A Systematic Comparison of Galaxy Cluster Temperatures Measured with NuSTAR and Chandra

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ABSTRACT

Temperature measurements of galaxy clusters are used to determine their masses, which in turn are used to determine cosmological parameters. However, systematic differences between the temperatures measured by different telescopes imply a significant source of systematic uncertainty on such mass estimates. We perform the first systematic comparison between cluster temperatures measured with Chandra and NuSTAR. This provides a useful contribution to the effort of cross-calibrating cluster temperatures due to the harder response of NuSTAR compared with most other observatories. We measure average temperatures for 8 clusters observed with NuSTAR and Chandra. We fit the NuSTAR spectra in a hard (3–10 keV) energy band, and the Chandra spectra in both the hard and a broad (0.6–9 keV) band. We fit a power-law cross-calibration model to the resulting temperatures. At a Chandra temperature of 10 keV, the average NuSTAR temperature was (10.5 ± 3.7)% and (15.7 ± 4.6)% lower than Chandra for the broad and hard band fits respectively. We explored the impact of systematics from background modelling and multiphase temperature structure of the clusters, and found that these did not affect our results. Our sample are primarily merging clusters with complex thermal structures so are not ideal calibration targets. However, given the harder response of NuSTAR it would be expected to measure a higher average temperature than Chandra for a non-isothermal cluster, so we interpret our measurement as a lower limit on the difference in temperatures between NuSTAR and Chandra.

Key words: cosmology: observations – galaxies: clusters: general – X-rays: galaxies: clusters

1 INTRODUCTION

Galaxy clusters are the largest gravitationally bound objects in the Universe. Massive galaxy clusters are ideal targets for studying cosmology as their number density is sensitive to cosmological parameters (see e.g. Allen et al. 2011, for a review). Cluster masses are essential for such cosmological studies. However, since clusters are dominated by dark matter, their masses must be inferred from observable properties (the main methods used are reviewed in Pratt et al. 2019). The X-ray emission from the intra-cluster medium (ICM) provides several observable quantities which may be used for this purpose. These include temperatures and densities of the ICM, radial profiles of which can be used to infer the total mass of a cluster assuming hydrostatic equilibrium. Where the X-ray data quality does not allow detailed measurements, scaling relations between ICM quantities (such as luminosity, temperature or gas mass) may be used to estimate masses if they are accurately calibrated.

There has been significant attention paid recently to the accuracy of cluster masses obtained from hydrostatic equilibrium analyses. If hydrostatic masses were systematically underestimated, this could help to resolve the discrepancy that has been observed in some of the cosmological parameters (principally $\sigma_8$) obtained from Planck measurements of the cosmic microwave background (CMB) anisotropies versus those obtained from number densities of massive clusters detected by Planck (Planck Collaboration et al. 2020a).

Hydrostatic masses may be underestimated if there is significant non-thermal pressure support in the ICM, since the X-ray observations only measure the thermal pressure (Laganá et al. 2010; Barnes et al. 2021; Ettori & Eckert 2022). This is known as the hydrostatic bias, and conventionally refers to the amount by which hydrostatic masses are...
biased low compared to the true mass. Comparisons between hydrostatic masses and masses obtained via weak gravitational lensing measurements suggest that a hydrostatic bias may be present but the size of the bias remains uncertain. Most analyses point towards hydrostatic masses being underestimated by \(\sim (0 \pm 20\%)\) (von der Linden et al. 2014; Okabe & Smith 2016; Herbonnet et al. 2020; Salvati et al. 2021; Logan et al. 2022), but underestimates as large as \((30 \pm 40\%)\) may be required to fully align the Planck CMB and cluster number counts constraints on \(\sigma_8\) (Planck Collaboration et al. 2020).

The calibration of X-ray telescopes is another possible source of systematic uncertainty on hydrostatic masses. In particular if ICM temperatures were systematically underestimated, this would lead to underestimates of hydrostatic masses. Absolute calibration of X-ray telescopes in orbit is challenging due to the lack of standard, unvarying astrophysical calibration sources, and the cross-calibration of different X-ray telescopes reveals some inconsistencies. One of the key instrumental properties that needs to be calibrated is the effective area of the X-ray telescopes. This is energy-dependent, and miscalibration at different energies would distort the slope of observed X-ray spectra, potentially biasing quantities such as ICM temperatures that are derived from spectral fits. Restricting spectral fitting to different X-ray energy bands can then help to reveal any energy-dependent problems with the effective area calibration. As discussed below, it is difficult to ascribe temperature differences directly to the effective area calibration due to the presence of other instrumental effects, such as the point spread function (PSF) in the case of extended sources, and detector gain. The contributions of multiple temperature components in the ICM to the observed spectrum also complicate the interpretation of temperature differences.

Cross-calibration work has been supervised by the International Astrophysical Consortium for High Energy Calibration (IACHEC), including the use of galaxy clusters as calibration sources. Nevalainen et al. (2010) and Schellenberger et al. (2015) both performed a cross-calibration using galaxy clusters observed with both Chandra and XMM-Newton, focussing on the ICM temperature measurements. Nevalainen et al. (2010) found that temperatures measured with XMM-Newton were systematically lower than those measured with Chandra by 10-15\% on average, but the difference was not significant if the spectral fitting was restricted to higher X-ray energies \((\gtrsim 2\text{ keV})\).

Schellenberger et al. (2015) found qualitatively similar results using a much larger sample, with the disagreement between Chandra and XMM-Newton increasing with cluster temperature. Chandra temperatures were \(\sim 20\%\) higher than those measured using XMM-Newton at a cluster temperature of 10 keV. Again the discrepancy was found to be dominated by the inclusion of softer X-rays \((\lesssim 2\text{ keV})\) in the spectral fitting. This work also tested the internal cross-calibration of the observatories’ instruments. There was good agreement between temperatures measured by Chandra Advanced CCD Imaging Spectrometer (ACIS) I and S arrays (which use the same optics) but inconsistencies between temperatures from the three XMM-Newton European Photon Imaging Camera (EPIC) detectors (which each use a different telescope).

A cross-calibration of Suzaku and XMM-Newton using galaxy clusters has also been performed (Kettula et al. 2013). The results showed that Suzaku systematically measured the temperature of galaxy clusters to be 2-6\% lower than those from XMM-Newton when the analysis was performed in the hard energy band of 2.0-7.0 keV and up to a 12\% difference for temperatures measured in the soft energy band of 0.5-2.0 keV. However, it was determined that up to half of this difference could be caused by Suzaku’s PSF scattering (typically softer) photons from the core regions.

The results from these cross-calibrations highlight the uncertainty in measurements between the different X-ray observatories and the importance of understanding how different detectors are calibrated.

\(\text{NuSTAR}\) presents a relatively untapped opportunity for the cross-calibration of cluster temperatures. The hard response of NuSTAR makes it more sensitive to the exponential cut-off of the bremsstrahlung continuum that dominates the ICM emission for hot clusters. This enables it to more accurately measure temperatures of hot clusters compared to e.g. Chandra, XMM-Newton or Suzaku. NuSTAR has been used for spectral analysis of a relatively small number of galaxy clusters, often with the aim of constraining any non-thermal component of the emission (e.g. Wik et al. 2014; Cova et al. 2019; Rojas Bolivar et al. 2021).

In this paper, we present the first systematic comparison of galaxy cluster temperature measurements with \(\text{NuSTAR}\) and Chandra. We compare the temperatures of a sample of eight galaxy clusters which have been observed with both NuSTAR and Chandra. The paper is organised as follows. We give an overview of the cluster sample in section 2. Section 3 discusses \(\text{NuSTAR}\) and Chandra data processing as well as the background and spectral analysis. The temperature measurements and cross-calibration results are presented in section 4. The results are then discussed in more detail in section 5, and our conclusions are presented in section 6. Throughout this paper, when referring to Chandra and XMM-Newton temperatures, we mean those measured with the Chandra ACIS and XMM-Newton EPIC detectors.

2 CLUSTER SAMPLE

In principle, galaxy clusters make good X-ray calibration sources since they are bright and non-varying, and generally unaffected by pile-up. However, the ICM can be thermally complex with multiphase gas projected along the line of sight. If a model with a single temperature component is fitted to an X-ray spectrum from a region of ICM, then the measured temperature will be an average of the different temperature components of the ICM along the line of sight, weighted by the emissivity of each component combined with the energy-dependent effective area of the telescope (Mazzotta et al. 2004; Vikhlinin 2006). If a galaxy cluster were perfectly isothermal, then all correctly-calibrated X-ray telescopes would recover the same temperature. However, when the observed spectrum comprises a combination of temperature components, then even perfectly calibrated telescopes would recover different average temperatures if their sensitivities were different at different X-ray energies. For example, a telescope with a hard response (like \(\text{NuSTAR}\)) would recover a higher average temperature than a telescope with a softer response (like Chandra).
For cross-calibration purposes it would be ideal, therefore, to select a sample of relaxed galaxy clusters which contain large volumes of approximately isothermal gas. However, the relatively small number of clusters that have been observed by NuSTAR are almost exclusively merging clusters. This is by design, since such systems are expected to contain very hot ICM regions related to merger shocks and radio halos (with possible associated non-thermal X-ray emission) so make good targets for NuSTAR observations.

As of January 2020, the NuSTAR public archive contained eight galaxy clusters that we deemed were suitable for our purposes. In particular, we required the clusters to be bright but sufficiently distant that the majority of the ICM emission was contained within the field of the Focal Plane Modules, giving a sample of eight clusters. All of these clusters had previously been observed by Chandra, many of them with a large number of observations. A subset of the available observations were chosen to provide a similar data quality to the NuSTAR data (as will be seen later, the statistical uncertainty on the Chandra temperature measurements is sufficiently small that there is no benefit to utilising all of the available data). The resulting sample is presented in Table 1.

3 DATA PROCESSING AND ANALYSIS

3.1 NuSTAR data processing

The NuSTAR observations of each cluster were processed with the latest calibration as of May 2020 (CALDB version 20200429). For four clusters (Abell 523, Abell 665, 1E 0657-56 and RX J1347.5-1145), there were two NuSTAR observations, and in these cases, both observations were processed and used in the analysis. The data reduction was performed for both focal plane modules A and B (FPMA and FPMB) for each cluster. The standard nupipeline processes were run on the observations, with the additional arguments saamode=STRICT and TENTACLE=yes, closely following the analysis done in Cova et al. (2019).

NuSTAR has a complex background, which must be accounted for when performing spectral analyses. The approach we use closely follows that described in Wik et al. (2014) and consists of extracting background spectra from the target observation, fitting a detailed model to those, and then simulating background spectra for the source region based on this model.

We briefly summarise the main components of the NuSTAR background below. A more detailed description can be found in Wik et al. (2014); Harrison et al. (2013); Madsen et al. (2017).

The focused cosmic X-ray background (“fCXB”) is due to unresolved sources in the field of view (FOV) and can be important below ~15 keV. However, ~90% of the cosmic X-ray background (CXB) photons detected in the FOV are due to stray light that seeps through the aperture stops, creating a spatial gradient across the FOV. This is the dominant background component at energies below ~15 keV, and is known as the “aperture” background. Stray light (from the CXB, the Sun and Earth’s albedo) is also present in the FOV due to reflection from surfaces of the spacecraft. This component can undergo significant fluctuations due to solar activity at the observation time. Above 15–20 keV, the instrument or internal background dominates. This component differs between the FPMA and FPMB detectors but is spatially uniform and consists of a continuum plus strong fluorescent and activation lines.

To model the background nuskybgd was used (Wik et al. 2014). This tool fits a model to background spectra extracted from the target observation and then produces a simulated background at the detector position of the source. This includes the spatial variation of the different background components where necessary, and geometric corrections for the different region sizes. This simulated background is then used in the analysis of the source spectrum.

Background regions were defined in each corner of the FOV, avoiding areas of high cluster emission when possible, similar to the approach used in Cova et al. (2019). For observations where the cluster was located in one of the corners of the FOV, background regions were defined in the remaining three corners. The same regions were used for both FPMA and FPMB. Figure 1 presents an example of an NuSTAR image of Abell 523, in the energy band of 3 – 20 keV, indicating the regions used to extract background spectra.

Because the target clusters are bright and relatively nearby, their emission fills a large fraction of the NuSTAR FOV, and so it is possible that emission from the cluster is present in the background regions at a non-negligible level. We accounted for this by including an additional APEC component in the background model to describe the ICM emission. The temperature, abundance and normalisation of this component were free to fit (with the values tied for matching regions on the FPMA and FPMB detectors). In general, the parameters of this model were not well constrained, and the normalisation was degenerate with other background model components. (The process was also performed with the temperature and abundance of the APEC component in the background region fixed at the values measured for the cluster, with consistent results.)

In all cases, the impact of this additional APEC component in the background model on the final temperatures measured for the clusters was negligible (the temperatures changed by < 3% compared to the case where no additional APEC component was included, and the change was random in direction for the eight clusters rather than a systematic increase or decrease). Our final temperature measurements used the background models where the additional APEC component was included, but this has no significant effect on our results.

Once the simulated background spectra were produced, the source spectra were then extracted and associated response matrices (RMF) and auxiliary response files (ARF) were produced using nuproducts. The parameter

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1 Subsequent to the completion of our analysis, NuSTAR CALDB 20211020 was released, which included an update to the effective area (Madsen et al. 2021). The change to the effective area is almost constant with energy below 10 keV, so is not expected to significantly impact cluster temperature measurements. We confirmed this by repeating our analysis for A2146 with the new calibration and found that temperature changed by 2%.

2 https://heasarc.gsfc.nasa.gov/docs/nustar/analysis/nustar_swguide.pdf
The background spectra were normalised to match the \( N_{\rm H} \) was determined from the Chandra exposures (Maughan et al. 2008, 2012), and we summarise the main steps below. For all clusters, Chandra ACIS-I observations were used. In this work CIAO version 4.12 and CALDB version 4.9.1 was used.

The data were reprocessed from level 1 events and lightcurves were produced (in the 0.3–12 keV band) and filtered to remove periods of high background. Blank-sky backgrounds events lists were used in the spectral analysis and were processed in a consistent way to the source observations. Exposure corrected images in the 0.3–7 keV energy band were used for the detection of point-like sources. All the point sources were excluded from the subsequent analysis.

We note that in all cases, any point sources detected in the Chandra data that fell within the 250” source region used for the spectral analysis were not resolved in the NuSTAR observations, and so were not excluded in the NuSTAR spectral analysis. However, in all cases these point sources were faint. Within the 250” source spectrum region, the count rate from resolved point sources measured with Chandra was at most 3% of the total emission, in any of the energy bands used for the Chandra and NuSTAR spectral analysis. We verified that excluding the point sources in the Chandra analysis did not impact the temperatures by measuring the temperature of A2146 (which had the maximum 3% point source contamination) without excluding the sources. Retaining the point sources increased the Chandra temperature by 1%.

Radial surface-brightness profiles of the cluster emission were used to define the radii beyond which the cluster emission was negligible compared to the background in the Chandra observations. This enabled the definition of local background regions within which the local and blank-sky background spectra could be compared.

The background spectra were normalised to match the count rate in the hard X-ray band (9.5–12 keV). The residual

\begin{table}
\centering
\begin{tabular}{llllllllll}
\hline
Cluster Name & \textit{NuSTAR} ObsID & \textit{Chandra} ObsID & \( t_N \) & \( t_C \) & Redshift & \( N_{\rm H} \) & RA & Dec \\
& & & ks & ks & & \( (10^{22} \text{ cm}^{-2}) \) & degrees & degrees \\
\hline
Abell 2146 & 70401001002 & 7001010002 & 226 & 12247, 12245 & 114 & 0.232 & 0.0337 & 239.042 & 66.355 \\
Abell 2163 & 70101002002 & 7001010002 & 99 & 1653 & 71 & 0.203 & 0.2060 & 243.942 & -6.143 \\
Abell 2256 & 70010103002 & 7001010002 & 86 & 16514, 16129 & 89 & 0.058 & 0.0494 & 255.975 & 78.636 \\
Abell 523 & 70301001002, 70102001004 & 184 & 15321 & 30 & 0.104 & 0.1590 & 74.779 & 8.753 \\
Abell 465 & 70201002002, 70201003002 & 164 & 13261, 12286 & 89 & 0.183 & 0.0507 & 127.729 & 65.853 \\
Abell 754 & 70201001002 & 104 & 10743 & 94 & 0.054 & 0.0579 & 137.346 & -9.684 \\
1E 0657-56 & 70010105002, 70010105002 & 251 & 3184, 4986 & 121 & 0.296 & 0.0643 & 104.621 & -55.944 \\
RX J1347.5-1145 & 70301001002, 70301001004 & 142 & 3592 & 57 & 0.451 & 0.0581 & 206.879 & -11.753 \\
\hline
\end{tabular}
\caption{Summary of the clusters analysed in this work. The columns give the cluster name, \textit{NuSTAR} ObsID(s) and total cleaned exposure time (\( t_N \)), \textit{Chandra} ObsID(s) and total cleaned exposure time (\( t_C \)), redshift, hydrogen column density (taken from Willingale et al. 2013), right ascension and declination. The coordinates given correspond to the centre of the source region used to extract the spectra for our analysis.}
\end{table}
als between the local and blank-sky background spectra were then primarily due to differences in soft Galactic foreground emission at < 2 keV. To account for this, the residuals were fit with an unabsorbed APEC model with a temperature of 0.18 keV and solar abundance, which was then included in the subsequent analysis of the source spectrum.

Since the target clusters are bright and relatively nearby, in some cases the cluster emission fills a large fraction of the Chandra FOV, and may be present in the regions defined for the background analysis. As discussed in §5, due to the high signal-to-noise of the source spectra, any cluster emission in the background region is not expected to significantly influence the temperature measurement.

The cluster spectra were then extracted for each observation using the 250” circular source regions defined for the NuSTAR analysis. For illustration, a comparison of the NuSTAR and Chandra images of 1E 0657-56 is shown in Figure 2, with the spectral extraction region shown in magenta, and the NuSTAR FOV overlaid on the Chandra image in white. The images of all clusters are presented in Appendix A.

3.3 Spectral fitting

The cluster spectra were modelled with a single temperature, absorbed APEC model convolved with the appropriate ARF and RMF for the regions used. The spectra were fit in XSPEC (Arnaud 1996), using the cstat statistic, with the normalisation, temperature and metallicity free to vary when fitting, while the N\H and redshift were frozen. The absorption was modelled with phabs, and the values for N\H were derived from Willingale et al. (2013), with XSPEC’s default abundance table from Anders & Grevesse (1989).

For the NuSTAR analysis, the spectra were fit between 3 – 10 keV (hereafter referred to as the hard band), which is close to optimal given the instrument response and typical cluster spectrum. For Chandra, the spectra were fit in the hard band for consistency with NuSTAR, and in the 0.6 – 9 keV band (hereafter referred to as the broad band), which is more suitable for Chandra analyses given the softer response.

For the NuSTAR observations, the temperature was measured for the FPMA and FPMB detectors individually, as well as by fitting a single source model to the spectra from the two detectors simultaneously. Clusters with two NuSTAR observations (Abell 523, Abell 665, 1E 0657-56 and RX J1347.5-1145) were fit individually and combined, with the same being done for Chandra data when two observations were used (Abell 665, Abell 2146, Abell 2256, and 1E 0657-56).

3.4 Notes on individual clusters

In this section we note any departures that were required from the standard analysis described in the preceding sections.

3.4.1 Abell 754

For Abell 754, the location of the cluster within the NuSTAR FOV meant that the 250” circular source region extended off the edge of the detectors in both observations. The part of the region that fell off the detector in any of the data was excluded from all of the NuSTAR and Chandra spectral extractions.
3.4.2 Abell 2163

For the *Chandra* analysis of A2163, the lightcurve showed a gradient over the duration of the observation, indicating possible a low-level background flare. The lightcurve was manually cleaned to select a 20 ks period where the background appeared stable. After this filtering, the comparison between the local and blank-sky background showed a strong excess in the local background below 2 keV, with some hints of excess emission up to ∼7 keV, which could indicate residual flare contamination. Abell 2163 is also located near the North Polar Spur (NPS), giving it a particularly complex soft background component and strong $N_H$ gradient across the cluster (Pratt et al. 2001; Bourdin et al. 2011; Rojas Bolivar et al. 2021).

As a result we consider the *Chandra* temperature measurement for this cluster to be less reliable than for the other clusters in our sample, particularly for the spectral fit in the broad band, and hence we exclude the broad-band temperature from our main analysis.

3.4.3 Abell 2256

For this cluster, the local background spectrum in the *Chandra* data had a significant excess above the blank-sky background below ∼2 keV. Unlike Abell 2163 there was no indication of residual flaring in the lightcurve. This is a bright, nearby cluster with significant emission from the ICM across most of the *Chandra* FOV (see Figure 9). We thus interpret the excess in the local background as being due to emission from the ICM and/or a particularly strong soft Galactic foreground, which was not modelled completely by the APEC component in the standard data processing. To account for this, the temperature of the APEC component used to model the soft Galactic foreground was unfrozen, and the best fitting values (0.86 keV and 0.94 keV for observations 16514 and 16129, respectively) were used in the subsequent analysis.

We note that if the excess in the local background were due to contamination of the background spectrum by emission from the ICM, then this could lead to the flux of the soft Galactic foreground model component being overestimated and hence the cluster temperature being overestimated. However, given the very high signal to noise of the cluster spectrum within 250", this is not expected to have a significant effect.

4 RESULTS

4.1 Temperatures

The global temperatures measured for each cluster are presented in Table 2. $kT_C(0.6-9)$ denotes the temperatures from the *Chandra* data when fit in the broad band, while $kT_C$ denotes the *Chandra* temperatures measured in the hard band. $kT_N$ denotes the temperatures measured from the *NuSTAR* data when fit in the hard band. The temperatures reported here are from joint spectral fits to all available detectors and observations for each cluster. When fit individually, the differences in temperatures between detectors and observations for a given cluster were consistent with the statistical uncertainties.

Figure 3 presents the comparison between the hard-band *NuSTAR* temperatures and those measured with *Chandra* in the broad band. This is intended to reflect the optimal energy bands used for temperature measurements with each observatory. This comparison clearly shows that the temperatures measured by *Chandra* are systematically higher than those measured by *NuSTAR* for the clusters in our sample.

While the 0.6–9 keV band is most appropriate for spectral analysis with *Chandra* due to the signal-to-noise of the cluster and effective area of the telescope, a more direct comparison with *NuSTAR* temperatures can be made using the *Chandra* temperatures made in the same hard band used for the *NuSTAR* analysis. In the presence of multi-phase gas in the ICM, one would expect the temperature measured with *Chandra* in the hard band to be higher than that measured in the broad band. This comparison is shown in Figure 4, which shows a tendency for the *Chandra* hard-band temperatures to be higher than the broad-band temperatures, but the effect is not statistically significant. As noted in §3.4.2, Abell 2163 is a significant outlier due to the unreliable *Chandra* temperature measurement in the broad band. It is also apparent from Figure 4 that the statistical error on the temperature is larger when fit in the hard band, particularly for the coolest cluster (Abell 523). This is unsurprising given the lower signal to noise in the *Chandra* data above 3 keV.

The clusters in our sample are well-known and have multiple temperature measurements in the literature from *Chandra*, and in many cases from *NuSTAR*. However, the complex thermal structures of these clusters (again, they were mainly selected for *NuSTAR* observation due to their disturbed dynamical state) means that temperature measurements will be sensitive to the region used for the spectral extraction and the energy range used for spectral fitting. For this reason, there is significant variation in temperature measurements from different analyses, and we forgo mak-
The fit is also performed with 

drawn in the 0

Figure 4. The 

Table 2. The temperature measurements for the cluster sample. \(kT_{C,(0.6-9)}\) denotes the temperatures from the *Chandra* data when fit in the 0.6-9 keV energy band, while \(kT_C\) denotes the *Chandra* temperatures measured in the 3-10 keV band. \(kT_N\) are the temperatures measured from the *NuSTAR* data when fit in the 3-10 keV energy band. \(^{†}\)We consider the \(kT_{C,(0.6-9)}\) measurement to be unreliable for this cluster (see §3.4.2).  

![Table 2](image)

**Figure 4.** The *Chandra* temperatures measured for spectra fit between 3-10 keV are plotted against those measured with *Chandra* in the 0.6-9 keV band. Note that Abell 2163 is a significant outlier due to the unreliable temperature measurement in the 0.6-9 keV band (see §3.4.2).

The temperature measurements for the cluster sample.

### 4.2 Cross-calibration

To quantify the cross-calibration between *NuSTAR* and *Chandra* temperatures, we follow Schellenberger et al. (2015) and fit a power law model to the data. The fitting was performed using a linear model in log space using *Linmix*, which performs a Markov chain Monte-Carlo sampling of the model likelihood, and accounts for measurement errors in both axes and intrinsic scatter (Kelly 2007). The form of the scaling relationship used for this analysis is

\[
\log_{10}(kT_N) = \beta \times \log_{10} \left( \frac{kT_C}{10 \text{ keV}} \right) + \alpha \quad (1)
\]

The fit is also performed with \(kT_{C,(0.6-9)}\) in place of \(kT_C\) when comparing *NuSTAR* temperatures with broad-band temperatures from *Chandra*. When using broad-band *Chandra* temperatures, Abell 2163 was excluded as discussed in §3.4.2.

The results of the fits are presented in Table 3, and the best fitting model for the broad-band *Chandra* temperatures is plotted along with the data in Figure 5. The uncertainties on the fit parameters are derived from the median and 68th and 95th percentiles of parameter chains sampled by *Linmix*, corresponding to \(\sigma\) uncertainty. For both *Chandra* energy bands, the power law slope is consistent with unity and the intrinsic scatter between *NuSTAR* and *Chandra* is negligible. However there is evidence for the *Chandra* temperatures being systematically higher. We quantify this by using the best fitting model to calculate the percentage difference between the *NuSTAR* and *Chandra* temperatures at a *Chandra* temperature of 10 keV.

We find that the broad-band *Chandra* temperatures are on average (10.5±3.7)% higher at a *Chandra* temperature of 10 keV than those measured with *NuSTAR* (in the 3-10 keV band). Similarly, the hard-band *Chandra* temperatures are found to be (15.7±4.6)% higher than *NuSTAR* temperatures at a *Chandra* temperature of 10 keV.

Figure 5 also shows the cross-calibration model for *Chandra* and XMM-Newton temperatures derived by Schellenberger et al. (2015) (for a different set of clusters). This gives an indication of the relative temperature calibrations of the three telescopes, and is discussed further in §5. Figure 6 shows the comparison between the cross-calibration fits for both the broad and hard-band *Chandra* temperatures.

### 5 DISCUSSION

Our comparison of cluster temperature measurements with *NuSTAR* and *Chandra* shows that the *Chandra* temperatures are systematically higher. In the following we discuss possible sources of systematic uncertainty on our temperature measurements, and the limitations and implications of our cross-calibration measurement.
Table 3. The cross-calibration between Chandra and NuSTAR. \( \alpha \) and \( \beta \) are the intercept and gradient from equation 1. \( \epsilon \) is the intrinsic scatter from Limma, and \( \Delta_{10k eV} \) is the percentage difference between the two detectors when the instrument \( X \) is at 10 keV. Energy Band \( C \) is the energy band in which a model was fit to the Chandra observation spectra.

| Chandra Energy Band | \( \alpha \) | \( \beta \) | \( \epsilon \) | \( \Delta_{10k eV} \) (\%) |
|---------------------|-------------|-------------|-------------|----------------|-----------------|
| 0.6–9 keV           | 0.952 ± 0.018 | 0.98 ± 0.13 | 0.002±0.003 | 0.006–0.001 | 10.5 ± 3.7 |
| 3–10 keV            | 0.926 ± 0.024 | 0.99 ± 0.19 | 0.002±0.006 | 0.006–0.001 | 15.7 ± 4.6 |

5.1 Systematics on temperature measurements

We explored the possible impact on our results of uncertainties in the background modelling in the spectral analysis. We found that due to the high signal-to-noise of the clusters on the background modelling in the spectral analysis. We tested the robustness of our temperatures by allowing the normalisations of the “aperture” background and “fCXB” components to fit independently to the spectra from each background region and then used the variation between regions as an estimate of the uncertainty on those components. The cluster temperatures were remeasured with the normalisation of those background components varied within these ranges.

For both the aperture and fCXB components, the resulting variation in cluster temperatures was less than or equal to the statistical uncertainty on the temperature measurement (with the exceptions of A523 where the aperture background gave a systematic of ±6\% on the temperature compared to a 2\% statistical error, and A2256 where the fCXB gave a systematic of ±4\% compared to a 1\% statistical error on the temperature. The change in normalisation of both background components is anti-correlated with the change in temperature, so if one of the background components were reduced by 1\sigma for all clusters, the temperatures would increase by an average amount that was less than the statistical errors. These systematics are thus subdominant to the systematic difference between NuSTAR and Chandra temperatures.

As discussed in §3.1 we also considered the uncertainty on the NuSTAR model background due to the possible presence of cluster emission in the background regions, and found this had negligible impact on the NuSTAR temperatures. The inclusion (or not) of this extra background com-
ponent produced a change in temperature that was always smaller than the statistical errors, and did not systematically increase or decrease the temperatures.

Furthermore, for all clusters, when the temperatures were measured independently for the FPMA and FPMB detectors, or independently for multiple observations, the agreement was good (e.g. the mean ratio of the FPMA to FPMB temperatures, computed in log space, was 0.99 with a standard deviation of 0.06).

For each cluster, the largest difference in temperature from any of the individual systematics investigated above was used as an estimate of the systematic temperature error for NuSTAR. The cross-calibration fit was repeated using these systematic errors in place of the statistical errors on the temperatures. This made a negligible difference to the values of the best-fitting parameters or their uncertainties (as presented in table 3). We thus used only the statistical uncertainties on the temperatures in our analysis.

For Chandra, the availability of blank-sky background spectra, and the ability to compare them with the in-field background meant the systematic uncertainties due to the background modelling were minimal.

5.2 Chandra / NuSTAR cross-calibration

Our cross-calibration analysis shows that for all clusters in the sample, NuSTAR measures their temperatures to be lower than Chandra. This is unexpected, since the harder response of NuSTAR should make it more sensitive to any hotter components present in the cluster spectrum. If both telescopes were perfectly calibrated then for any non-isothermal cluster, it would be expected that NuSTAR would measure a higher temperature than Chandra.

The use of different energy bands for the spectral fitting between the two telescopes would also contribute to systematic temperature differences. The broader band typically used for Chandra spectral analysis (0.6 – 9 keV here), compared with the harder band (3 – 10 keV here) used for NuSTAR should further exacerbate any temperature discrepancy, increasing the contribution of lower temperature components in a multiphase ICM to the global Chandra temperature measurement.

Our results show that regardless of the energy band used, the Chandra temperatures were systematically higher than those measured with NuSTAR. When the broad band was used, the Chandra temperatures were (10.5 ± 3.7)% higher at a Chandra temperature of 10 keV. When the hard band was used for the Chandra analysis, the Chandra temperatures increased (as would be expected) and were higher than the NuSTAR temperatures by (15.7 ± 4.6)% at a Chandra temperature of 10 keV.

The fact that the temperature difference is significant when the data from both telescopes were fit in the hard (3 – 10 keV) band is interesting. This contrasts to some extent with previous cross-calibration work that has identified the calibration of X-ray telescopes at lower energies as largely responsible for temperature differences.

For example, Schellenberger et al. (2015) found strong evidence that cluster temperatures from Chandra and XMM-Newton were inconsistent (at > 5σ) when the spectra were fit in either soft (0.7 – 2 keV) or broad (0.7 – 7 keV) energy bands. When temperatures were measured in a hard (2 – 7 keV) band, the inconsistency was less significant (at the ≈ 1 – 4σ level depending on the combination of XMM-Newton detectors used). For these hard-band temperatures, the average XMM-Newton temperature was between 0% and 10% lower than the average Chandra temperature at a Chandra temperature of 10 keV.

The disagreement we find between Chandra and NuSTAR when Chandra temperatures are measured in the hard band suggests that temperature difference is not driven by factors affecting the Chandra measurements at low energies. This disfavors some possible origins for the temperature difference. For example, the uncertainty associated with the soft Galactic foreground modelling, or variations in the absorbing column (e.g. §3.4.2 and 3.4.3) will not impact the temperatures measured in the hard band. Similarly, uncertainties on the modelling of the contamination build-up on Chandra’s optical blocking filter (Weisskopf et al. 2000) should not impact the hard-band temperatures.

5.3 Implications for Chandra / XMM-Newton cross-calibration

Figure 5 presents the scaling relationship between Chandra and XMM-Newton derived in Schellenberger et al. (2015) alongside the NuSTAR-Chandra cross-calibration derived in our analysis. Here we show the “ACIS-Combined XMM Full” model from Schellenberger et al. (2015), measured in the 0.7 – 7 keV energy band, while our NuSTAR and XMM-Newton temperatures are measured in the 0.6 – 9 keV and 3 – 10 keV bands, respectively. The scaling relationship from Schellenberger et al. (2015) is not directly comparable with our results due to a number of differences in the analyses (e.g. the comparison was made for different clusters, using a different definition for regions for the spectral extraction, and different energy bands for the spectral fitting), but it provides a useful indication of the relative direction and size of the differences between the temperatures measured with different instruments.

Taken at face value, this comparison suggests that both NuSTAR and XMM-Newton temperatures are systematically lower than those measured with Chandra (in the conventionally used broad band). Furthermore, while we lack the data to directly compare NuSTAR and XMM-Newton temperatures for the same clusters, the comparisons of each with Chandra in Figure 5 imply that the NuSTAR temperatures would be systematically higher than XMM-Newton. Hotter NuSTAR temperatures are expected in the presence of multi-phase ICM, given the harder NuSTAR response relative to XMM-Newton. The implication of this indirect comparison (that NuSTAR temperatures are hotter than XMM-Newton but cooler than Chandra) thus qualitatively favours consistency between NuSTAR and XMM-Newton, with Chandra being the outlier.

The picture is more complicated when hard-band temperatures are considered. This is illustrated in Figure 7, which shows the cross-calibration between Chandra hard-band temperatures and NuSTAR, along with the best-fitting relation between XMM-Newton and Chandra temperatures measured in the hard band from Schellenberger et al. (2015), we show their “ACIS-Combined XMM Hard” model, measured in the 2 – 7 keV band). Again, this relation was derived for different clusters with a different hard-band definition,
so is intended only as an illustration of the relative calibrations. This comparison implies that the hard-band temperatures measured with XMM-Newton may be hotter than those measured with NuSTAR, however the systematic differences between these studies make it difficult at present to explore this in more detail.

The relatively good agreement between hard-band Chandra and XMM-Newton temperatures found by Schellenberger et al. (2015) and illustrated in Figure 7 imply that NuSTAR may be the outlier in this band. It is thus reasonable to consider whether the differences we find between NuSTAR and Chandra temperatures could be driven by uncertainties in the NuSTAR calibration. However, in their recent NuSTAR calibration update (CALDB 20211020), Maesen et al. (2021) found good agreement between measurements of the Crab made with light that passed through the optics compared with stray light (which has a trivial effective area). Although we did not use CALDB 20211020 for our main analysis, we have verified that this CALDB update has negligible effect on our cluster temperatures, and so this increases confidence that the discrepancy we have found is not due to NuSTAR calibration uncertainties.

Furthermore, two new (optional) updates to the XMM-Newton effective area have recently been released which improve the internal agreement between the MOS and pn detectors, and also produce agreement with NuSTAR in the hard band\(^4\). This is expected to move XMM-Newton hard-band temperatures into better agreement with NuSTAR. We thus conclude that the apparent agreement between hard-band Chandra and XMM-Newton temperatures, and discrepancy with NuSTAR implied by the comparison between our work and Schellenberger et al. (2015) does not constitute strong evidence that the difference is driven by uncertainties in the NuSTAR calibration.

5.4 Impact of multi-phase ICM

As discussed previously, systematic differences in global temperatures are expected even for perfectly calibrated instruments if their energy responses differ and the source has multiple temperature components. It is therefore instructive to measure the temperature structure of the ICM in our target clusters. This was done by measuring radial temperature profiles from the Chandra data.

The profiles were constructed by extracting and fitting spectra following the methods described in §3.2 and 3.3. Spectra were extracted from annular regions centred on the same location used for the global temperature measurement, with the widths of each annulus set such that the signal to noise of the resulting spectrum was at least 30.

The measured temperature profile of Abell 2256 is shown as an example in Figure 8, with the profiles of the other clusters shown in Appendix B. On the temperature profile plots we also show the global temperatures measured by Chandra and NuSTAR. For these comparisons the Chandra temperatures were measured in the 0.6 – 9 keV band, while the 3 – 10 keV band was used for NuSTAR.

The temperature profiles show that for each cluster,

\(^4\) https://xmmweb.esac.esa.int/docs/documents/CAL-TN-0018.pdf

Figure 7. The cross-calibration between NuSTAR and Chandra temperatures measured in the 3 – 10 keV band. The best fitting power-law model to the data is shown in blue, and the black dashed line indicates a perfect agreement between the temperatures. The dashed pink line shows, for illustrative purposes, the best fitting power-law to the cross-calibration of temperatures measured with XMM-Newton versus Chandra derived in Schellenberger et al. (2015) (we show their “ACIS-Combined XMM hard” model, with XMM-Newton temperatures in place of NuSTAR temperatures on the vertical axis). Note that the comparison with the result from Schellenberger et al. (2015) is not precise due to the different energy bands used for their temperature measurements, but illustrates the relative cross-calibration of the temperatures between the three telescopes.

the global NuSTAR temperature is lower than the Chandra temperature found in the majority of the radial bins that overlap with the global temperature region. This underlines the systematic nature of the temperature difference. While each temperature bin will contain multiphase gas across its radial extent and projected along the line of sight, the profiles do not suggest that the global Chandra temperature is higher than NuSTAR due to their different weighting of different temperature components across the 250 arcsecond global temperature region.

In principle, the global NuSTAR and Chandra temperature could differ due to X-ray photons scattered into the global temperature extraction region by the large NuSTAR PSF. In order for this to produce systematically lower NuSTAR temperatures, there would need to be bright, cool regions of emission outside the 250 arcsecond global temperature region (possibly outside the NuSTAR FOV). No such emission was apparent in the Chandra images of these clusters, and the temperature profiles show no evidence for the systematic presence of large amounts of cool gas outside the global temperature extraction region.

It is clear from the temperature profiles of the clusters in our sample that they have complex thermal structures, which will contribute differently to the NuSTAR and Chandra global temperatures. The optimal calibration sources would be isothermal to avoid this effect. For example, Schellenberger et al. (2015) removed the central regions of cool core clusters to create spectra that were closer to isothermality. For our sample, the clusters are mainly mergers, without
The impact of temperature calibration uncertainties was explored by Wan et al. (2021) in the context of combining X-ray and Sunyaev-Zel’dovich effect (SZE) measurements of the pressure in the ICM to constrain the Hubble constant. Wan et al. (2021) found that the uncertainty on the temperature calibration was the dominant systematic, with a ≈ 10% decrease in X-ray temperatures leading to an increase in $H_0$ of ≈ 10 km s$^{-1}$ Mpc$^{-1}$. When using external priors on the value of $H_0$, they found evidence that the Chandra temperatures used in their analysis were over-estimated by ≈ 10% due to calibration uncertainties. This is consistent with the results of our comparison of Chandra and NuSTAR temperatures.

6 SUMMARY AND CONCLUSIONS

We performed an X-ray spectral analysis on a sample of eight bright galaxy clusters to produce the first cross-calibration between NuSTAR and Chandra temperature measurements of the ICM. We found that Chandra systematically finds ICM temperatures that are higher than those measured with NuSTAR. We fit a power-law model to the temperatures and found that at a Chandra temperature of 10 keV, the average NuSTAR temperature was (10.5 ± 3.7)% and (15.7 ± 4.6)% lower than that of Chandra, when the Chandra spectra were fit in the broad (0.6 – 9 keV) and hard (3 – 10 keV) energy bands, respectively (the NuSTAR spectra were always fit in the hard band).

We examined the impact of uncertainties on the background modelling and found that due to the high signal-to-noise of the cluster spectra, our results were insensitive to the details of the background modelling. We also examined the thermal structure of the clusters using temperature profiles from the Chandra data, and found no evidence that NuSTAR temperatures were being biased by emission from cool gas scattered from outside the spectral extraction region by the larger NuSTAR PSF.

The fact that, when limited to the hard band for spectral fitting, the Chandra temperature remains systematically higher than that from NuSTAR, implies that the discrepancy is not driven by factors influencing the modelling at soft energies. These include systematics in the modelling of the absorbing column in the spectral analysis, and the calibration of the Chandra effective area at soft energies to account for the ACIS contamination build-up.

We conclude that the difference is most likely due to

Figure 8. The Chandra temperature profile of Abell 2256 is plotted in green. The global temperature across a circular region of radius 250 arcseconds is also shown for Chandra (red) and NuSTAR (blue). Chandra and NuSTAR temperatures are measured in the 0.6 – 9 keV and 3 – 10 keV bands respectively.

5.5 Implications of the NuSTAR temperature calibration

Our results imply a systematic uncertainty on X-ray temperature measurements of clusters that is of order 10 – 15%. This is much larger than the typical statistical uncertainty on temperatures for clusters with good-quality data such as those studied here, and is one of the dominant systematics for many applications of cluster temperatures. For example, hydrostatic masses depend directly on temperatures and their radial gradients so are directly impacted by temperature systematics. Schellenberger et al. (2015) showed that the difference between their broad-band Chandra and XMM-Newton temperatures gave rise hydrostatic masses that were ≈ 15% higher when assuming the Chandra calibration was correct compared to assuming the XMM-Newton calibration was correct.

Measuring hydrostatic masses for our sample is beyond the scope of the current paper (and the dynamically unrelaxed of the clusters make them unsuitable for such analyses), but as discussed in 5.2, our NuSTAR temperatures appear more consistent with broad-band temperatures from XMM-Newton rather than Chandra. We thus expect that assuming the NuSTAR temperature calibration would lead to results similar to those derived from XMM-Newton temperatures by Schellenberger et al. (2015), with hydrostatic masses that were ≈ 15% lower than those determined from Chandra. This would then mean that determinations of the hydrostatic bias derived from Chandra data would underestimate the level of hydrostatic bias by ≈ 15%. In other words, assuming the NuSTAR temperatures were correct would not reduce the amount of hydrostatic bias needed to fully align the Planck constraints on $\sigma_8$.
systematic uncertainties in the calibration of one or both of the instruments. However, given that the presence of multiphase gas in the ICM is expected to lead to a more average temperature than Chandra or XMM-Newton, combined with previous findings that Chandra temperatures are systematically higher than those of XMM-Newton (Schellenberger et al. 2015), we cautiously conclude that the evidence from NuSTAR favours the XMM-Newton temperature calibration when temperatures are fit in the conventional broad bands. However, the picture is less clear for temperatures measured in the hard band, and a more robust conclusion will require a direct comparison of NuSTAR, Chandra, and XMM-Newton temperatures for the same clusters. Given that the sample used for the current analysis are thermally complex, merging systems, the definitive cross-calibration study should be deferred to a sample of relaxed clusters for which isothermal regions can be defined.

Our overall conclusion is that the average NuSTAR temperature measurement is 10 – 15% lower than that of Chandra (at 10 keV), most likely due to calibration differences between the observatories. Given the non-isothermal nature of the clusters studied, this is likely to be a lower limit on the difference in the relative temperature scales.

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DATA AVAILABILITY
All observations for the X-ray data analysis are publicly available at the Chandra and NuSTAR Data Archives.

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A CLUSTER IMAGES
The Chandra and NuSTAR images of the eight clusters in the sample are shown in Figures 9 – 11. In each image, the magenta circle shows the region in which the source spectra were extracted. The white square shows the region covered by the NuSTAR detectors overlaid on the Chandra image.

B TEMPERATURE PROFILES
Figures 12 and 13 show the temperature profiles created using Chandra for the eight galaxy cluster in this sample, following the methods described in §3.2, 3.3 and 5.4. Over-plot are the global temperatures of the clusters measured by Chandra and NuSTAR across the chosen source region.

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Figure 9. Chandra (left) and NuSTAR (right) images of A2146, A2163 and A2256. The NuSTAR images are background subtracted and in the 3 – 20 keV energy band, while the Chandra image is in the 0.7 – 2 keV energy band. All images are smoothed with a Gaussian with $\sigma = 6.25^\circ$. The magenta circle shows the region in which the source spectra were extracted. The white square shows the region covered by the NuSTAR detectors overlaid on the Chandra image.
Figure 10. Chandra (left) and NuSTAR (right) images of A523, A665 and A754. The NuSTAR images are background subtracted and in the 3 – 20 keV energy band, while the Chandra image is in the 0.7 – 2 keV energy band. All images are smoothed with a Gaussian with $\sigma = 6.25^\circ$. The magenta circle shows the region in which the source spectra were extracted. The white square shows the region covered by the NuSTAR detectors overlaid on the Chandra image.
Figure 11. Chandra (left) and NuSTAR (right) images of 1E 0657-56 and RX J1347.5-1145. The NuSTAR images are background subtracted and in the 3 – 20 keV energy band, while the Chandra image is in the 0.7 – 2 keV energy band. All images are smoothed with a Gaussian with $\sigma = 6.25''$. The magenta circle shows the region in which the source spectra were extracted. The white square shows the region covered by the NuSTAR detectors overlaid on the Chandra image.
Figure 12. Temperature profiles of clusters A2256, A665, A754 and A2163 plotted in green. The global temperature across a circular region of 250 arcseconds is shown for Chandra (red) and NuSTAR (blue). Chandra and NuSTAR temperatures are measured in the 0.6 – 9 keV and 3 – 10 keV bands respectively. Notes that due to problems in the background of the Abell 2163 Chandra observation at low energies ($\S$3.4.2), the global temperature from the fit between 0.6-9 keV was not used in our main analysis. The temperature fit between 3-10 keV (pink) was alternatively plot.
Figure 13. Temperature profiles of clusters A523, A2146, 1E 0657-56 and RX J1347.5-1145 plotted in green. The global temperature across a circular region of 250 arcseconds is shown for Chandra (red) and NuSTAR (blue). Chandra and NuSTAR temperatures are measured in the $0.6 - 9$ keV and $3 - 10$ keV bands respectively.