Investigating the scatter origin in CHEX-MATE galaxy cluster X-ray surface brightness profiles

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Abstract. We present the statistical properties and the investigation on the origin of the scatter within the spatially resolved emission measure profiles of the CHEX–MATE sample, formed by 118 galaxy clusters selected via the SZ effect. These objects cover a wide mass, \( M_{500}^{\text{YSZ}} = [2 - 15] \times 10^{14} M_\odot \), and redshift, \( z = [0.02, 0.6] \), range. They have been observed by XMM-Newton with a dedicated program that ensures an unprecedented homogeneous and high quality data. We leveraged this exceptional data set by studying the statistical properties of the surface brightness and emission measure radial profiles. We found that there is a critical scale, \( R \sim 0.4 R_{500}^{\text{YSZ}} \), within which the most morphologically relaxed and disturbed object profiles diverge. Above that radius these differences tend to be within 20%.

We complemented the CHEX–MATE clusters with a twin sample drawn from the Three Hundred suite of cosmological simulations. Leveraging this sample, we were able for the first time to investigate separately the scatter due to projection effects and the one due to cluster-to-cluster differences. We found that projection effects have a smaller impact on the scatter compared to object-to-object differences across all scales. Building on this, we found that below \( 0.4 R_{500}^{\text{YSZ}} \) the scatter is of the order of 110% reflecting the wide plethora of gas distribution in cluster cores. The scatter is at its minimum, 0.56, in the intermediate range, \( [0.4-0.8] R_{500}^{\text{YSZ}} \), despite their morphological status suggesting that clusters are close to the self-similar scenario within this radial range.

1 Introduction

The spatial distribution of the hot, \( \sim 5 \text{ keV} \), and rarefied plasma, \( n_e \sim 10^{-2} \text{ cm}^{-3} \), that fills the cluster volume known as Intra-Cluster Medium (ICM) represents a powerful tool to study how cluster form and evolve. Merging activities induce phenomena such as shocks or cold fronts [7] that impact the spatial distribution of the ICM as well as its density and temperature.

The ICM emits in the X-ray via the thermal Bremsstrahlung effect which is proportional to the plasma density and temperature. For this reason, X-ray observations of galaxy clusters are the ideal tool to study this component. In particular, the surface brightness (SX) radial profile is a cheap measurement that can be done with current X-ray instruments such as Chandra or XMM-Newton allowing the investigation of the ICM spatial properties. For instance, numerous works in the literature use the SX profiles or the related emission measure (EM) to test the self-similar evolution scenario [1] or selection effects [9].

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In this proceeding we summarise the results obtained in [2], which are based on the Cluster HEritage project with XMM-Newton - Mass Assembly and Thermodynamics at the Endpoint of structure formation (CHEX-MATE) program. The details of this project and the sample presentation are given in [4]. The uniqueness of the CHEX–MATE sample is that its objects are covered by unprecedented homogeneous data quality and that its selection is based on the Sunyaev Zel’Dovich effect (SZ, [10]), which ensures a minimum biased sample. We also leveraged a twin sample selected from the suite of cosmological simulations of the Three Hundred project [5]. This has been used for the first time to discriminate the components of the scatter relative to variations between objects and the one due to projection effects i.e. the same cluster may appear different if projected along different line of sights.

The proceeding is structured as follows: in Section 2 we describe the construction of observation and simulation samples, in Section 3 we show the statistical properties of the CHEX–MATE sample, in Section 4 we discuss the origin of the scatter and in Section 5 we draw our conclusions.

2 The sample

In this section we present the sample of observations and simulated dataset used for this work.

2.1 The CHEX–MATE sample

The details on the construction of the CHEX–MATE sample are given in [4]. We report here briefly its main characteristics. The distribution in the mass-redshift plane of the sample is shown in the left panel of Fig. 1 and is formed by 118 galaxy clusters drawn from the

![Figure 1](https://example.com/figure1.png)

Figure 1. Presentation of the CHEX–MATE and simulation samples. *Left panel:* the CHEX–MATE sample in the mass redshift plane. The grey points are all the clusters published in the PSZ2 Planck catalogue [8]. The magenta and green points represent the Tier 1 and Tier 2 clusters of the CHEX–MATE sample, respectively [4]. The triangles and squares identify the morphologically relaxed and disturbed clusters, respectively, which were identified according to the classification scheme in [3]. The two red crosses identify clusters that were not analysed as detailed in [2].

*Right panel* Mass distribution of the CHEX–MATE and simulation samples. The former and the latter are shown with black and green shades, respectively. The simulation sample distribution is shifted as respect to CHEX–MATE because of the hydrostatic bias (see text and [2] for details.)

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Planck all sky catalogue of diffuse sources PSZ2 [8]. The scientific objective is to investigate the ultimate manifestation of structure formation in mass and redshift by studying the radial thermodynamical and dynamic properties of the clusters. The SZ selection ensures that this sample is minimally biased towards the X-ray selection effects described, e.g., in [9]. The CHEX–MATE sample can be divided in two tiers tailored to match different science requirements. The Tier 1 comprises 61 clusters in the [0.05-0.2] redshift range spanning a mass range of $[2 - 9] \times 10^{14} M_\odot$ mass range. These objects represent a local anchor for any evolution study. The Tier 2 is formed by massive clusters, $M_{500}^{ysz} > 7.25 \times 10^{14} M_\odot$ in the [0.2-0.6] redshift range. These objects represent the culmination of cluster evolution in the Universe. The distribution of the Tier 1 and 2 clusters are shown in the left panel of Fig. 1 with magenta and green point, respectively. It is worth noting that 2 clusters, shown with a cross in Fig. 1, are excluded from the analysis because of analysis issues as detailed in [2]. That is, all the CHEX–MATE results shown here are derived using 116 objects.

2.2 The simulation sample

We defined a twin CHEX–MATE sample of simulated clusters selecting 115 clusters from the from the Three Hundred collaboration [6]. The selection criteria are described in detail in Section 4 of [2]. Briefly, for each CHEX–MATE cluster we identify a simulated counterpart by matching the mass and morphological condition i.e. an undergoing merger CHEX–MATE cluster is paired with a cluster that presents similar dynamical condition. The simulations are extracted from six redshift snapshots $z = 0.067, 0.141, 0.222, 0.333, 0.456,$ and 0.592, to match the redshift extension of the CHEX–MATE sample. It is worth noting that the CHEX–MATE masses are derived under the assumption that they underestimate the real mass of the cluster by 20% (see Planck Collaboration XX 2014) because of the hydrostatic equilibrium assumption. We take in account this effect when matching the cluster mass with the simulated cluster for which we know the real total mass value. For this reason, the mass distribution of the simulation sample shown in the right panel of Fig. 1 has the same shape as CHEX–MATE but is shifted towards higher masses. We projected each simulated cluster along 40 lines of sight. That is, we produced 40 EM maps for each of the 115 clusters.

3 The CHEX–MATE profile statistical properties

We derived the radial SX profiles following the techniques described in [2]. Briefly, we extracted the background-subtracted and exposure-corrected SX radial profiles within concentric annuli centred on the X-ray peak, requiring that in each bin there are enough counts to ensure a $3\sigma$ precision over the background. We converted these profiles in EM profiles following Equation 2 and scaling them by Equation 5 of [2]. These profiles are shown in the left panel of Fig. 2 color-coded according to their morphological status. [3] identified the most relaxed and the most disturbed clusters which are shown with the blue and red solid lines, respectively. There is a clear segregation between the two populations in the central part at $R < 0.4R_{500}^{ysz}$ where they are not consistent with the 68% dispersion of the full sample shown with the grey envelope. The difference between the two population diminishes at $R > 0.4R_{500}^{ysz}$. The comparison of the medians of the two populations with the full CHEX–MATE sample is shown in the right panel of Figure 2. The ratio shown on the bottom quantifies the behaviour described above. The ratio between the medians are greater than 100% for both relaxed and disturbed and then reaches its minimum at $0.4R_{500}^{ysz}$. Above that radius the differences are within 20%. That is, the shape of the EM radial profile in the core is not strongly correlated with the outer parts.
Figure 2. Statistical properties of the EM profiles of the CHEX–MATE sample. Left panel: EM radial profiles of the CHEX–MATE sample scaled by $R_{500}^{YSZ}$. The blue and red solid lines correspond to the most relaxed and disturbed objects, respectively, according to the morphological classification of [3]. The grey shahed area correspond to the $1\sigma$ dispersion around the median of the profiles. Right panel: comparison of the CHEX–MATE sample with the sub-samples formed by the most morphologically relaxed and disturbed objects. On the top we show the median of the former and latter samples with blue and red solid lines, respectively. The black line is the median of the full CHEX–MATE sample. On the bottom we show the ratio between the medians. The solid black line is the unity level and the dotted represent the 0.8 and 1.2 levels.

4 The origin of the scatter

The scatter between the EM profiles of a minimally biased sample can be used to identify the quantities by which profiles can be scaled to minimise the dispersion and find universal behaviours. Another application is the generation of realistic simulation catalogues that can reproduce the distribution of the profiles. For these reasons, the analysis of the profiles dispersion is fundamental. This quantity can be quantified by measuring the intrinsic scatter, defined as the dispersion between profiles once statistical errors are taken in account as detailed in Section 6 of [2]. The $1\sigma$ envelope of the CHEX–MATE EM profiles intrinsic scatter is shown in Fig. 3 with black dotted lines. The scatter starts from a maximum value of $\sim 1.2$ at $R\sim 0.1R_{500}^{YSZ}$ and then slowly decreases to its minimum value of $\sim 0.4$ at $R\sim R_{500}^{YSZ}$. The relative errors on the profiles are on average $\sim 0.03$ and 0.06 within $0.7R_{500}^{YSZ}$ and at $R_{500}^{YSZ}$, respectively, (cfr. Table 1 of [2]) and are smaller than the intrinsic scatter term by at least of a factor 5 on the entire radial range considered of $[0.06-1]R_{500}^{YSZ}$.

A limitation to the study of the intrinsic scatter is that we have access only to the projection of a cluster on the celestial sphere. The same cluster EM profile could be different if it is derived from different line of sights. For this reason, the intrinsic scatter can be divided in the scatter we measure within a sample of objects, namely the total scatter, and the one related to projection effects, namely the projection scatter. We used simulations to break down these components. We derived the projection term computing the scatter between the 40 EM profiles derived from the maps for each simulated cluster. Then, the total scatter term is computed fixing a line of sight and computing the intrinsic scatter of the EM profiles extracted from the 115 maps. The EM profiles extracted from the simulations dataset are not affected by statistical errors. For this reason, the scatter term due to the statistical errors is not considered for simulations. The scatter terms computed this way are shown in Fig. 3 with coloured envelopes. The projection scatter is shown in magenta and raises slowly from 0.1.
at $R \sim 0.1 R_{YSZ}^{SZ}$ to 0.3 at $R \sim R_{YSZ}^{SZ}$. The total scatter is maximum, $\sim 1$, at $0.1 R_{YSZ}^{SZ}$ and reaches its minimum of 0.4 at $R \sim 0.4 R_{YSZ}^{SZ}$ and then raises again to 0.8 at $R_{YSZ}^{SZ}$. There is an excellent agreement between the total and CHEX–MATE scatter below $0.4 R_{YSZ}^{SZ}$, suggesting that simulations are capable to reproduce the wide plethora of EM profile shapes in the cluster central regions. The two scatters diverge above that radius. We argue that this could be due to the presence of substructures and clumps which are visible in simulations and are too faint in X-ray observations. For more details refer to [2]. The projection scatter is smaller than the total and the CHEX–MATE scatter at all the scale considered except for $R_{YSZ}^{SZ}$. This last result indicates for the first time that the intrinsic scatter of the EM radial profiles within $R_{YSZ}^{SZ}$ is capable of measuring the dispersion due to different properties of the objects such as density, temperature or dynamical state and is not dominated by projection effects.

**Figure 3.** The separation of the scatter components compared to the intrinsic CHEX–MATE scatter. The green and magenta solid line represent the median value of the total and projection scatter, respectively. The coloured envelopes represent the $1\sigma$ uncertainty. The dotted black lines represent the CHEX–MATE intrinsic scatter of the EM profiles.

### 5 Conclusions

We report in this proceeding the analysis of the statistical properties of the EM profiles and break down the scatter components of the CHEX–MATE sample. This contains 118 clusters drawn from the PSZ2 catalogue in the [0.02-0.6] redshift range and $M_{YSZ}^{SZ} = [2 - 15] \times 10^{14} M_\odot$ mass range. The SZ selection ensures that this simple is minimally biased. Furthermore, this sample has been covered by exceptional high quality and homogeneous X-ray observations using XMM-Newton. We also created a twin-sample of 115 simulated clusters with the same mass and redshift distribution from the The Three Hundred cosmological simulation suite.

Leveraging this exceptional dataset we were able to investigate the statistical properties of the CHEX–MATE EM radial profiles. We found that there is a typical scale, $R \sim 0.4 R_{YSZ}^{SZ}$, within which the most relaxed and disturbed cluster EM profiles show the maximum differences. Despite the morphological status, the EM profile differences are within 20% at
We measured the intrinsic scatter of the EM profiles of the CHEX–MATE sample and found that the scatter is maximum, \( \sim 1.2 \), at \( R \sim 0.1 R_{500}^{Ysz} \) and slowly reaches the value of 0.4 at \( R_{500}^{Ysz} \). We leveraged the simulation dataset to break down the components of the intrinsic scatter of the EM profiles in the projection and total term. The former is due to projection effects for which the same cluster could appear different depending on the line of sight. The latter represents the scatter of EM profiles we would measure for a given sample. We found that the total scatter is in excellent agreement with CHEX–MATE within \( \sim 0.4 - 0.5 R_{500}^{Ysz} \). The differences above that radius could be due to substrutures visible in simulations but not in the observations. Finally, we found that the projection scatter is smaller that then total scatter at all scales except for \( R_{500}^{Ysz} \). We were then able for the first time to highlight the fact that we are capable of discriminating the total scatter from the projection one within \( R_{500}^{Ysz} \).

References