Cosmological Simulation of Galaxy Groups and Clusters. II. Studying Different Modes of Feedback through X-Ray Observations

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Abstract

The impact of feedback from active galactic nuclei (AGNs) on the cosmological evolution of the large-scale structure is a long-studied problem. However, it is still not well understood how the feedback energy couples to the ambient medium to influence the properties of AGN host galaxies and dark matter halos. In this work we investigate different modes of AGN feedback and their effect on the surrounding medium by probing the diffuse X-ray emission from the hot gas inside galaxy groups and clusters. For this purpose, we use the cosmological hydrodynamic simulation SIMBA to theoretically calculate the X-ray emission from simulated galaxy clusters/groups with the help of the Astrophysical Plasma Emission Code. We also perform synthetic observations of these systems with the Chandra X-ray telescope using the ray-tracing simulator Model of AXAF Response to X-rays.

Our results show that in addition to the radiative wind mode of feedback from the AGNs, jet and X-ray modes of feedback play significant roles in suppressing the X-ray emission from the diffuse gas in the vicinity of the black hole. Our mock observational maps suggest that the signatures of AGN feedback from high-redshift objects may not be detected with the instrumental resolution of current X-ray telescopes like Chandra, but provide promising prospects for detection of these features with potential X-ray missions such as Lynx.

Unified Astronomy Thesaurus concepts: Active galactic nuclei (16); Galaxy clusters (584); X-ray telescopes (1825)

1. Introduction

The existence of supermassive black holes (SMBHs) at the centers of massive galaxies in the universe has been widely established in the literature in the past few decades (e.g., Soltan 1982; Eckart & Genzel 1996; Ghez et al. 1998; Event Horizon Telescope Collaboration et al. 2019). Enormous amounts of energy released by a fraction of the SMBH population, in the form of radiative winds, energetic jets, and other mechanisms (Fabian 2012; King & Pounds 2015; Harrison et al. 2018; Roy et al. 2021), influence several properties of the SMBH host galaxies (e.g., Dressler & Richstone 1988; Kauffmann & Haehnelt 2000; Ferrarese & Merritt 2000; Gebhardt et al. 2000; Graham et al. 2001; H"aring & Rix 2004; Cattaneo et al. 2009; Kormendy & Ho 2013; Salvadori et al. 2015; Fiore et al. 2017; Mutlu-Pakdil et al. 2018; Schutte et al. 2019; de Nicola et al. 2019; Marsden et al. 2020). Some of the other signatures of AGN feedback involve: a reduced star formation rate in host galaxies (e.g., Vitale et al. 2013; Costa et al. 2015; Harrison 2017), the absence of cooling flows (e.g., David et al. 2001; Peterson et al. 2003), or the change in slope of the $L_\text{X} - T$ relation in galaxy clusters and groups (e.g., Andersson et al. 2009; Maughan et al. 2012; Molham et al. 2020). Despite these series of observational results, a full theoretical understanding of how the energy released from the black hole couples to its surrounding medium, a phenomenon termed active galactic nuclei (AGN) feedback, is yet to arise (e.g., Silk & Rees 1998; Nath & Roychowdhury 2002; Fabian 2012; Li et al. 2018; Heinrich et al. 2021).

One of the most efficient processes for detecting AGN feedback is X-ray observations of the diffuse gas inside galaxy groups and clusters (e.g., Wise et al. 2007; McNamara & Nulsen 2007, 2012; Gitti et al. 2012; Fabian 2012; Pandge et al. 2019; Eckert et al. 2021). Energetic outflows from AGNs are believed to remove the diffuse X-ray-emitting gas from their vicinity, creating regions that are underluminous in X-rays (Gitti et al. 2010; David et al. 2011). This signature has also been observed in the X-ray surface brightness profiles of the gas surrounding the AGNs in galaxy groups and clusters (Chatterjee et al. 2015; Mukherjee et al. 2019), but systematic effects need to be characterized to properly exploit the significance of the results. To understand the role of AGN feedback in the cosmological context a series of subgrid models of SMBH growth and AGN feedback, which are motivated by observational constraints, have been explored in the literature (e.g., Di Matteo et al. 2005, 2008; Booth & Schaye 2009; Thacker et al. 2006; Sijacki et al. 2007, 2015; Dubois et al. 2012; Barai et al. 2014; Taylor & Kobayashi 2015; Weinberger et al. 2017; Davé et al. 2019; Kar Chowdhury et al. 2020; Chadayammuri et al. 2021; Koudmani et al. 2021; Habouzit et al. 2022; Irodotu et al. 2022).

Our work is focused on investigating the phenomenon of AGN feedback in more detail by looking at different modes of feedback from the AGNs modeled in cosmological simulations as well as carrying out synthetic observations of these systems. One of the motivations behind the synthetic observations lies in a realistic comparison of the feedback models with actual observational results found in the literature. We begin by modeling diffuse X-ray emission from the simulated galaxy groups and clusters with the help of the Astrophysical Plasma
Emission Code (APEC: Smith et al. 2001), then we perform the synthetic observations of the statistical sample of galaxy clusters in the simulation with the Chandra X-ray telescope using the photon simulator, namely the Model of AXAF Response to X-rays (MARX: Davis et al. 2012).

We follow the mock observation technique of the Chandra X-ray telescope proposed by Kar Chowdhury et al. (2021, hereafter D21) using the cosmological simulation by Davé et al. (2019, SIMBA). SIMBA is one of the best state-of-the-art high-resolution cosmological volume simulations and includes sophisticated modeling of black hole accretion and feedback from the AGNs. This simulation takes into account three different modes of AGN feedback, which are wind, jets, and—for the first time in the literature—the X-ray mode of feedback (Choi et al. 2012), in which the feedback due to X-ray emission from the accretion disks of black holes is included in the simulation. Most other simulations consider either radiative feedback (Di Matteo et al. 2005; Booth & Schaye 2009), kinetic feedback (Thacker et al. 2006; Barai et al. 2014), or a combination thereof (Dubois et al. 2012; Weinberger et al. 2017). In addition to incorporating a detailed modeling of AGN feedback, SIMBA also implements a rigorous black hole accretion process by considering the torque-limited accretion model (Hopkins & Quataert 2011; Anglés-Alcázar et al. 2013, 2015, 2017) along with the Bondi model (Bondi & Hoyle 1944; Bondi 1952). Another advantage of using SIMBA is its metal enrichment model, which tracks a number of metal elements in the simulation that are essential for calculating the X-ray flux in galaxy clusters.

In this paper we try to examine the impact of feedback from AGNs on their surrounding medium by studying diffuse X-ray emission coming from the simulated galaxy groups and clusters using theoretical models as well as synthetic X-ray observations. Apart from this central goal, this paper also aims to study the robustness of the synthetic observation technique proposed by R21. The method was primarily developed in R21 using the cosmological simulation performed by Di Matteo et al. (2008, hereafter D08). However, it is important to test the technique with another cosmological simulation to establish its fidelity; this has been carried out in the current work using SIMBA. Results from this study are consistent with R21, showing that the synthetic observation technique is broadly applicable and does not depend on particular simulation parameters. Besides, we find that feedback from the AGNs is responsible in evacuating diffuse X-ray-emitting gas from their vicinity, consistent with previous studies (e.g., Mukherjee et al. 2019; Robson & Davé 2020; Kar Chowdhury et al. 2020, 2021). We also show that radiative wind feedback alone is not sufficient to evacuate hot gas from the vicinity of the AGNs. Jet and X-ray modes of feedback play important roles in this regard, supporting previous studies (e.g., Choi et al. 2015).

We find that with the resolution limit of the Chandra telescope, differences in the X-ray surface brightness in the presence and absence of feedback cannot be resolved in a few central pixels for high-redshift objects, while a clear difference can be observed for objects at low redshift. Our study thus creates an avenue to examine the possibility of detecting these phenomena at a range of redshifts with current as well as potential future missions such as Lynx (Gaskin et al. 2017). The paper is organized as follows. In Section 2, we discuss the cosmological simulation used in this work and theoretical modeling of X-ray emission, as well as briefly mentioning the synthetic observation technique. In Section 3, we present and discuss the results obtained from this work. Finally, in Section 4, we summarize the work presented in this paper.

2. Simulation

As mentioned before, we have used one of the most updated cosmological simulations, SIMBA (Davé et al. 2019), which includes hydrodynamics, dark matter dynamics, and radiative cooling as well as star formation and the associated feedback along with accretion and feedback from black holes for modeling the X-ray emission in groups and clusters. SIMBA uses the meshless finite mass technique introduced in GIZMO code (Hopkins 2015, 2017) as the hydrodynamics solver and the tree–particle mesh approach described in GADGET-2 code (Springel 2005) for the gravity solver. Photoionization heating and radiative cooling are incorporated in the simulation with the help of the GRACKLE-3.1 library (Smith et al. 2017). A subgrid $H_2$-based model (Krumholz & Gnedin 2011) has been followed for calculating the star formation rates. Various elements (H, He, C, N, O, Ne, Mg, Si, S, Ca, Fe) are considered to be produced from Type II and Type Ia supernovae as well as from the asymptotic giant branch stars.

SIMBA employs one of the most updated models of black hole accretion and the associated feedback from the AGNs. Most previous cosmological simulations use spherical Bondi parameterization to model the accretion of the black holes (Bondi & Hoyle 1944; Bondi 1952), in which black holes are assumed to self-regulate their own growth through AGN feedback, after reaching a threshold mass (Di Matteo et al. 2005; Hopkins et al. 2006; Sijacki et al. 2007, 2015; Booth & Schaye 2009; Choi et al. 2012; Steinborn et al. 2015). At this stage, gas surrounding the black holes is heated to a high temperature or expelled, halting further accretion. However, despite the feedback effect, the limiting factor of black hole growth might depend on the inflow of gas and the rate at which angular momentum is transferred by gravitational torque in galactic disks (Anglés-Alcázar et al. 2017). Hence it is important to include an updated model of the inflowing gas in the cosmological simulation.

SIMBA considers the physically motivated angular momentum transport model during the accretion of gas onto the black hole from the inner galactic disk (Hopkins & Quataert 2011; Anglés-Alcázar et al. 2013, 2015, 2017). This torque-limited accretion model is applied to the cold gas ($T > 10^5$K), whereas Bondi accretion is considered for the hot gas ($T > 10^5$K) as they are prone to a spherical geometry. Black holes are seeded in the galaxies on-the-fly in SIMBA using a friends-of-friends algorithm. If a galaxy exceeds a certain critical stellar mass but does not host a black hole, then the star particle nearest to the center of mass of that galaxy is converted to a seed black hole. Galaxies having threshold mass $\geq 10^{9.5} M_\odot$ are populated with an initial black hole of mass $10^5 h^{-1} M_\odot$.

SIMBA incorporates a novel subgrid technique for feedback from the black hole that includes three different modes of AGN feedback, i.e., radiative winds, collimated jets, and—for the first time in cosmological simulations—the X-ray mode of feedback. Kinetic feedback is implemented in SIMBA to model the jet mode as well as the effect of radiative feedback in terms of energetic winds. Outflows from black holes with high Eddington ratios are modeled based on the observations by Perna et al. (2017). The outflow
velocity is parameterized in terms of black hole mass and is given by

\[ v_{\text{wind}} = \frac{500 + 500(\log M_{\text{BH}} - 6)}{3} \text{ km s}^{-1}, \]

where \( M_{\text{BH}} \) is the mass of the black hole in solar masses and \( v_{\text{wind}} \) is the wind velocity that results from the radiative feedback.

For AGNs having Eddington ratio \( f_{\text{edd}} \leq 0.2 \), the jet mode of feedback sets in, in which the velocity is modeled as

\[ v_{\text{jet}} = v_{\text{wind}} + 7000 \log(0.2/f_{\text{edd}}) \text{ km s}^{-1}. \]

Thus jet feedback is assumed to induce an additional velocity, which is capped to a maximum value of 7000 km s\(^{-1}\), achieved at \( f_{\text{edd}} \sim 0.02 \).

In addition to the feedback in the form of radiative winds and jets, SIMBA also incorporates the feedback due to the photoionization heating from the X-ray photons coming from the accretion disk of the AGN (Choi et al. 2012). The volume heating rate caused by the X-ray photons is calculated following the prescription of Choi et al. (2012) and the heat is distributed to the gas particles that are closer than a specific distance from the black hole determined by the accretion kernel. In this mode of feedback, gas that is not part of the interstellar medium (ISM) is thermally heated to a high temperature, while for the ISM gas half of the energy is applied kinetically and the rest is transferred as heat. We refer the reader to Davé et al. (2019) for a comprehensive discussion of the subgrid model for black hole accretion and feedback employed in SIMBA.

SIMBA is one of the largest cosmological simulations run, with a box size of 100 h\(^{-1}\) Mpc that provides extremely high resolution as well. It has also been run with a smaller volume (50 h\(^{-1}\) Mpc) in which different modes of AGN feedback have been explored. In addition to the scenario in which all the feedback modes mentioned before are included, a mode of no feedback from the AGN is included in the simulation. SIMBA has also been run in the “NoJet” and “NoX” modes. The jet mode of feedback is deactivated in the “NoJet” mode while both the X-ray and jet modes are turned off in the “NoX” mode while running the simulation. All the runs have the same initial conditions and use the same cosmology adapted from Planck Collaboration et al. (2016). Parameters of the simulation runs are shown in Table 1.

### Table 1

| \( L_{\text{box}} \) (h\(^{-1}\) Mpc) | \( N_p \) | \( m_{\text{gas}} \) (M\(_{\odot}\)) | \( m_{\text{DM}} \) (M\(_{\odot}\)) | \( \epsilon \) (h\(^{-1}\) kpc) |
|----------------|--------|----------------|----------------|--------|
| 100            | \( 2 \times 10^{24} \) | \( 1.82 \times 10^5 \) | \( 9.6 \times 10^5 \) | 0.5 |
| 50             | \( 2 \times 51^{24} \) | \( 2.28 \times 10^6 \) | \( 1.2 \times 10^7 \) | 0.25 |

Note. \( N_p \) denotes total number of gas and dark matter particles in the simulation. \( m_{\text{gas}} \) and \( m_{\text{DM}} \) denote the initial mass resolution of gas and dark matter particles respectively in different runs of SIMBA. \( \epsilon \) represents the gravitational softening length, which in turn indicates the maximum resolution of the simulation.

The X-ray surface brightness thus obtained is then smoothed according to the common B2 smoothing spline (Dolag et al. 2008) given by

\[ W(r, h) = \frac{\sigma}{h^\nu} \begin{cases} 
1 - 6 \left( \frac{r}{h} \right)^2 + 6 \left( \frac{r}{h} \right)^3, & 0 \leq \frac{r}{h} < 0.5 \\
2 \left( 1 - \frac{r}{h} \right)^3, & 0.5 \leq \frac{r}{h} < 1.0 \\
0, & 1.0 \leq \frac{r}{h} 
\end{cases} \]

where \( \nu \) is the dimension of the simulation and its value is chosen to be 3, \( h \) is the smoothing length, taken from the simulation at the position of each gas particle, and \( \sigma \) is the normalization, whose value is fixed at 7\( \pi/8 \). Using this, we generate theoretical X-ray maps of diffuse gas around each SMBH with different modes of feedback within a region of 50 kpc radius. Examples of these are shown in Figures 1 and 2 and discussed in detail in Section 3. It should be mentioned here that the X-ray emission from the AGN itself has not been modeled in this work. As we are focusing on the diffuse emission surrounding the AGN, the signal from the AGN would have the potential to contaminate this (Chatterjee et al. 2015). This is discussed again in Section 3.

#### 2.2. Synthetic Observation

In order to make realistic comparison with actual observations and investigate the detection probability of the telescope involved in X-ray observation, we aim to convolve the theoretical X-ray maps with the telescope response functions. For that we have performed synthetic observations with the Chandra X-ray telescope using the photon simulator MARX (Davis et al. 2012). We refer the reader to R21 for a detailed discussion on MARX and the performance of synthetic observations with it. Here we briefly mention the key characteristics of MARX. It is a ray-tracing simulator of the on board Chandra X-ray telescope that minutely tracks all the phases of individual photons from distant sources. MARX simulates the photons that are incident on
the high-resolution mirror assembly, pass through the diffraction grating, and are finally detected by the detector. Detailed physics of all the integrated instruments of the telescope is also incorporated in MARX.

We consider diffuse emission from the simulated galaxy clusters as the source while performing the synthetic observation using MARX. All the observations are done in the 0.5–2 keV energy band using the ACIS-I detector of Chandra for 200 ks
exposure time. We have considered the default value of the TSTART parameter of MARX, which is 2009.5 for all the synthetic observations performed in this work. Example mock X-ray maps at \( z = 1 \) and \( z = 0.016 \) are shown in Figures 6 and 7, respectively. Details of these figures are discussed in the next section.

3. Results and Discussions

In this work, we focus on the impact of the feedback from the AGNs on their surrounding medium by investigating the X-ray emission from the diffuse gas inside galaxy groups and clusters. For that, we first theoretically model the diffuse X-ray
emission from the simulated groups and clusters at two different redshifts ($z = 1$ and 0.016) in SIMBA as discussed in Section 2.1.

3.1. Theoretical X-Ray Maps

We have selected central black holes with mass $> 10^7 h^{-1} M_\odot$ inside a host dark matter halo of mass $> 10^{12} h^{-1} M_\odot$ from SIMBA for the purpose of this work. The choice of these systems is motivated mainly by the effect of mass resolutions in our simulation. Readers are referred to Kar Chowdhury et al. (2020) for a detailed discussion of the selection criteria. Systems with different feedback modes at different redshifts have been selected by tracking their host dark matter halos. Figures 1 and 2 show examples of the theoretical X-ray maps of four companion systems that have four different modes of AGN feedback at $z = 1$ and $z = 0.016$ respectively. X-ray emission from the hot and diffuse gas around the black holes within regions of radii $50 h^{-1}$ kpc has been calculated using APEC as discussed in Section 2.1. As mentioned earlier, X-ray emission from the AGN has been excluded from our analysis. In both figures, the top left panel shows the X-ray map in the presence of all the feedback modes (radiative wind + jet + X-ray), the top right panel represents the scenario when X-ray feedback is absent, the bottom left panel is representative of the situation when only radiative wind feedback is active, and the bottom right panel shows the X-ray maps when no AGN feedback is included in the simulation. The color code denotes the X-ray surface brightness in units of erg cm$^{-2}$ s$^{-1}$ in both figures. It can be seen from both figures that inclusion of all the feedback modes from AGNs disperses the surrounding gas, resulting in a lower X-ray emission at the center than in the simulation where no feedback from the AGN is included.

3.2. Profiles

To investigate this phenomenon in more detail, we aim to statistically study the signature of different modes of feedback on their surrounding diffuse X-ray emission at different redshifts. Hence, we select all the systems above the threshold mass mentioned earlier ($M_{BH} > 10^7 h^{-1} M_\odot$, $M_{halo} > 10^{12} h^{-1} M_\odot$) from simulation runs of SIMBA with various feedback modes and we model X-ray emission from the diffuse gas surrounding them within a region of radius $50 h^{-1}$ kpc. Figure 3 shows the distribution of characteristic mass ($M_{500}$) and radius ($r_{500}$) of the host halo of the systems that satisfy our selection criteria. We note an abundance of massive halos at lower redshift compared to $z = 1$. Figure 4 shows the radial profiles of the stacked X-ray surface brightness obtained theoretically at $z = 1$ (left panel) and $z = 0.016$ (right panel) for scenarios with different AGN feedback modes. Stacking has been done by taking the average of the surface brightness of all systems.

Both panels of Figure 4 show that the X-ray surface brightness is significantly lower in the central region when all the feedback modes are included in the simulation at both high and low redshifts. Besides, it can also be seen that although the radiative wind mode alone is not sufficient to suppress the X-ray emission at the center, the inclusion of jet and X-ray feedback removes a large amount of the X-ray-emitting gas from the vicinity of the AGN, thereby reducing the X-ray surface brightness at the center. The minor impact of radiative wind mode feedback on the X-ray surface brightness profile is a consequence of the AGN feedback model incorporated in SIMBA. It relies on a fixed momentum input, which results in insufficient energy injection in the presence of the radiative wind described by Equation (1). We refer to Davé et al. (2019) for a thorough discussion on this. However, it can be mentioned here that the wind power in SIMBA is weak and could have underestimated the wind feedback (Proga et al. 2000). Interestingly, Figure 4 shows an overall suppression of the X-ray surface brightness, mainly driven by adding the jet mode, whereas inclusion of the X-ray mode in addition to the jet feedback leads to a suppression of the diffuse emission at smaller scales. This is anticipated because X-ray feedback is more dominant in the vicinity of the black hole. We also observe similar effects in the Sunyaev–Zeldovich profiles of similar systems (A. Chakraborty et al., 2022, in preparation).

By comparing the two panels of Figure 4, we observe that emitted X-ray flux diminishes at lower redshift. We explain this as a consequence of the higher gas density inside the high-redshift halos that is the dominating factor in calculating X-ray emission in galaxy groups and clusters (Sarazin 1988; Böhringer & Werner 2010). In addition to this, the presence of all the AGN feedback modes evacuates the gas particles from the vicinity of the black holes, leading to the suppression of emission in the central region. This is also reflected in the radial profile of the gas density in the presence of different feedback modes as discussed next.

Along with the stacked X-ray surface brightness profiles for different feedback modes at two redshifts, we have also studied smoothed density, temperature, entropy, and pressure profiles of the same systems, shown respectively from top to bottom panels in Figure 5. Left and right panels represent the profiles at $z = 1$ and $z = 0.016$ respectively. All the panels follow the same color scheme as Figure 4. Entropy is defined as $K = k_B T/n_e^{2/3}$ (Voit 2005). This is normalized to the value of $K_{500}$ in order to incorporate the mass distribution of galaxy groups and clusters in the entropy profile, which is adopted from Nagai et al. (2007):

$$K_{500} = 1963 \left(\frac{M_{500}}{10^{15} h^{-1} M_\odot}\right)^{2/3} E(z)^{-2/3} \text{keV cm}^2,$$

where $M_{500}$ is the total mass within the radius $r_{500}$ and $E^2(z) = \Omega_m (1 + z)^3 + \Omega_\Lambda$, calculated based on the cosmological parameters used in SIMBA. Pressure is defined as $P = k_B n_e T$, which is again normalized to $P_{500}$ following Nagai et al. (2007):

$$P_{500} = 1.45 \times 10^{-11} \left(\frac{M_{500}}{10^{15} h^{-1} M_\odot}\right)^{2/3} E(z)^{8/3} \text{erg cm}^{-3}.$$

Stacked profiles are obtained by first calculating the profiles of each system normalized to the respective $r_{500}$ value and finally taking the average of profiles of all the systems. Density profiles in Figure 5 at both redshifts indicate a suppression at the center in the presence of jet and X-ray modes of feedback. This is in accordance with many previous works using different cosmological simulations where a lower gas density was obtained in the presence of feedback from AGNs than in the no-feedback scenario (Gaspari et al. 2011; Le Brun et al. 2014; Correa et al. 2018; Kar Chowdhury et al. 2020). Comparing the density profiles at two redshifts, it can be seen that suppression of gas density at low redshift is greater at the center in the presence of jet (blue stars) and X-ray (red dots).
modes of feedback than in the cases of no feedback (green crosses) and radiative wind feedback (black diamonds), supporting our previous claim. This is in accordance with the results obtained using the SIMBA data in previous works (Robson & Davé 2020, 2021). From the temperature profiles (second row in Figure 5), it is seen that the temperature of the gas in the presence of jet and X-ray feedback modes is lower than without feedback. However, it is higher in the radiative mode, and as reported by Davé et al. (2019), it seems to be more prominent in lower-mass halos. Similar results have been reported by Robson & Davé (2021), where they have looked at the redshift evolution of the profiles in different halo mass bins using SIMBA data. This result is in agreement with Kar Chowdhury et al. (2020), who use the D08 simulation; the model for AGN feedback in D08 is equivalent to that of the “radiative wind” mode.

We also compare the radial profiles with the observations in order to understand the feasibility of using the X-ray properties of SIMBA galaxy groups and clusters to make observational predictions. Density and pressure profiles (top and bottom rows of Figure 5 respectively) show reasonable agreement with profiles of radial density (Croston et al. 2008) and pressure (Arnaud et al. 2010) of the galaxy cluster sample from the representative XMM-Newton cluster structure survey (REXCESS) (Böhringer et al. 2007). Entropy profiles of the galaxy clusters have also been studied with the REXCESS sample (Pratt et al. 2010). Sun et al. (2009) studied the entropy profiles of galaxy groups using the Chandra archival data. Compared to both of these works, the entropy profiles shown in Figure 5 (third row) are fairly flat at both redshifts over the spatial scale we are interested in. However, the entropy profiles are in agreement with those obtained by Robson & Davé (2020) using SIMBA runs for different feedback modes. We note that the observed entropy profiles show a shallower slope in the very central regions. Pratt et al. (2010) have discussed that the entropy slopes are shallower in low-mass systems of their sample, because non-gravitational interactions are more dominant in lower-mass halos. Thus, we understand that the flat nature of the stacked radial entropy profile in Figure 5 is likely to be a manifestation of the low-mass halos present in our sample as seen from the characteristic mass distribution in Figure 3.

Moreover, in a recent study Ghirardini et al. (2019) looked into the thermodynamical properties of 12 galaxy clusters taken from the XMM Cluster Outskirts Project. Pressure and density profiles of this sample are in agreement with our results. They
have also found a significant flattening of the entropy profiles from their sample, consistent with the results of this work. This has been confirmed again by Zhu et al. (2021), who studied the entropy profiles of 47 galaxy groups and clusters observed with different X-ray telescopes (Chandra, XMM-Newton, Suzaku) in order to understand the non-gravitational process in those systems. A fraction of this sample shows a flattened entropy profile around $r_{500}$, which is attributed to the gas clumping effect.

Here we need to mention that different X-ray scaling relations of the galaxy groups and their redshift evolution have been thoroughly studied by Robson & Davé (2020, 2021) using the SIMBA cosmological simulation. Scaling relations obtained using SIMBA are in agreement with the results obtained with different simulation models, such as cosmo-OWLS (Le Brun et al. 2014), C-EAGLE (Barnes et al. 2017), and BAHAMAS (McCarthy et al. 2017), as well as broadly consistent with the results from various observations (Sun et al. 2009; Vikhlinin et al. 2009; Pratt et al. 2010; Eckmiller et al. 2011; Anderson et al. 2015; Lovisari et al. 2015). Scaling relations for different AGN feedback modes have also been investigated by Robson & Davé (2020, 2021), where they have found that jet mode of feedback plays an important role in evacuating the hot gas from the halos and reducing their temperature. This is in agreement with our findings from this work.

### 3.3. Mock X-Ray Observations

After modeling theoretical X-ray emission inside simulated galaxy groups and clusters, we aim to perform synthetic Chandra observations of the systems with the help of MARX as described in Section 2.2. Mock X-ray maps of the systems corresponding to Figures 1 and 2 are shown in Figures 6 and 7 respectively. Synthetic Chandra observations have been performed for each system for 200 ks exposure time in the soft energy band (0.5–2 keV) within a region of radius 50 $h^{-1}$ kpc that corresponds to angular scales of 6$^\circ$/5 and 2$^\circ$/5 at $z = 1$ and $z = 0.016$ respectively. Figures 6 and 7 show zoomed-in maps of diffuse gas surrounding the AGNs having different feedback modes. In both figures, the top left panel shows the X-ray maps in the presence of all modes of AGN feedback, the top right panel represents the scenario when all but X-ray feedback are present, the bottom left panel illustrates the X-ray map in which only the radiative wind feedback is present, and the bottom right panel is representative of the scenario when no feedback is provided from the central black hole. Color bars represent the photon number counts per pixel in both of these figures where the pixel size is $\sim 0.5^\circ$. No distinctly visible signature of AGN feedback can be identified from the X-ray maps of high-redshift objects (Figure 6). We explain this as a consequence of limited angular resolution of the Chandra telescope, which is $\sim 0.5^\circ$ (see R21). This is in agreement with the findings of R21 (Figure 1 of that paper). However, it is noted that the signature of AGN feedback of the low-redshift objects can be resolved from their synthetic X-ray maps (Figure 7).

We statistically study the imprint of feedback from AGNs on their surrounding medium to understand the importance of different modes of feedback from the AGN along with the possibility of their detection at different redshifts. Hence, we perform synthetic X-ray observations of all the systems used in Figure 4 for a 200 ks exposure time using the Chandra telescope in the soft energy (0.5–2 keV) band. Then we stack the total X-ray surface brightness obtained from synthetic observations of all the systems and construct the radial profiles accordingly. Stacked X-ray surface brightness profiles obtained from synthetic observations of various AGN feedback scenarios at high ($z = 1$) and low ($z = 0.016$) redshifts are shown in Figure 8. The same color scheme is maintained in both panels. Error bars represent the standard errors.

No significant difference in the X-ray surface brightness for different AGN feedback modes is seen within the few central pixels of the stacked radial profiles of the high-redshift objects (left panel). However, a notable excess of X-ray emission is observed at the outer radius in the presence of all the feedback modes (blue stars). A similar result has been obtained by R21...
from a synthetic Chandra observation of the simulated galaxy groups and clusters at $z = 1$ using the D08 simulation. This indicates that the synthetic observation method results in the same conclusion using two different cosmological simulations. Also, the results are in accordance with the findings of Mukherjee et al. (2019), who showed the reduction in X-ray emission from the hot gas inside active galaxies as well as an excess emission at the outer radius detected from deep X-ray observations. We explain the excess X-ray emission at the larger radii as coming from the accumulation of the hot gas displaced from the center by feedback effects. This excess emission could be a viable signature of AGN feedback of high-redshift objects where the feedback features cannot be detected at the center due to limited angular resolution of the telescope involved.

From the stacked radial profiles of the low-redshift objects including different feedback modes in the right panel, a clear difference in the X-ray surface brightness is visible between various feedback modes within the central pixels. X-ray surface brightness is suppressed in the vicinity of the AGN in the presence of all three feedback modes compared to the scenario when the central black hole provides no feedback to the surroundings. It is also obvious from the plot that inclusion of the X-ray mode of feedback along with the radiative wind and jet modes significantly decreases the X-ray emission surrounding the black hole. An excess emission is observed also in these low-redshift objects at the larger radii when all feedback modes are active compared to the scenario when no feedback is offered by the central black holes (green diamonds). From Figure 8 we observe that it is possible to resolve the AGN feedback signatures with Chandra from the low-redshift objects, while for the high-redshift sources excess emission in the AGN host systems at the outer radii could be a plausible signature for detecting feedback effects.
Although we have not considered the X-ray emission coming from the central AGN itself (a limitation of the subgrid model), as mentioned earlier, here we try to qualitatively estimate the AGN contribution to assess the detectability of this effect. For that we first convert the bolometric luminosities of the AGNs to the corresponding X-ray luminosities using the bolometric correction proposed by Marconi et al. (2004). Then we simulate the point-spread function (PSF) using MARX at the central pixel assuming a flat spectrum of the point source at 0.5 keV. Figure 9 shows the point-source contribution to the diffuse emission at the central pixel for one system at $z = 1$ (left panel) and $z = 0.016$ (right panel). It can be seen from this figure that emission from the central AGN significantly suppresses the diffuse emission at the very core ($< 1''$). The central PSF contribution to the diffuse emission has been studied in many previous works (e.g., Chatterjee et al. 2015; Mukherjee et al. 2019). Chatterjee et al. (2015) studied the extended X-ray emission from a sample of normal galaxies and X-ray-bright AGN hosts and reported a confusion in detecting the extended X-ray emission due to the extended PSF wings of the central AGN. Chatterjee et al. (2015) proposed that a sample of AGNs that are not detected in X-rays might be a better sample to study the extended X-ray emission in galaxies and to characterize the effect of AGN feedback on this extended emission. In a later work, Mukherjee et al. (2019) studied the X-ray surface brightness profiles of optically selected AGNs in order to minimize the PSF contribution of the X-ray-bright AGNs, where they found suppressed X-ray emission in the AGN host galaxies, supporting the results of our work.

3.4. Reconstruction of Feedback Energy

Finally, we estimate the maximum energy difference in the presence of different modes of feedback as previously proposed by Chatterjee et al. (2015) and discussed in R21. The difference in the surface brightness between two modes can be calculated as

$$\Delta I(r) = I_i(r) - I_{wi}(r),$$

where $I_{wi}(r)$ is emitted surface brightness at a distance $r$ when no feedback from the AGN is delivered and $I_i(r)$ denotes X-ray surface brightness in the presence of different feedback modes at a distance $r$. Hence, the approximate energy delivered by different modes of feedback can be obtained as follows:

$$E = 4\pi D_L^2 \int 2\pi r \Delta I(r) dr,$$

where $D_L$ is the luminosity distance.

![Figure 6. Zoomed-in image of synthetic Chandra X-ray maps of the systems shown in Figure 1 within the region of radius 50 $h^{-1}$ kpc ($\sim 0.5$) at $z = 1$. In all panels color bars represent the photon number counts per pixel, where the pixel size is $\sim 0.5''$. Top left: mock X-ray map of the diffuse gas around an AGN having all the feedback modes. Top right: synthetic X-ray map of hot gas in the vicinity of an AGN that provides radiative wind as well as jet feedback to its ambient medium. Bottom left: diffuse X-ray map of a synthetic observation surrounding an AGN in which only the radiative wind mode of feedback is present but jet and X-ray feedback are absent. Bottom right: mock X-ray map surrounding a black hole having no feedback mode. See Section 3.3 for discussions.](image-url)
Using Equation (7) and Figure 8, we calculate the feedback energy for various AGN feedback modes at $z = 1$ and $z = 0.016$. We find that the integrated feedback energy varies from $1.1 \times 10^{47}$ erg s$^{-1}$ considering all the feedback modes to $\approx 2.8 \times 10^{46}$ erg s$^{-1}$ in the case of the "NoX" and "NoJet" modes for the high-redshift objects. The value of the integrated feedback energy for the low-redshift objects varies a little for different modes of AGN feedback and it is found to be $\approx 10^{41}$ erg s$^{-1}$.

By comparing the feedback energy obtained for various modes from our work with that from actual observations, we can comment on the feedback modes that are at play in the real universe. Previous studies have been done to measure the feedback energy estimated from the X-ray cavities produced by the AGN (Birzan et al. 2004, 2008; Rafferty et al. 2006; Kokotanekov et al. 2017). Our results show an agreement with the energy scale at low redshift obtained from these observations. We find that the suppression of X-ray emission in the medium surrounding an active galactic nucleus depends on the mode of feedback and the effect is scale-dependent. Although it is difficult to observationally distinguish different feedback channels in a particular system, we emphasize that the magnitude of suppression may give us clues toward the mode of feedback that is dominating. We further note that cross-correlation studies with other wavelengths (e.g., Sunyaev–Zeldovich signal, see Chatterjee et al. 2008) may also provide stronger constraints on feedback modes of AGNs. Thus by comparing the simulated results with the observations it is possible to provide limits on the plausible modes of feedback. This is discussed again in the next section.

4. Conclusions

In this work we have tried to understand the influence of feedback from AGNs on their adjacent gas and the importance of different modes through which the energy outflow from the AGNs interacts with their surroundings by analyzing the diffuse X-ray emission from galaxy groups and clusters. In addition to this, we examine the robustness of our theoretical model by performing synthetic observations and comparing those with previous results. From the X-ray surface brightness profile of the theoretical model (Figure 4), we can see a clear deficit in the X-ray emission surrounding the black holes in the presence of all the feedback modes compared to the scenario when no feedback is offered by the central black holes. This result statistically stays consistent for both the high- and low-redshift objects. The emergence of lower X-ray surface brightness at the center of the AGN host galaxy groups and clusters is consistent with the works of many previous groups using cosmological simulation as well as actual X-ray observations (e.g., Gaspari et al. 2011; Pellegrini et al. 2012; Mukherjee et al. 2019; Robson & Davé 2020; Kar Chowdhury et al. 2021). Sun et al. (2009) studied the gas properties of a sample of 43 galaxy groups at low redshifts (0.012–0.12).
observed with Chandra, among which AGN feedback activity has been detected in some systems from their entropy and surface brightness profiles. Moreover, X-ray cavities resulting from the AGN feedback activity can be detected from the surface brightness profiles of galaxy groups and clusters (Hlavacek-Larrondo et al. 2015; Kokotanekov et al. 2018; Liu et al. 2019; Pandge et al. 2019; Kolokythas et al. 2020).

A major goal of this work is to investigate the importance of different modes of AGN feedback on their surrounding X-ray-emitting gas. It has been seen from Figure 4 that inclusion of jet and X-ray modes of feedback with the radiative wind feedback from the AGN is more efficient in reducing the diffuse X-ray emission adjacent to the black holes. The difference in the X-ray surface brightness profile obtained by R21 in their study (Figure 2 of R21) in the presence and absence of AGN feedback is small compared to the difference observed in this work when all the feedback modes are included (red dots) and excluded (green squares) at z = 1 (left panel of Figure 4). We explain this as a consequence of different feedback models used in R21 and SIMBA.

We examine the possibility of detecting AGN feedback at different redshifts using the synthetic observation technique developed by R21. Stacked X-ray surface brightness profiles obtained from the mock Chandra observations for different feedback modes at z = 1 and z = 0.016 are shown in Figure 8. They show no significant difference in the X-ray surface brightness between different feedback modes of high-redshift objects within a few central pixels. This can be understood as a consequence of the limited angular resolution of the Chandra telescope. However, an excess emission is observed at the outer radii, which could be an outcome of the accumulation of the hot gas that is displaced from the black hole neighborhood by the feedback activity. Detection of this excess emission in the presence of all feedback modes could be a viable method for observing the signature of AGN feedback in high-redshift objects.

We note that R21 used the D08 simulation to make a statistical analysis of the influence of AGN feedback on their ambient medium, where only the radiative mode of feedback from the AGN is considered in the simulation. On the other hand, SIMBA takes into account jet and X-ray modes along with the radiative mode while modeling the AGN feedback. Thus we see from Figure 4 that radiative wind feedback alone might not be effective in sufficiently evacuating the diffuse X-ray-emitting gas around the AGN. Jet and X-ray modes of feedback play substantial roles. Besides, by comparing the results of this work with the existing and upcoming X-ray observations it would be possible to comment on the mode of feedback effective in the observed systems. Our results are consistent with the findings of R21, who use the D08 simulation to make similar predictions. We are thus confident about the ubiquity of our results, which we observe using multiple simulations.

For the low-redshift objects, the right panel of Figure 8 shows that the difference in the X-ray surface brightness in the presence of different AGN feedback modes can be detected even within the central pixels of the stacked maps. Also, it is observed that X-ray emission decreases significantly in the central regions after incorporating the X-ray feedback, demonstrating the importance of this feedback mode in the cosmological simulation to properly explain different observables. In a recent work aimed at disentangling AGN feedback from stellar feedback, Chadayammuri et al. (2022) studied the importance of different modes of feedback on the circumgalactic medium using the galaxies from eROSITA Final Equatorial Depth Survey (eFEDS). Their results show a decrement in the X-ray luminosity in the presence of feedback from the AGNs, supporting the result of this work. They have also compared their results with different cosmological simulations offering different modes of feedback and commented that kinetic jet feedback needs to be modeled with a dependence on the halo mass.
From this work we conclude that with the specifications of existing X-ray telescopes, the imprint of AGN feedback reflected from the X-ray surface brightness profile of the diffuse gas inside galaxy groups and clusters can be resolved for objects at lower redshift while this signature is unresolved in the central few pixels for high-redshift objects. It is important to discuss the possibility of detecting direct observational signatures of AGN feedback from the X-ray maps of the high-redshift objects with upcoming X-ray missions such as XRISM and Athena, as well as the concept mission Lynx. XRISM and Athena are designed to be capable of achieving a great field of view, larger effective area, and high count rate (Barcons et al. 2012; Nandra et al. 2013; XRISM Science Team 2020; Barret et al. 2020), which will enhance the probabilities of detecting faint objects such as AGNs, galaxy groups, and clusters extending to very high redshift (Cucchetti et al. 2018; Mernier et al. 2020; Oppenheimer et al. 2021; Habouzit et al. 2022). However, the angular resolution of XRISM is \( \sim 1.7 \), which is much lower than that of Chandra. While Athena is designed to achieve a better resolution of \( \sim 5'' \), this is still lower than Chandra’s. Hence, it can be qualitatively understood that the signature of AGN feedback from the X-ray surface brightness profile of high-redshift objects cannot be resolved with XRISM and Athena in the vicinity of black holes. However, Lynx is proposed to have an excellent angular resolution of \( \sim 0.3'' \) (The Lynx Team 2018), which can enable us to resolve the X-ray surface brightness profiles of high-redshift objects in the presence and absence of the feedback from AGNs. We plan to continue the search for feedback signatures from high-redshift galaxy clusters with future X-ray telescopes based on the techniques developed in this work and R21 in a future study.

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**Appendix A**

**Dependence on Exposure Time**

We have performed synthetic observations of an example system for different exposure times. Figure A1 presents a system that is observed for exposure times of 200 ks (left panels) and 2 Ms (right panels) at both \( z = 1 \) (top panels) and \( z = 0.016 \) (bottom panels). Here we show X-ray maps of the system including all the feedback modes at both high and low redshifts observed for two different exposure times. The top and bottom left panels are the same X-ray maps as shown in the top left panels of Figures 6 and 7 respectively, but shown here with a different color scheme for visual purposes. Comparing the left and right panels, it can be noticed that the signal-to-noise ratio (S/N) increases moderately with the longer exposure time (right panel) at both redshifts. However, we carry on the analysis throughout this paper using the exposure time of 200 ks because the S/N is high enough at this exposure time for a significant detection at both \( z = 1 \) and \( z = 0.016 \).
Figure A1. X-ray maps for different exposure times. Top left: X-ray map of a system at $z = 1$ including all the AGN feedback modes, observed for an exposure time of 200 ks (same as shown in top left panel of Figure 6). Top right: X-ray map of the same system observed for 2 Ms. Bottom left: X-ray map of a system at $z = 0.016$ including all the modes of feedback from AGNs, observed for an exposure time of 200 ks (same as shown in the top left panel of Figure 7). Bottom right: X-ray map of the same system observed for a longer exposure time of 2 Ms. Color bars represent photon number counts per pixel in all the panels. An increase in S/N is observed for the longer exposure time as expected.

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