all three sample clusters, the heavy clumps approached from the left-hand side, while the light clumps came from the right-hand side. The clumps merged into cores, and the X-ray peaks are located at the center of the images. The elongation axes of density cores roughly represent the merger axes. Merger shocks (both axial shocks and equatorial shocks) are manifested as sharp jumps in the temperature and density distributions. In addition, structures induced by turbulent flow motions and other dynamic activities are evident.

### 3.2. Properties of Merger Shocks

In our sample, merging clusters from LSS formation simulations, in addition to merger-driven shocks, numerous shocks form and disappear as a consequence of background activities. So it is not straightforward to clearly isolate merger shocks from shocks of other types (i.e., turbulent and infall shocks) and track their evolution. Bearing in mind the merging process described above, we attempted to pick up merger shocks “visually” using three-dimensional (3D) images, such as those in Figure 2, as well as 2D slices and 1D line-cut plots, such as those in Figures 3 and 4.

Merger shocks were divided into three different categories, axial shocks ahead of LDMC, axial shocks ahead of HDMC, and equatorial shocks. As illustrated in Figure 1, for the axial shocks we counted those within the two polar cones with opening angles of \(\Delta \theta = 45^\circ\), confined by either the polar angle of \(\theta < 22.5^\circ\) or \(\theta > 157.5^\circ\) around the merger axis. For the equatorial shocks, we considered those located within a disk-like zone confined by \(-22.5^\circ \leq (\theta - 90^\circ) \leq 22.5^\circ\) around the equatorial plane. Here, the cluster center is the peak of X-ray emission at each epoch. The mean distance, \(d_s\), of the three shock categories were estimated by taking the average value of \(d_s\) of the shocks that belong to each category. Then, the shock selection process was repeated and re-defined with shocks within \(d_s \pm 0.3\) Mpc for axial shocks, and with shocks within \(d_s \pm 0.5\) Mpc for equatorial shocks. A larger distance span was considered for equatorial shocks, because they form over \(360^\circ\) of the azimuthal angle, thus showing a larger fluctuation in the position. Figure 5(g) shows the time evolution of the converged value of \(d_s\). In this iteration procedure, some of the
merger shocks could be missed, and some shocks of other types, particularly turbulent shocks, could be counted erroneously. However, we find that, overall, the statistical properties of merger shocks are not very sensitive to the choice of the opening angle, nor to the distance spanning. Figure 6, for instance, shows the kinetic energy flux through shock surfaces, \( f_{\phi} \), a statistics presented below (see Figure 5(e)), for different \( \Delta \theta \)'s, demonstrating its insensitivity to \( \Delta \theta \).

As a reference point of time, we use the axial shock launching time, \( t_i \), which was calculated as follows. Once two types of axial shocks were identified, the average distance between them as a function of time, \( D(t) \), was estimated. At the initial stage of mergers, shocks are difficult to identify reliably, since they are very weak with \( M_s \sim 1-2 \) and form in the turbulent core regions. Reliable identification of axial shocks becomes feasible typically after the core passage epoch. So \( t_i \) was calculated by extrapolating the shock distance backward in time, that is, as the time when \( D(t_i) = 0 \). The redshift of \( t_i \) is given in the last column of Table 1.

The selection of merger shocks and the calculation of their statistics were made at 15 epochs after \( t_i \) with separation \( \Delta z \sim 0.01 \) (corresponding \( \Delta t \sim 0.09 \) Gyr) for the five sample clusters in Table 1. The means and dispersions of shock properties were calculated for each shock category over all the shocks detected in five sample clusters. The number of counted shocks (shock zones) in each category increases from \( N_s \lesssim 100 \) at the axial shock launching time to \( \sim 1500-2000 \) (corresponding to the shock surface area of \( \sim 2-3 \) (Mpc\(^2\)) during the time period of 1.4 Gyr in each sample cluster.

In Figure 5, the mean properties of axial shocks ahead of LDMC (red), axial shocks ahead of HDMC (blue), and equatorial shocks (black) are presented as a function of time, counted from \( t_i \). Although the statistical fluctuations (error bars in the figure) are rather large, the mean values exhibit clear trends. We note that the noisiness of these physical quantities should come from the inherent nature of merger shocks induced in the turbulent ICM during the hierarchical structure formation.

As shown in Figure 5(g), the mean distance of equatorial shocks is the largest among three shock categories, since they launch earlier. And \( \langle d_s \rangle \) for axial shocks ahead of LDMC is larger than that for axial shocks ahead of HDMC, indicating that the X-ray peaks are close to HDMCs in our merging clusters. The mean distances of all three shock categories increase in time, and axial shocks, for instance, reach \( \langle d_s \rangle \sim 1-2 \) Mpc by the time \( t - t_i \sim 1 \) Gyr.

The top panels of Figure 5 show the mean values of shock Mach numbers, \( \langle M_s \rangle \), weighted with shock kinetic energy flux \( f_{\phi} \), and \( \langle M_s \rangle_{CR} \) weighted with CR energy flux \( f_{CR} \). First, the Mach numbers overall increase in time, while the mean shock speed, \( \langle v_s \rangle \), in Figure 5(d) increases in the early phase during \( \sim 0.6 \) Gyr, but then fluctuates afterward. The overall increase of shock Mach numbers in the late stage reflects the fact that the gas temperature tends to decrease in the cluster outskirts (\( \gtrsim 1 \) Mpc), as can be seen in Figures 3 and 4. Second, both \( \langle v_s \rangle \) and \( \langle M_s \rangle \) of equatorial shocks have the largest values, since they propagate mostly to low density regions surrounding merging clumps. Moreover, \( \langle v_s \rangle \) and \( \langle M_s \rangle \) of axial
shocks ahead of HDMCs are larger than those of axial shocks ahead of LDMCs. However, \( \langle d_s \rangle \) for axial shocks ahead of HDMCs is smaller, owing to the fact that \( \langle d_s \rangle \) includes not only the propagation of shocks but also the displacement of X-ray peaks. Third, while \( \langle M_s \rangle \) and \( \langle M_s \rangle_f \) are comparable, \( \langle M_s \rangle_{CR} \) is larger by about unity or so, especially in the late stage. This is due to the dependence of the CR acceleration efficiency, \( \eta(M_s) \), on the shock Mach number; our model \( \eta(M_s) \) is larger for stronger shocks (see Section 2.2).

The average kinetic energy flux through shock surfaces, \( \langle f \rangle \), in Figure 5(e) tends to decrease in time as shocks move outward, since the gas density decreases in the cluster outskirts. The average CR energy flux produced at shocks, \( \langle F_{CR} \rangle \), in Figure 5(f), on the other hand, shows complicated time evolution, reflecting the Mach number dependence of the CR acceleration efficiency. Both \( \langle f \rangle \) and \( \langle F_{CR} \rangle \) for axial shocks ahead of LDMC are the largest because these shocks propagate into the gas with higher density that is originally associated with heavier gas clumps.

Figures 5(h) and (i) show the shock kinetic and CR energy fluxes integrated over shock surfaces, \( \langle F \rangle \) and \( \langle F_{CR} \rangle \), averaged for five sample clusters. Again, \( \langle F \rangle \) and \( \langle F_{CR} \rangle \) of axial shocks ahead of LDMC are the largest, while those of equatorial shocks are the smallest. Although axial shocks ahead of LDMC are the weakest with smallest \( \langle M_s \rangle \) among shocks of three categories, they are energetically the most important; that is, they process the largest amount of kinetic energy and also generate the largest amount of CRs, especially at late times of \( t - t_i \sim 0.8-1.4 \text{ Gyr} \).

In particular, in Figure 5(h), \( F_{CR} \) for axial shocks ahead of LDMC peaks at \( \sim 10^{42}-10^{44} \text{ erg s}^{-1} \) during \( t - t_i \sim 0.8-1.4 \text{ Gyr} \). The total energy processed during the period is...
approximately several $\times 10^{50}$ erg, which is a substantial fraction of the merger energy $\sim 10^{54}$ erg (see the Introduction). $F_{\phi}$ for axial shocks ahead of HDMC is about an order of magnitude smaller, and $F_{\phi}$ for equatorial shocks is even smaller by a factor of several. So axial shocks ahead of LDMC should have the best chance to be observed as X-ray shocks, especially at $\sim 1$ Gyr after the launching of the shocks. During the peak period, for these axial shocks, the $f_{\phi}$-weighed Mach number ranges $\langle M_{\phi} \rangle \sim 2-3$ and their distance from the cluster center ranges $\langle d_{i} \rangle \approx 1-2$ Mpc. These are in reasonable agreement with the observed characteristics of X-ray shocks, as noted in the Introduction.

In Figure 5(i), again, $F_{CR}$ for axial shocks ahead of LDMC is several to tens of times larger than $F_{CR}$ for other category shocks during $t - t_{i} \approx 0.8-1.4$ Gyr. So they should have the best chance to light up as radio relics and thus be observed in radio. The $f_{CR}$-weighed Mach number for the shocks during the peak period is, on the other hand, in the range of $\langle M_{\phi} \rangle \sim 3-4$, higher than $\langle M_{\phi} \rangle_{0}$, as noted above. This range of $\langle M_{\phi} \rangle_{CR}$ is consistent with the range of the shock Mach numbers estimated from the radio spectral indices of observed radio relics (see the references in the Introduction). The potential manifestation of larger $M_{\phi}$ in radio relic observations than in X-ray shock observations was pointed out in Hong et al. (2015). Our results confirm such a tendency, indicating that the difference between $M_{\phi}$ and $M_{radio}$ might be due to the representations of different parts of shock surfaces, that is, higher $M_{\phi}$ for radio observations while lower $M_{\phi}$ for X-ray observations, as noted in the Introduction. The range of $\langle d_{i} \rangle \approx 1-2$ Mpc for axial shocks ahead of LDMC during the peak of CR production is also comparable to the positions of observed radio relics.

We note that the Sunyaev–Zel’dovich (SZ) decrements found CIZA J2242.8+5301 could be interpreted as high pressure regions generated by equatorial shocks propagating in the direction perpendicular to the merger axis (see Rumsey et al. 2017). An X-ray temperature break found in the merger system between Abell 399 and Abell 401 could also indicate a signature of equatorial shocks (see Akamatsu et al. 2017). Although the nature of these observed features should be further investigated, their positions are consistent with the equatorial shocks defined in this study. These indicate that although energetically subdominant, equatorial shocks could have possibly observable imprints.

From Figure 5(d), one can see that $\langle v_{i} \rangle$ increases during the peak period of $F_{\phi}$ and $F_{CR}$. The adiabatic blast wave solution for a point explosion requires a density gradient steeper than $\rho^{-\frac{3}{2}}$ for accelerating shock fronts (see, e.g., Ryu & Vishniac 1991). Apparently, the blast wave assumption does not hold for merger-driven shocks, since the kinetic and gravitational energies of merging clumps are continuously dissipated through shocks and additional energies are supplied by secondary infall and multiple minor mergers. In addition, $\langle v_{i} \rangle$ includes the contributions not only from the shock propagation, but also from turbulent flow motions ahead of shocks. As a matter of fact, large fluctuations in $\langle v_{i} \rangle$ as well as in $\langle M_{\phi} \rangle$ reflect complicated flow dynamics of clusters.

### 3.3. DM Distribution

From Figures 2–4, we can see the relative positions of merger shocks, X-ray peak, and DM clumps in Cluster 1 at $z = 0.25$ or $t - t_{i} \approx 1$ Gyr, an epoch close to the peak of $F_{\phi}$ and $F_{CR}$. Particularly, in Figure 3, with the peak of X-ray emission located in the middle ($d = 0$), the axial shock ahead of LDMC is at $d \approx -2.3$ Mpc, whereas the HDMC is at $d \approx 0.6$ Mpc. Shocks ahead of LDMC are the most energetic, as discussed above. Assuming that the shock appears as the main radio relic, this configuration is consistent with that of the Sausage relic in CIZA J2242.8+5301, at least qualitatively (see Akamatsu et al. 2015; Okabe et al. 2015). In RX J0603.3+4214, on the other hand, the Toothbrush relic is located close to the HDMC, as mentioned in the Introduction. While our sample clusters undergo almost head-on collisions of mass ratio $\sim 2$ clumps, the Toothbrush relic seems to have been produced by a merger involving multiple clumps (see Brüggen et al. 2012b; Jee et al. 2016). The detailed distributions of shocks, X-ray emission, and DM in merging clusters should depend on a number of parameters, including the number of clumps and their masses and impact parameters. Studies of the...
dependences on such parameters would need a much large sample of merging clusters and are beyond the scope of this paper.

4. Summary

In the currently favored paradigm of hierarchical structure formation, galaxy clusters form through successive mergers of subcluster clumps, and shock waves are naturally induced as a consequence. Major mergers in relatively recent epochs of $z < 0.5$ are among the most energetic events in the universe, and the merger shocks associated with them are observed in X-ray and radio.

In this study, we examined the properties of merger shocks in galaxy clusters from cosmological hydrodynamic simulations for the LSS formation of the universe. We first compiled a sample of five merging clusters in 10 simulations with different initialization; all occur through almost head-on collisions of mass ratio $\sim 2$ at $z < 0.5$, which result in merged systems with $T_X \sim 5$ keV. We then isolated shocks produced by merger activities and quantified their properties such as the shock speed, Mach number, and shock energy flux. Due to the turbulent nature of the ICM, the properties of the shocks can be described only statistically with means and standard deviations for a population of identified shocks associated with merger events. We also calculated the time evolution of those shock properties.

We described the merging process in our sample clusters as follows (see Figures 2 and 3). (a) As the gas is compressed during the approach of two clumps, “equatorial shocks” launch near the equatorial plane toward the direction perpendicular to the merger axis. (b) As the clumps get closer, “axial shocks” launch along the merger axis. (c) The core passage of DM clumps and the formation of a single gas core occur after the launching of the axial shocks. (d) X-ray shocks and radio relics are likely to be observed in the cluster outskirts ($\sim 1$–$2$ Mpc) at $\sim 1$ Gyr after the shock launching.

Our findings are summarized as follows.

(1) The surfaces of merger shocks are not smooth. The Mach number distribution on the surfaces is highly intermittent and the high Mach number parts form filamentary structures.

(2) As the merger shocks propagate out from the cores to the outskirts, the shock Mach number, $M_s$, on average, increases over time, while the shock speed does not necessarily do the same.

(3) The kinetic energy flux through shock surfaces, $f_{\text{ke}}$, decreases in time, since the gas density is lower in the outskirts. However, the CR energy flux produced at shocks, $f_{\text{CR}}$, shows complicated time evolution.

(4) Axial shocks propagating ahead of LDMC are most energetic. They process large amounts of the kinetic energy, $f_{\text{ke}}$, and the CR energy, $f_{\text{CR}}$, and thus have the best chance to be observed as X-ray shocks and radio relics.

(5) $f_{\text{ke}}$ and $f_{\text{CR}}$ of axial shocks ahead of the LDMC peak at $t - t_1 \sim 1$ Gyr after the shocks launched, or when the shocks are located at $d_1 \sim 1$–$2$ Mpc from the cluster center. At the time, the shocks have $(M_{\text{s,ke}}) \simeq 2$–$3$ (weighted with $f_{\text{ke}}$), while $(M_{\text{s,CR}}) \simeq 3$–$4$ (weighted with $f_{\text{CR}}$). This is because the CR acceleration is more efficient at the parts of shock surfaces with higher Mach numbers.

(6) Both DM clumps survive through merger, and their peaks persist. In our sample clusters, after the DM core passage, the LDMC is located behind the most energetic axial shocks, while the HDMC lies in the other side but closer to the peak of X-ray emission which coincides with the gas core.

Finally, we note that the properties of merger shocks, as well as their positions relative to the X-ray peak and DM clumps should depend on a number of merger parameters. A more comprehensive investigation of such dependence requires a very large sample of simulated merging clusters, and we will leave this for future work.

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ORCID iDs

Ji-Hoon Ha https://orcid.org/0000-0001-7670-4897
Dongsu Ryu https://orcid.org/0000-0002-5455-2957
Hyesung Kang https://orcid.org/0000-0002-4674-5687

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