SHOCK-INDUCED STRIPPING OF SATELLITE ISM/CGM IN ILLUSTRISTNG CLUSTERS AT Z ∼ 0

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ABSTRACT

Using the IllustrisTNG simulation, we study the interaction of large-scale shocks with the circum-galactic medium (CGM) and interstellar medium (ISM) of star-forming (SF) satellite galaxies in galaxy clusters. These shocks are usually produced by mergers and massive accretion. Our visual inspection shows that approximately half of SF satellites have encountered shocks in their host clusters at z ≤ 0.11. After a satellite crosses a shock front and enters the postshock region, the ram pressure on it is boosted significantly. Both the CGM and ISM can be severely impacted, either by stripping or compression. The stripping of the ISM is particularly important for low-mass galaxies with log(M∗/M⊙) < 10 and can occur even in the outskirts of galaxy clusters. In comparison, satellites that do not interact with shocks lose their ISM only in the inner regions of clusters. About half of the ISM is stripped within about 0.6 Gyr after it crosses the shock front. Our results show that shock-induced stripping plays an important role in quenching satellite galaxies in clusters.

1. INTRODUCTION

Galaxy properties are correlated with the environment in which they reside. It is well known that early-type galaxies are preferentially found in galaxy clusters (e.g. Dressler 1980), and late-type galaxies in clusters and fields are systematically different in their atomic and molecular gas contents (Solanes et al. 2001; Catinella et al. 2013; Boselli et al. 2014). The fraction of quiescent galaxies is also found to increase with the local number density of galaxies, with halo mass, and with decreasing distance to halo center (halo-centric distance) (e.g. Baldry et al. 2006; Peng et al. 2010; Wetzel et al. 2013; Woo et al. 2013; Wang et al. 2018; Bluck et al. 2020). Comparing satellite and central galaxies suggests that environmental effects on galaxies are complicated (e.g., van den Bosch et al. 2008; Wetzel et al. 2013; Li et al. 2020) and depend strongly on intrinsic properties, such as galaxy stellar mass, morphology, and details of formation processes (see e.g. Li et al. 2020). Various mechanisms have been proposed to explain the observed environmental dependence of galaxy properties, such as galaxy mergers and interactions (Toomre & Toomre 1972; Moore et al. 1996, 1998; Cox et al. 2006; Cheung et al. 2012), tidal stripping (TS, e.g. Read et al. 2006), strangulation (Larson et al. 1980; van den Bosch et al. 2008; Peng et al. 2015), and ram pressure stripping (RPS, Gunn & Gott 1972; Abadi et al. 1999; Boselli et al. 2014, 2022).

The ram pressure (P_RP) on a galaxy depends both on the density of the ambient gas and on the velocity of the galaxy relative to the ambient gas, and so is expected to be strong in clusters of galaxies where the intra-cluster medium (ICM) is dense and typical velocity of member galaxies is high. The effectiveness of the RPS on the gas associated with a galaxy depends also on how strongly the gas is bound by the galaxy. Thus, the RPS has often been invoked for galaxy evolution in clusters, particularly for low-mass satellite galaxies, where the interstellar medium (ISM) and the circum-galactic medium (CGM) may be stripped relatively easily. Direct evidence for the RPS comes from the observed asymmetric gas distribution, particularly as long cometary tails that do not contain significant amounts of stars (Boselli et al. 2022). Such stripped tails have been detected in both the inner regions and outskirts of nearby clusters and rich groups (e.g., Gavazzi et al. 1995; Kenney et al. 2004; Sun et al. 2007; Smith et al. 2010; Ebeling et al. 2014; Jáchym et al. 2014; Poggianti et al. 2017; Chen et al. 2020; Wang et al. 2021).

Based on galaxy properties and ICM density profiles obtained from observational data and simulations, analytic models have been developed to estimate the efficiency of the RPS and its dependence on both galaxy and cluster properties (e.g. Gunn & Gott 1972; Hester 2006; Köppen et al. 2018; Boselli et al. 2022; Vega-Martínez et al. 2022). For a late-type galaxy of stellar mass M∗ = 10^9 − 10^10 M⊙, it is found that the ram pressure can effectively strip the ISM at its stellar effective radius when P_RP ≈ 10^{-12} dyn cm^{-2}, and that the ISM can be fully stripped only when the satellite falls into the inner region of a cluster (see e.g. Boselli et al. 2022). For massive late-type galaxies (M∗ > 10^10 M⊙), a much higher ram pressure, P_RP ≈ 10^{-11} dyn cm^{-2} is required for a significant stripping of the ISM. RPS models based on these results have been implemented in some semi-analytic galaxy formation models to explain observed properties of satellite galaxies (e.g. Guo et al. 2011; Henriques et al. 2015).

The details of the RPS can be better understood using hydrodynamic simulations. To explore the dependence on various model parameters, controlled simulations are often employed, in which galaxy properties, galaxy orbits...
and inclinations, and ICM properties are set up by hand (Farouki & Shapiro 1980; Abadi et al. 1999; Quilis et al. 2000; Marcolini et al. 2003; Roediger & Hensler 2005; Roediger & Brüggen 2007; Haan & Braun 2014; Roediger et al. 2014; Steinhauser et al. 2016; Steyrleithner et al. 2020). The simulation results are broadly consistent with analytic models, although there are significant differences in details. These simulations demonstrate that ram pressure can produce a long cometary gas tail without significantly affecting stellar components. Sometimes the ram pressure can even compress the ISM at the leading edge and in the central region of stripped galaxies, thereby enhancing the star formation activity. The typical timescale for gas stripping in dwarf galaxies is about 100–500 Myr, while massive spirals can only be severely stripped in some extreme cases.

There are also attempts to investigate the effects of RPS using cosmological hydrodynamic simulations, where the properties of satellites mimic those of real galaxies and the evolution is followed in a realistic ICM (e.g. Tonesnes & Bryan 2008; Bahé & McCarthy 2015; Lotz et al. 2019; Arthur et al. 2019; Yun et al. 2019). It is found that the efficiency of the RPS can be suppressed or enhanced depending on different circumstances. For instance, some satellites may fall into clusters along with the IGM in filaments and have their gas protected by the filament gas until they reach the inner regions of clusters (Kotecha et al. 2022). In such cases, the ram pressure must first get rid of the IGM and CGM associated with satellites, before it can strip the ISM. It was also found that feedback from active galactic nuclei (AGNs) in central galaxies can significantly change the ICM, consequently affecting the efficiency of RPS (Martín-Navarro et al. 2021). Moreover, the RPS is also sensitive to the presence of substructures in a cluster, where the ICM density is expected to be higher (Tonnesen & Bryan 2008). The RPS efficiency also depends on satellites themselves. For example, ram pressure usually compresses the ISM and enhances star formation for gas-rich satellites (Troncoso-Iribarren et al. 2020), and internal processes, such as stellar feedback, may make the ISM fluffy and more susceptible to stripping (Bahé & McCarthy 2015).

It is well known that many galaxy clusters are undergoing or have undergone merging processes of massive accretion. The collision of the ICM with the infalling gas and mergers can induce strong shocks (e.g. Kang et al. 2007; Bykov et al. 2008; Zinger et al. 2018; Li et al. 2022), which are the hallmark of ICM environments. These shocks can generate jumps in gas pressure, density, temperature, and velocity, thus leading to significant enhancements in the ram pressure. Roediger et al. (2014) used controlled simulations to study the impact of ICM shocks on a massive spiral galaxy, and found that shocks can effectively strip its ISM. However the investigation focused on whether or not the interaction with shocks can produce star-forming tails, rather than on gas stripping. Some indirect observational studies provide support to the role played by shocks in stripping the ISM. For example, NGC 4522 has an asymmetric gas distribution, which is hard to explain using the RPS of a static ICM and hints the importance of shocks (Kenney et al. 2004). Signatures of RPS are expected to be more common in merging clusters where shocks are generated (e.g. McPartland et al. 2016; Stroe et al. 2017; Ebeling & Kalita 2019; Ruggiero et al. 2019). Consistent with this, stripping signatures are observed in several galaxies around merger shocks in A1367 (see discussion in Boselli et al. 2022) and Abell 2744 (e.g. Owens et al. 2012).

In this paper, we use hydrodynamic simulations in IllustrisTNG to study whether or not shocks in galaxy clusters have significant impacts on satellite galaxies. In particular, we focus on the stripping of CGM and ISM of satellites. Our goal is to understand the role of RPS in quenching star formation of cluster galaxies. In Section 2, we introduce the simulations, cluster and galaxy samples, and the method to identify events of shock-satellite interaction. Section 3 shows the effects of large-scale shocks on the CGM and ISM of satellites, their dependence on stellar mass and halo-centric distance, and results on stripping timescale. We compare these satellites with those that do not interact with large-scale shocks. Finally, we summarize and discuss our results in Section 4.

2. METHOD

2.1. The IllustrisTNG Simulation

We investigate the interaction between shocks and satellite galaxies using data from the IllustrisTNG simulations (e.g. Naiman et al. 2018; Pillepich et al. 2018a; Nelson et al. 2018; Springel et al. 2018), run with the AREPO code (Springel 2010). The gravitational forces are evaluated using a particle-mesh and oct-tree algorithm, and the solutions to hydrodynamic equations are obtained by using a finite-volume Godunov method on a moving unstructured mesh defined by Voronoi tessellations of discrete points. The code thus captures the advantages of both Lagrangian and Eulerian methods. A series of tests presented in Springel (2010) and Schaaf & Springel (2015) show that the moving-mesh technique can resolve shocks that are difficult to resolve in SPH-based techniques (see also Figure 1). TNG simulations include key physical processes for the formation and evolution of galaxies, such as gas cooling and heating, star formation in a multiphase ICM, stellar population evolution, metal enrichment of gas, and feedback from both supernovae and supermassive black holes. The details of these physical processes are described in the two method papers (Weinberger et al. 2017; Pillepich et al. 2018b). The simulations can reproduce the observed bimodal color distribution of galaxies, the fraction of quiescent galaxies and their dependence on galaxy stellar mass and environment (e.g. Nelson et al. 2018; Donnari et al. 2021). This indicates that key processes related to quenching of star formation, such as AGN and stellar feedback, ram pressure stripping, tidal stripping, are modeled realistically in these simulations.

The cosmological parameters for the TNG simulations are consistent with recent Planck measurements (Planck Collaboration et al. 2016): \( \Omega_m = 0.28, \Omega_b = 0.0486, \sigma_8 = 0.8159, H_0 = 100h \text{ km s}^{-1} \text{Mpc}^{-1} \) with \( h = 0.6774 \) and \( n_s = 0.9667 \). A series of simulations were carried out by TNG. To obtain a large sample of satellites with sufficiently high mass resolution, we decide to use the highest-resolution run
Fig. 1.— The propagation of a strong shock in gas pressure, temperature, density and radial velocity maps in a TNG cluster with log(M$_{200}$/M$_\odot$) = 14.4. The white circle indicates the center of the cluster. A bow-like shock propagates from the cluster center to the right side, and an accretion shock appears to the left of the cluster.

The ~100 Mpc simulations, TNG100-1$^4$, one of the three flagship simulations of the IllustrisTNG project. It follows the evolution of 1820$^3$ dark matter (DM) particles and approximately 1820$^3$ gas cells from $z = 127$ to $z = 0$. The masses of DM particles and gas cells are $\sim 7.5 \times 10^9 M_\odot$ and $\sim 1.4 \times 10^9 M_\odot$, respectively. One hundred snapshots between $z = 20$ and $z = 0$ are dumped. There are 10 snapshots between $z = 0.11$ and $z = 0$, the redshift range we are interested in. The time interval between two adjacent snapshots ranges from 0.130 to 0.204 Gyr, much smaller than the dynamic timescales of halos.

Halos and subhalos used here are obtained using the Friends-of-Friends (FoF) (Davis et al. 1985) and SUBFIND algorithms (Springel et al. 2001; Dolag et al. 2009). Galaxies are defined as the baryonic component in subhalos. The most massive subhalo in an FOF halo is classified as the central subhalo, and its galaxy is regarded as the central galaxy of the halo. The baryonic components in other subhalos are referred to as satellite galaxies. The subhalo and galaxy merger trees are constructed over the 100 snapshots by the SUBLINK algorithm (Rodriguez-Gomez et al. 2015). In the following, we use galaxy merger trees to follow the motion of satel-

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$^4$ https://www.tng-project.org/
lites in galaxy clusters and trace their evolution.

The halo mass, $M_{200}$, used in this paper is defined as the mass contained in a sphere centered at the halo center, within which the mean mass density equals 200 times the critical density of the Universe. The radius of the sphere is referred to as the virial radius, $R_{200}$. The galaxy stellar mass, $M_*$, is the sum of all stellar particles within $2r_e$, where $r_e$ is the stellar half mass radius. We are particularly interested in the stripping of the CGM and ISM. We define the ISM of a galaxy as the cold gas cells ($\log(T/K) < 5$) within $2r_e$. For CGM we focus on the gas medium within a spherical shell between $2r_e$ and $4r_e$. The details of the CGM and ISM quantities are given in the relevant sections.

### 2.2. Galaxy clusters, large-scale shocks and satellite samples

In the TNG run used here, there are 14 galaxy clusters with $\log(M_{200}/M_\odot) > 14.0$ at $z = 0$. We investigate satellite galaxies in these clusters, their interaction with ICM shocks, and the stripping and compression of the CGM and ISM. Clusters are usually growing rapidly, and may be undergoing recent massive mergers. Our inspection shows that the fourteen clusters experienced 8 mergers with merger mass ratios above 0.1 at $z \leq 0.2$. As shown in previous studies (Ryu et al. 2003; Zinger et al. 2018), cluster mergers and accretions of filament gas can induce strong shocks, with scales comparable to the clusters themselves.

Figure 1 shows the propagation of a large-scale shock in a cluster with $\log(M_{200}/M_\odot) = 14.4$ and $R_{200} = 1.33$ Mpc at $z \sim 0$. From the evolution of the radial velocity map, we can see that, at $z = 0.11$, the gas stream with a large infall (blue) velocity plunged into the very center of the cluster. Zinger et al. (2018) demonstrated that such a deeply penetrating stream in galaxy clusters can generate multiple strong shocks. Indeed, we see that bow shocks are generated in the cluster center and propagating outwards. It is clear that the post-shock region has higher pressure, density and temperature than the pre-shock region, and that the two regions have very different velocity structures. The shock surface, where jumps in gas pressure, temperature, density and velocity are located, is sharp and can be identified easily.

These large-scale shocks cover a large fraction of the sky viewed from the galaxy clusters, and so they must interact with satellite galaxies as they propagate. It is then interesting to identify satellites that have interacted with these shocks. To avoid potential evolution effects of galaxy clusters and satellites, we only consider interactions that occurred recently, i.e. at $z \leq 0.11$. We only consider galaxies of $M_\star \geq 10^9 M_\odot$, which have at least 1000 star particles and can be well resolved by the simulation. Since we are interested in satellite galaxies, we only select galaxies that have been identified as satellites at least once in its history and have ever reached a distance less than $1.5R_{200}$ from the centers of their host clusters at $z \leq 0.11$. To avoid satellites that have been severely influenced by environmental processes before interacting with shocks, we require that, at $z = 0.11$, the satellite resides in the outskirt of its host cluster, i.e. at a distance $r > 0.8R_{200}$ from the central galaxy. We also discard satellites that are quenched ($\log(sSFR) \leq -10^{-11}$ yr$^{-1}$) or have a low gas fraction (with the ISM to stellar mass ratio $< 5\%$) at $z = 0.11$. Because we want to trace the evolution of the CGM and ISM of satellite galaxies in detail, the merger trees of satellites are required to be complete at $z \leq 0.11$. We discard seven satellites whose merger trees miss at least one snapshot.

For each satellite, we generate gas pressure, density, temperature and velocity maps in $2 \times 2$ $h^{-1}$Mpc slices with a thickness of $0.15$ $h^{-1}$Mpc centered on the satellite. To avoid uncertainties due to projection effects, we inspect each map in three different ($X - Y$, $Y - Z$ and $X - Z$) planes. We trace the maps of the four properties from $z = 0.11$ to 0, and visually identify whether or not the satellite has ever crossed a shock surface at $z \leq 0.11$. In most cases, the shock crossing event is easy to identify visually. We show three examples of the crossing events in Figure 2. As long as a satellite has crossed a shock surface, it is referred to as a ShSAT. Otherwise the satellite is referred to as a NsSAT. NsSATS are used to compare with ShSATS. Note that these large-scale shocks are not produced by satellites themselves. So in general a ShSAT moves from a pre-shock region to a post-shock region, as shown in Figure 2.

Due to the time resolution between snapshots, we cannot determine accurately when and where a shock-crossing event occurs. We thus choose the snapshot just before a satellite enters the post-shock region as the shock-crossing time, and we denote it by $t_{sh}$. The distance of the satellite to the central galaxy at $t_{sh}$ is denoted by $r_{sh}$. To study the effect of shocks on satellites, we also consider two additional times corresponding to the two snapshots before and after the snapshot of $t_{sh}$, respectively, each of which is separated from the std by two snapshots. These two times are denoted as $t_b$ and $t_d$, respectively. A few satellites cross the shock surface in the last two snapshots of the simulation and thus have no $t_a$. They are excluded from our analysis. And as shown in Section 3, if a satellite meets a shock at a large radius, the shock usually only has a weak impact on the satellite, we thus also discard shock-crossing events with $r_{sh} > 1.5R_{200}$. Finally, we obtain a total of 122 ShSATS and 122 NsSATS, as listed in Table 1. The fact that the numbers of ShSATS and NsSATS are comparable suggests that shock-crossing is very common for satellites in clusters of galaxies.

| Mass range $M_{200}/M_\odot$ | ShSAT | NsSAT | All |
|-----------------------------|-------|-------|-----|
| $[9.0, 10.0)$                | 94    | 91    | 185 |
| $[10.0, \infty)$            | 28    | 31    | 59  |
| $[9.0, \infty)$             | 122   | 122   | 244 |

The stellar mass ($\log(M_*/M_\odot)$) range

There are three reasons for us to rely on visual inspections to identify shock-crossing events of satellites. First, as shown in Figure 1, shocks in simulated clusters are usually very sharp and are easily recognizable by eye. Second, the shock crossing can sometimes distort the shock surface, making it difficult to identify with an automated algorithm. Third, we are interested mainly in large-scale shocks produced by mergers and massive accretion of filament gas, and visual inspections can easily distinguish them from small-scale shocks that are abundant. However, such visual identifications may have some

### 2.3. Cluster merger trees and satellite interactions

Cluster merger trees play an important role in understanding the evolution of satellite galaxies in clusters. As the mass contained in a sphere centered at the halo center, within which the mean mass density equals 200 times the critical density of the Universe, we can see that, at $z = 0.11$, the gas stream within $2r_e$ and $4r_e$. The details of the CGM and ISM quantities are given in the relevant sections.
Fig. 2.— Three ShSAT examples (examples one, two and three) and the evolution of the medium in and around these satellites. For each example, the first row shows the gas pressure map at a large scale (cluster size) and the second row shows the gas density at a scale comparable to the galaxy size. The panels in the second column show the maps at $t_{sh}$ when the satellites encounter the shock surfaces. In each panel, we show $\rho_{CGM}$, $v_{CGM}$, the halo-centric distance ($r/R_{200}$) and redshift ($z$). The red stars in the first rows mark the position of the galaxies and the black circles in the second rows have radii of 2$r_e$. 
potential problems. They may miss events of weak or small-scale shocks that are potentially interesting. Visual inspections also limit our ability to extend similar analysis to a much larger sample. Thus, the results presented in the following sections should be interpreted with these caveats.

3. GAS STRIPPING BY SHOCKS

Based on the satellites selected in Section 2.2, we investigate the stripping and compression of the CGM and ISM for ShSATS. Subsection 3.1 shows results for the CGM, while the results for the ISM is presented in Subsection 3.2. These results for ShSATSs are compared with those for NsSATS in Subsection 3.3 to demonstrate impacts of shock crossing on the gas contents of satellite galaxies.

3.1. Stripping of the CGM

To investigate the impact of shocks on the CGM of ShSATSs, we first identify the CGM gas cells, defined as the ones which are separated from satellites with distances ranging from 2r_e to 4r_e, and then calculate the mean velocity (relative the satellites, v_CGM), mean density (ρ_CGM) and mean temperature (T_CGM) of the CGM gas. Figure 3 shows the comparison of the CGM properties at t_b and t_a, representing times before and after the shock-crossing time t_{sh}, respectively (see last section). Before shock crossing, the CGM velocities are generally low, usually less than 100 km s\(^{-1}\) relative to the corresponding satellites, much smaller than the typical virial velocity of galaxy clusters. This is expected, because the CGM is physically associated with the satellite before shock crossing. The CGM density ranges from approximately 1000 to 10^5 times the mean cosmic baryon density (ρ_b), consistent with the density in the inner region of a halo but much smaller than that of the ISM (typically > 10^6ρ_b). The CGM temperature, ranging from 10^4.5 to 10^6.5 K, is much lower than the virial temperature of a galaxy cluster. These results show that, before shock crossing, the CGM of most ShSATSs has properties expected from the gas medium associated with galaxies and their halos. Note that the CGM defined here is close to satellites. Thus, our results do not mean that CGM at much larger distances is not affected before shock crossing (see the tests for larger scales shown below).

After interacting with a shock, the CGM velocity changes dramatically. Among the 122 ShSATSs, 54 of them now have v_CGM(t_a) > 100 km s\(^{-1}\), 28 have v_CGM > 500 km s\(^{-1}\), and some of them can even reach a value ~ 1000 km s\(^{-1}\), comparable to the typical virial velocity of a galaxy cluster. However, there is a fraction of satellites, for which the CGM velocity is actually reduced after shock crossing. Similar behavior can also be observed in CGM density and temperature. Most satellites have their CGM density significantly reduced after shock crossing, and the amount of reduction can sometimes reach one dex. On average, the mean temperature of the CGM increases by a factor of more than ten. The lower panels of Figure 3 show the correlations among Δ log ρ_CGM = log(ρ_CGM(t_a)/ρ_CGM(t_b)), Δ v_CGM = v_CGM(t_a) − v_CGM(t_b) and T_CGM(t_a). The strong correlations between these quantities indicate that shock crossing simultaneously reduces the CGM density and enhances the velocity and temperature of the CGM. The correlation between Δ v_CGM and T_CGM(t_a) is tighter than other correlations, and it consists of three populations. The first one has Δ v_CGM > 500 km s\(^{-1}\), with temperature T_CGM(t_a) ~ 2.5 × 10^7 K similar to that of the ICM and almost independent of Δ v_CGM. As shown in the left panel of Figure 4, the median CGM temperature of this population is about 6.7 × 10^7 K before shock crossing. This temperature is comparable to the virial temperature of their subhalos, but much lower than the temperature after shock crossing. These satellites have Δ v_CGM ranging from 0 to −1.5, indicating that the original CGM is completely replaced by, or mixed with the ICM in their clusters. Thus, the medium around a galaxy at t_a does not retain its original definition of the CGM that it is bound to its host galaxy. For simplicity, however, we still refer such a medium as the CGM. In the first and second rows of Figure 2, we show an example (Example one) for this population. As one can see, the CGM density drops quickly after interacting with the shock, and the temperature changes from ~ 3.0 × 10^6 K at t_b to ~ 4.2 × 10^7 K at t_a.

The second population has T_CGM(t_a) < 10^6 K. These galaxies have Δ v_CGM that are very close to zero, independent of T_CGM(t_a). The lower-right panel of Figure 3 shows that they have Δ log ρ_CGM between 0.3 and −0.5, with a median value close to zero. These results suggest that shock crossing does not strip the CGM of these satellite galaxies. However, there are large variations of the CGM density between t_a and t_b. For these galaxies, although shock crossing cannot strip the CGM quickly, it may compress it. Example three shown in Figure 2 belongs to this population. We can see a clear bow-like edge surrounding the example galaxy after t_{sh}, produced by the interaction between the CGM and the shock surface. Its CGM is compressed by the interaction so that its density increases, but it is still moving with the galaxy. In other cases, the interaction with the shock surface causes the CGM to disperse and its density to decrease, but has not yet stripped the gas.

The third population has T_CGM(t_a) > 10^6 K and Δ v_CGM < 500 km s\(^{-1}\). Different from the first two populations, this population exhibits a tight correlation between T_CGM(t_a) and Δ v_CGM, indicating that the stripping is ongoing. In these cases, the gas component between 2r_e and 4r_e at t_a is a mixture of the hot ICM and the colder stripped gas. An example of this population (Example two) is also presented in Figure 2. Here one can see that the CGM and ISM are being stripped and the stripped gas forms an extended tail. The interaction between the CGM and the shock surface. Its CGM is compressed by the interaction so that its density increases, but it is still moving with the galaxy. In other cases, the interaction with the shock surface causes the CGM to disperse and its density to decrease, but has not yet stripped the gas.

A detailed inspection of our sample galaxies shows that some satellites are severely affected by shocks while others are not. To understand the cause of such difference, we show Δ v_CGM versus T_CGM(t_b), ρ_CGM(t_b) and r_{sh} in Figure 4. Here, Δ v_CGM is used to indicate the strength of the stripping. As one can see, the first population (with the most severe stripping effect) only has T_CGM(t_b) > 10^6K, ρ_CGM(t_b) < 3 × 10^4ρ_b, and r_{sh} < 1.2r_{200}. In some cases, the CGM gas is actually dominated by the extension of spiral arms of galaxies,
where the gas is dense and difficult to strip by the ram pressure. The dependence on $r_{sh}$ may reflect the fact that the stripping efficiency is related to the strength of shocks. It is expected that shocks at larger distances are weaker, as their density decreases.

Other environmental processes, such as tidal stripping, may also lead to similar results. To evaluate the contribution of tidal stripping, we examined the dark matter mass distribution around satellites, which is also affected by tidal force. We estimated the dark matter mass in a spherical shell with radius from $2r_e$ to $4r_e$. This mass is denoted as $M_{dm}$. We then used $\Delta \log M_{dm} = \log M_{dm}(t_a) - \log M_{dm}(t_b)$ to measure the effect of tidal stripping. We found that $\Delta \log M_{dm}$ is independent of $\Delta V_{CGM}$, $\Delta \rho_{CGM}$, and $T_{CGM}(t_a)$. Moreover, the median, 16 and 84 percents of the $\Delta \log M_{dm}$ distribution are -0.003, -0.028, and 0.028 dex respectively. These results indicate that tidal stripping is not important in the satellite galaxies considered here.

We also investigated the CGM on a larger scale, such as in the range of $[4r_e, 6r_e]$ and $[6r_e, 8r_e]$. The results are quite similar to those shown in Figure 3 and Figure 4, so we do not present them here. There are three small differences. The first is that, at scales larger than...
4\(r_e\), a considerable fraction of the CGM is affected by the cluster environment even before satellites cross the shock surface. Second, the CGM on these large scales is more easily affected by shocks than that in the inner region, as expected. Third, we found that the \(\Delta M_{\text{ISM}}\) distribution on these scales is broader than that for the inner region, indicating a more important role played by tidal stripping.

3.2. Stripping of ISM

![Figure 5](image.png)

**Fig. 5.**—Comparison of the ram pressures on ISM exerted by the surrounding gas at \(t_e\) and \(t_a\). The solid line shows the one-to-one relation and the dashed lines show 1 dex offsets from the solid line.

For our analysis, we define cold gas within 2\(r_e\) in a satellite galaxy as the ISM gas. Our tests show that before the shock crossing, the cold gas cells are closely attached to their host galaxies, with relative velocities close to the local rotational velocity. The ram pressure on the ISM is produced by its motion relative to the local ICM, and is estimated as

\[
P_{\text{rm}} = \rho v_{\text{ICM}}^2,
\]

where \(\rho_{\text{ICM}}\) and \(v_{\text{ICM}}\) are computed using gas cells in a half spherical shell (with a radius from 6 to 8\(r_e\)) in front of the galaxy moving in the ICM. This radius is chosen so that the ram pressure obtained is relevant to the ISM while the influence of any extended gas disk (see Figure 2) is reduced. We present the details of our method and additional tests in Appendix. Figure 5 compares the ram pressure before and after the shock crossing. Before shock crossing, the ram pressure is typically less than 10\(^{-12}\) dyn cm\(^{-2}\). At \(t > t_{\text{sh}}\), the ram pressure on most of the satellites becomes larger than that at \(t < t_{\text{sh}}\), and for some of them the increase is by one to three orders of magnitude. A large fraction of satellites have \(P_{\text{rm}} > 10^{-12}\) dyn cm\(^{-2}\) at \(t > t_{\text{sh}}\). Thus, ram pressure can play an important role in stripping the ISM (Boselli et al. 2022). We cannot see any significant dependence of the ram pressure enhancement on stellar mass of galaxies, but a clear dependence on \(r_{\text{sh}}\) can be seen. As shown in Figure 4, the CGM is affected significantly only at \(r_{\text{sh}} < 1.2R_{200}\). The change of ram pressure is thus expected to be smaller at the larger radius. After the CGM is stripped, its velocity increases while the density decreases (Figure 3). This implies that the boost of the ram pressure is mainly produced by the increase of the velocity of the gas.

We now investigate the impact of shock crossing on the ISM mass, \(M_{\text{ISM}}\). Only gas with \(\log T/K < 5\) is considered here. Figure 6 shows the change of the ISM mass, \(\Delta \log M_{\text{ISM}} = \log M_{\text{ISM}}(t_a) - \log M_{\text{ISM}}(t_e)\), versus the ram pressure at \(t_a\). For the 20 satellites that do not have cold ISM within 2\(r_e\) at \(t_a\), we set \(M_{\text{ISM}} = 1.4 \times 10^9 M_\odot\), the gas mass resolution of the TNG simulation. We use down-pointing arrows to indicate that the value plotted may represent an upper limit. One additional ShSAT has no ISM gas cell at both \(t_e\) and \(t_a\), and we show it as a dashed vertical line. Our inspection reveals that before interacting with the shock, the galaxy has already encountered a moving stream and has lost its ISM slowly since then. This is different from the other systems which lost their ISM quickly after interactions with a shock.

In Figure 6, one can see two distinct populations. The first population, consisting of 22 satellites, has a substantial ISM loss with \(\Delta \log M_{\text{ISM}} < -1.0\), and the other population has only small changes in the ISM mass, with \(\Delta \log M_{\text{ISM}} > -1.0\). Among the first population, 20 of the 22 satellites have no ISM gas at \(t_a\), indicating complete stripping of the ISM. At \(t_a\), the median \(M_{\text{ISM}}/M_\ast\) of the 20 satellites is approximately 0.10, and 10 of the 20 galaxies are on the star formation main sequence, with specific star formation rates larger than 10\(^{-10.5}\)/yr. Most of these galaxies have \(P_{\text{rm}} > 10^{-12}\) dyn cm\(^{-2}\) at \(t_a\). Consistent with the results of Boselli et al. (2022), this pressure can overcome the gravity of the galaxy and strip the ISM very effectively. A clear gap can be seen between the two populations in Figure 6, indicating that the timescale of ram pressure stripping is short so that only a small number of galaxies can be observed with parts of their ISM stripped. This is consistent with results of some previous studies, which found that the ISM can be severely stripped over a time scale of 0.1–0.5 Gyr as long as the ram pressure overcomes the gravity of the galaxy (e.g. Quilis et al. 2006; Marcolini et al. 2005; Tonnesen & Bryan 2009). Figure 2 shows the evolution of the gas density map in an example (Example one). Here one can see that the ISM is rapidly stripped after it crosses the shock surface. We also show the mass change of the ISM as a function of \(r_{\text{sh}}\) (right panel). As one can see, the first population has a very broad distribution in \(r_{\text{sh}}\), and so the stripping of ISM can sometimes be important even at large \(r_{\text{sh}}\). This is different from the predictions of conventional models of ram pressure stripping (e.g. Roberts et al. 2019; Boselli et al. 2022), in which the effect is expected to be important only for small \(r_{\text{sh}}\). For example, as shown in Boselli et al. (2022), the predicted stripping-radius for a galaxy with \(M_\ast = 10^{10.5} M_\odot\) in a cluster of \(10^{14} M_\odot\) is about 1.67\(r_e\) at \(R_{200}\) of the cluster, about \(r_{\text{sh}}\) at 0.5\(R_{200}\), and 0\(r_e\) at 0.2\(R_{200}\). We find two galaxies at \(r_{\text{sh}} > 1.2R_{200}\), which also have their ISM severely stripped. This seems to conflict with the CGM results, which showed that the CGM was not significantly affected at \(r_{\text{sh}} > 1.2R_{200}\). Our detailed inspection reveals that one of these two galaxies is massive, and its ISM is significantly influenced by internal processes, such as AGN feedback. The other one is a low-mass galaxy, which is stripped by a strong shock induced by a massive
merger with a mass ratio of 0.18. The latter case suggests that shocks induced by massive mergers can even strip a galaxy located outside the virial radius of its host cluster.

For the second population with small ISM loss, a trend also exists that $\Delta \log M_{\text{ISM}}$ decreases with increasing ram pressure. We used the Spearman rank correlation coefficient to evaluate the strength of the correlation. The correlation coefficient obtained is $\rho_s = -0.35$, with $P_{\text{null}} = 0.001$. For ShSATs with $r_{sh} < 1.2 R_{200}$, the correlation is stronger, with $\rho_s = -0.40$ and $P_{\text{null}} = 0.001$. The correlation for ShSATs with $r_{sh} > 1.2 R_{200}$ is almost zero. Apparently, ram pressure can also affect this population of galaxies, particularly those with $r_{sh} < 1.2 R_{200}$, although the stripping effect is much weaker than that for the first population.

There is a wide range of diversity among galaxies. Some are fully stripped by shock crossing, as shown by Example one in Figure 2, while others are affected only slightly, as shown by Examples two and three in Figure 2. As discussed in previous studies, effects of RPS depend not only on the density and velocity of the surrounding gas considered here, but also on many other factors (see e.g. Gunn & Gott 1972; Hester 2006; Bahé & McCarthy 2015; Boselli et al. 2022). For example, the orbital shapes, inclinations and intrinsic properties of satellite galaxies, as well as internal processes, such as feedback, can all affect the RPS efficiency, and can produce variances among individual galaxies in their suffering of the RPS.

Another important issue is whether or not these galaxies are also significantly affected by tidal stripping, instead of RPS. To check this, we examined the changes of the stellar mass ($M_*$) and dark matter mass $M_{\text{dm}}$ within $2r_e$. The assumption is that tidal stripping also affects stars and dark matter. We found that both $M_{\text{dm}}$ and $M_*$ remain almost constant from $t_0$ to $t_a$ for all galaxies in our sample. The median, 16 and 84 percentiles of the $\Delta \log M_{\text{dm}}$ distribution are -0.0023, 0.028, and 0.017 dex, respectively, while the values for the $\Delta \log M_*^5$ distribution are 0.0003, -0.0002 and 0.0019, respectively. These results suggest that tidal stripping may not be important for the loss of ISM on the scales interested in here, and are consistent with results obtained earlier (e.g., Bahé & McCarthy 2015).

Figure 7 shows the mass change of the cold ISM as a function of the halo-centric distance, $r/R_{200}$. Here, the mass change is defined as $\Delta \log M_{\text{ISM}}(r) = \log M_{\text{ISM}}(r) - \log M_{\text{ISM}}(1.5 R_{200})$. Here the results are presented in terms of the 16%, 50%, and 84% of the $\Delta \log M_{\text{ISM}}$ distribution. We only consider results before the satellite first reaches the pericenter of its orbit. After the pericenter, the distance increases with time and the change of ISM mass actually reflects the stripping effect at the pericenter, not at the current location. If the ISM gas of a satellite is completely stripped, we assign $M_{\text{ISM}} = 1.4 \times 10^6 M_\odot$, as we did in Figure 6. It is thus possible that the results sometimes only reflect upper limits. At $r > 0.8 R_{200}$, low-mass satellites show very small mass change. At $r \sim 0.8 R_{200}$, mass change becomes important for some galaxies, and about 25% of the galaxies have lost more than half of their ISM mass. The percentage of galaxies of more than half mass loss increases to $\sim 50%$ at $r = 0.5 R_{200}$. Almost no distance dependence of the mass change is observed for massive galaxies.

We can also investigate the timescale of RPS by shock crossing. Figure 8 shows the mass change of the cold ISM, $\Delta \log M_{\text{ISM}}(t) = \log M_{\text{ISM}}(t)/M_{\text{ISM}}(t_{sh})$, as a function of time ($\Delta t = t - t_{sh}$). Note that 5 ShSATs have lost all their ISM at $t_{sh}$ and are excluded from the analysis. Before $t_{sh}$, the environmental effect is very weak, and there is almost no time dependence of the mass loss for both low-mass and massive satellites. This result is consistent with the value of the ram pressure before $t_{sh}$ (Figure 5), which is generally lower than the typical value, $P_{\text{rm}} \sim 10^{-12}$ dyn cm$^{-2}$, required to overcome the gravity of satellites with $9 \leq \log(M_*/M_\odot) \leq 10$ (see figure 4 in Boselli et al. 2022). After $t_{sh}$, low-mass satellites show a quick decline in $M_{\text{ISM}}$. On average, about half of cold ISM is stripped on a timescale of 0.6 Gyr after interacting with the shock. About one Gyr after $t_{sh}$, sixty percent of the galaxies have lost $\sim 90\%$ of their ISM. Since we

\[ \Delta \log M_* = \log M_* (t_a) - \log M_* (t_0) \]
Fig. 7.—The upper panels show the cold ISM mass change as a function of the halo-centric distance and the lower panels show the results of CGM. The left panels are for low-mass galaxies while the right panels are for massive galaxies. The lines and shaded regions show the median, 16 and 84 percents of the distributions. The results for ShSATs and NsSATs are shown in blue and orange respectively. For each satellite, we only consider the data before the pericenters of its orbit. Please see the text for the details.

set the snapshot just before shock crossing as \( t_{sh} \) and the estimated timescale includes that for the stripping of the CGM, the timescale for ISM stripping may be significantly shorter than estimated here. The stripping effect for massive galaxies is generally weaker than that for low-mass galaxies. Only a few high-mass galaxies show a significant signature of ISM stripping one Gyr after \( t_{sh} \), likely because most of the massive galaxies have gravitational potential wells deep enough to withstand RPS. Detailed inspection shows that these galaxies are also affected by shocks, but the impact is weaker, as shown by Example three in Figure 2. In this particular case, the ram pressure compresses the CGM and enhances the ISM density within the galaxy, instead of stripping it.

3.3. Comparison between ShSATs and NsSATs

One important question is whether ShSATs are different from NsSATs in their CGM and ISM. Note that NsSATs are also moving in the ICM, although they have not interacted with a strong shock front, and so the comparison can provide information about the effects of RPS generated by shock crossing. Figure 7 shows the variation in CGM mass (\( \Delta \log M_{CGM} = \log M_{CGM}(r) - \log M_{CGM}(1.5R_{200}) \)) with halo-centric distance, \( r/R_{200} \). As before, the CGM mass is estimated using gas cells within a shell between \( 2 - 4 \ r_e \). Similar to the results for ISM, we only show results for satellites before they reach the pericenters of their orbits. We can see a weak but significant trend that the CGM mass decreases as satellites move toward the cluster center. This trend exists for both low-mass and massive galaxies, although it is weaker for the latter. The trend exists for both ShSATs and NsSATs. For low-mass galaxies, the trend for NsSATs is weaker than that for ShSATs. However, for massive galaxies, no significant difference is found between the two populations, probably because the sample is too small.

In Figure 7, we also show the variation in ISM mass as a function of \( r \) for NsSATs in comparison with ShSATs. For low-mass NsSATs, there is almost no radial dependence, and most of the ISM can remain as long as \( r > 0.5R_{200} \). When satellites move to the inner region
of the cluster ($r < 0.5R_{200}$), the ISM stripping starts to become important. Again massive galaxies show almost no dependence on $r/R_{200}$ in both the inner and outer regions of the clusters. Note that we do not consider the evolution after the pericenter, where a significant ISM loss exists for both ShSATs and NsSATs. As discussed in section 3.2, ShSATs can be stripped significantly at $r \sim 0.8R_{200}$, much more effectively than NsSATs, demonstrating that shocks can significantly enhance the RPS of the ISM, particularly for low-mass galaxies.

In the previous section, we discussed $\Delta \log M_{\text{ISM}}$ as a function of $t - t_{\text{sh}}$ for ShSATs. For comparison, we also show this dependence for NsSATs. Unfortunately, NsSATs do not have a reference time, such as $t_{\text{sh}}$. We thus design a control NsSAT sample as follows. For a given ShSAT with $r_{\text{sh}}$, we first search for NsSATs with a mass similar to the ShSAT (with difference in $M_*$ less than 0.1 dex). From these mass-matched galaxies, we randomly select one NsSAT whose halo-centric distance has reached $r_{\text{sh}}/R_{200}$ of the ShSAT at $z \leq 0.11$. The selected NsSAT is referred to as the control galaxy for the ShSAT. We match both $M_*$ and halo-centric distance to eliminate potential dependencies of the gas mass on these two quantities. The time when the control galaxy first reaches $r_{\text{sh}}/R_{200}$ is defined as the reference time for the control galaxy, and we denote as $t_{\text{ns}}$. We calculate $t_{\text{ns}}$, $M_{\text{CGM}}(t_{\text{ns}})$, and $M_{\text{ISM}}(t_{\text{ns}})$ by using a linear interpolation between the two adjacent snapshots.

Figure 8 shows $\Delta \log M_{\text{CGM}}$ and $\Delta \log M_{\text{ISM}}$ as functions of $\Delta t = t - t_{\text{ref}}$, where $t_{\text{ref}} = t_{\text{sh}}$ for ShSATs and $t_{\text{ref}} = t_{\text{ns}}$ for the control sample of galaxies. Here, $\Delta \log M_{\text{CGM}}(t) = \log M_{\text{CGM}}(t) - \log M_{\text{CGM}}(t_{\text{ref}})$ and $\Delta \log M_{\text{ISM}}(t) = \log M_{\text{ISM}}(t) - \log M_{\text{ISM}}(t_{\text{ref}})$. Note that there are 4 ShSATs for which we do not find control galaxies. Our tests show that excluding the four ShSATs does not change the results significantly; we include them when showing results for ShSATs.

We first examine the CGM evolution. For low-mass ShSATs, there is a weak trend of CGM mass loss at
shocks. The mass loss is in good agreement with that for the control sample at \( t < t_{sh} \). The mass loss is in good agreement with that for the control sample at \( t < t_{sh} \). The mass loss is in good agreement with that for the control sample at \( t < t_{sh} \). The mass loss is in good agreement with that for the control sample at \( t < t_{sh} \). At \( t > t_{sh} \), the slope of the \( M_{CGM} \) curve for ShSATs becomes steeper, suggesting that the interaction with shocks enhances the RPS of CGM. However, the slope for the control sample does not change with time. The difference leads to a significant deviation between ShSATs and NsSATs at \( \Delta t > 0 \). For massive galaxies, however, we see quite different results. At \( \Delta t < 0 \), there is a significant difference between the two samples, while at \( \Delta t > 0 \), the difference becomes weaker. It is unclear whether this reflects the effect of some underlying physical processes or it is due to the small sample size (Table 1).

A similar but much stronger difference can be found in the evolution of the ISM. For both the low-mass and massive galaxies in the control sample, the median ISM loss usually varies slowly with time. Only a small fraction of the low-mass NsSATs have prominent ISM loss about one Gyr after the reference time. This is broadly consistent with the radial dependence shown in Figure 7. In contrast, ShSATs lose their ISM rapidly after the reference time. These results suggest that after shock crossing, ShSATs are much more affected by RPS than they are before the shock crossing and than NsSATs.

4. SUMMARY AND DISCUSSION

In this work, we use the IllustrisTNG simulation to study the interaction of large-scale shocks with satellites in galaxy clusters at \( z \sim 0 \). The large-scale shocks induced by mergers and accretion of gas from massive filaments are common in the local universe. Since shock fronts are sharp in the TNG simulation, we can visually identify satellite galaxies that have crossed strong shocks. Approximately half of star-forming satellites with \( \log(M_*/M_\odot) \geq 9.0 \) have encountered the shocks when they move in galaxy clusters. These satellites are referred to as ShSATs. Satellites that have not interacted with a strong shock are referred to as NsSATs. We analyze shock-induced ram pressure stripping (RPS) and other effects on satellite galaxies in clusters of galaxies.

We trace the evolution of the CGM and ISM of the ShSATs and compare them with the NsSATs. After shock crossing, the CGM of ShSATs can be strongly impacted. In some satellites, the cold and dense CGM is completely replaced by the hot and diffuse ICM after shock crossing. In others, the CGM is not affected significantly, and in some cases is even compressed by the shock. After entering the post-shock region, the ram pressure on the ISM is strongly enhanced in some satellites. For satellites with \( P_{\text{ram}} > 10^{-12} \text{dyn cm}^{-2} \), the ram pressure can overcome gravity and effectively strip the ISM, particularly for low-mass galaxies with \( \log(M_*/M_\odot) < 10 \). A significant fraction (50%) of the ISM can be removed shortly after the interaction with shocks (less than 0.6 Gyr). Sometimes severe stripping of the ISM can occur even in the outskirts of galaxy clusters because of the enhancement of ram pressure by shocks. The RPS in NsSATs is much weaker than that in ShSATs. Only in the inner region of galaxy clusters can the ISM of NsSATs be affected significantly.

Our results suggest that the interaction with large-scale strong shocks can enhance RPS. Shocks can accelerate the ICM gas and enhance its density, both increasing the ram pressure. Given that a large fraction of satellites have interacted with shocks and shocks can affect the properties of the CGM and ISM, shocks may play an important role in the evolution of satellite galaxies, particularly in galaxy clusters, where the ICM is dense, merger driven shocks are abundant, and member galaxies are moving at high speeds. Our results further suggest that the conventional model, in which the ICM is assumed to be static, is inappropriate for modeling the evolution of satellite galaxies.

As we have shown, shock-induced RPS is quite common in present-day clusters of galaxies. This may explain that many satellites in the outskirts of galaxy clusters show tail-like structure in their cold gas distribution. In contrast, the RPS by a static and smooth ICM is expected to be effective only in the inner regions of clusters. Our results also suggest that a large fraction of low-mass satellites can lose their CGM and ISM after the emergence of large-scale shocks. Thus, the quenching of star formation of satellite galaxies may follow massive mergers that drive large-scale shocks. Since large-scale shocks are usually anisotropic, the shock-induced RPS may lead to an anisotropic distribution of star-forming and quenched populations in clusters. The shock-induced RPS may also impact central galaxies if they are swept by shock fronts.

The sample used in this paper is limited by the volume of the simulation and by the visual identification used to identify shock fronts. A large sample with more objective selection criteria is needed to carry out a detailed investigation of the impact of large-scale shocks on galaxies and its dependence on the properties of shocks and the impacted galaxies themselves. We will come back to some of these questions in the future.

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APPENDIX

In this Appendix, we present details of our method for calculating the ram pressure on the ISM of a satellite produced by its surrounding ICM. According to Equation 1, we need both the density ($\rho_{\text{ICM}}$) and relative velocity ($v_{\text{ICM}}$) of the surrounding ICM. For a given satellite, we first select all gas cells in a spherical shell with a given thickness. We then calculate the mean velocity of the gas shell relative to the satellite. Using the velocity vector so obtained, we determine the half spherical shell in front of the satellite. Finally, we use the gas cells within this half spherical shell to calculate $\rho_{\text{ICM}}$ and $v_{\text{ICM}}$.

One uncertainty in calculating the ram pressure is the radius of the spherical shell adopted for the calculation. If the radius is chosen to be too small, the density and velocity obtained may be affected significantly by the CGM and the ICM. On the other hand, if the radius is chosen to be too large, the estimated ram pressure may not represent well that on the ISM of the satellite. In order to find an appropriate scale, we perform tests using four different choices for the radius, ranging from $r \sim 3r_e$ to $r \sim 9r_e$. In Figure 9 we compare the $P_{\text{rm}}$ obtained using $r \sim 9r_e$ (vertical axis) with those obtained using smaller $r$. Note that the ram pressure at $t_a$ and $t_b$ are both presented using different symbols.

Before analyzing these results, we emphasize that the density and velocity of the original CGM bound to a galaxy varies significantly with the distance to the galaxy, while the ICM properties are expected to be independent of the distance to the galaxy. Thus, if the gas contents of two different shells are both dominated by the ICM, the values of the ram pressure obtained from the two shells should be similar. On the other hand, if the gas contents of the two

\begin{align*}
\text{Shocks and Stripping} & 13
\end{align*}
Fig. 9.— The three panels show the ram pressure calculated using the gas cells at 8–10 $r_e$ versus those at 2–4 $r_e$ (left), 4–6 $r_e$ (middle) and 6–8 $r_e$ (right), respectively. The red and blue dots show the results at $t_a$ and $t_b$, respectively. The solid lines show the one-to-one relation.

Shells are dominated by different components or both dominated by CGM, we should expect no correlation or a biased correlation between the values of their ram pressure.

As one can see from Figure 9, $P_{rm}(8–10r_e)$ and $P_{rm}(6–8r_e)$ are tightly correlated for both $t_a$ and $t_b$, and the values of the ram pressure estimated from the two shells are nearly the same. This suggests that at $r > 6r_e$ the gas is dominated by the ICM. As $r$ decreases, the difference becomes larger and the correlation becomes much looser, indicating that the estimate of the ram pressure at smaller $r$ is significantly affected by the CGM. The difference is more significant for $t_b$ than for $t_a$, and at lower $P_{rm}$. This is expected because the medium at $t_b$ or low $P_{rm}$ is more likely dominated by the original CGM. These tests show that our choice of $r = (6–8)r_e$ is appropriate for estimating the ram pressure from the ICM.