

Cool Cores in Clusters of Galaxies in the Dark Energy Survey

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ABSTRACT

We search for the presence of cool cores in optically-selected galaxy clusters from the Dark Energy Survey (DES) and investigate their prevalence as a function of redshift and cluster richness. Clusters were selected from the redMaPPer analysis of three years of DES observations that have archival Chandra X-ray observations, giving a sample of 99 clusters with a redshift range of $0.11 < z < 0.87$ and a richness range of $25 < \lambda < 207$. Using the X-ray data, the core temperature was compared to the outer temperature to identify clusters where the core temperature is a factor of 0.7 or less than the outer temperature. We found a cool core fraction of approximately 20% with no significant trend in the cool core fraction with either redshift or richness.

1. INTRODUCTION

Galaxy clusters and the intra-cluster medium (ICM) are excellent probes of the evolution of large-scale structure. Understanding the thermodynamics of clusters and the ICM is essential to understanding their growth. The X-ray emitting ICM in the center of clusters is dense enough that it should be able to radiatively cool in less than the Hubble time (e.g. Fabian 1994; White et al. 1997). This central cooling gas would be compressed by the external, hotter gas creating a “cooling flow”. However, observations show that the central gas does not cool all the way down producing the expected star formation and neutral gas, forming instead a “cool core” and indicating the presence of some form of feedback such as AGN feedback that prevents the cluster from fully cooling (e.g. Peterson & Fabian 2006). Cool-core clusters are of interest as understanding their evolution may help understand the processes like cluster mergers and AGN feedback which can disrupt cooling and

provide sources of heating (e.g. Voit 2005; McNamara & Nulsen 2007; Hudson et al. 2010; Fabian 2012; McNamara & Nulsen 2012; McDonald et al. 2018).

One might expect trends in the level of cooling and the fraction of clusters with cool cores as a function of redshift and cluster mass (e.g Santos et al. 2010; McDonald et al. 2013; Pascut & Ponman 2015). Redshift trends in the cool-core fraction will depend on factors such as the possibly evolving level of AGN feedback, the AGN on-off duty cycle and its relation to cooling, the cluster merger rate, the extent to which mergers disrupt cooling, and the post merger relaxation timescale (e.g. Henning et al. 2009; Gaspari et al. 2011). The evolution of cool core clusters as a function of mass is also of interest. As the gas in low mass clusters and groups is less gravitationally bound, AGN feedback can be more effective (e.g. McCarthy et al. 2010; Eckert et al. 2021), and in fact strong cool cores are not observed in groups hosting a strong, radio-loud AGN, opposite the trend seen for clusters (Sun 2009; Bharadwaj et al. 2014).

This paper examines the cool core fraction in a sample of 99 optically-selected clusters as a function of redshift and richness. We also investigate the distributions of the ratio of core temperature to the temperature of the cluster at larger radii ignoring the core in bins of redshift and richness.

2. DATA ANALYSIS AND RESULTS

Our sample is drawn from Chandra observations of DES clusters selected by the redMaPPer algorithm (Rykoff et al. 2014), specifically the Y3 6.4.22+2 catalog. We used the Mass Analysis Tool for Chandra (MATCHa, Hollowood et al. 2019) pipeline to determine cluster X-ray temperatures and luminosities, as well as to perform centering measurements for the redMaPPer clusters which have archival Chandra data (Kelly et al. in prep.). In this work, we use an updated version of MATCHa that fits the core temperature of clusters within $0.15r_{500}$ of the X-ray peak as well as core-cropped r_{500} temperature, where r_{500} is the radius at which the density is 500 times the critical density. Clusters with observations of insufficient depth such that the core temperature or r_{500} core-cropped temperature fits failed were not included; we also removed clusters that were flagged as contaminated by a foreground/background cluster, had Chandra data taken in a non-imaging mode, or had a signal-to-noise ratio within a radius of 500 kpc less than 9 (see Hollowood et al. 2019; Kelly et al. in prep.). With these filters, we were left with a sample of 99 clusters with $0.11 < z < 0.87$ and $25 < \lambda < 207$. This sample size is similar to previous works that analyzed cool core fraction using X-ray data (e.g Santos et al. 2010; McDonald et al. 2018; Ruppin et al. 2021).

To classify cool-core clusters, we measured the ratio of core temperature within $0.15r_{500}$ to the r_{500} core-cropped temperature (T_{core}/T_{r500}). Core temperatures had an average uncertainty of approximately 20%; temperature errors had a negligible effect on the derived cool-core fractions compared to the statistical errors given the limited sample size. Any cluster with a ratio of core to non-core temperature less than 0.7 was defined to be a cool core cluster. This definition is a simplification of the definition in Hudson et al. (2010) whose well-sampled data allowed fitting of the temperature profile to the virial radius and determination of the core size. By this definition, our sample contained 21 cool-core clusters and 78 non cool-core clusters. We looked at the distributions of T_{core}/T_{r500} in bins of redshift and richness to see if cooling occurs at comparable levels. We used two bins for each with nominal splits at $z = 0.45$ for redshift and $\lambda = 100$ for richness, roughly the means of the sample's redshift and richness, respectively. These split values were varied, but had little to no impact on the resulting distributions. The nominal redshift bins had 32 high-redshift clusters and 67 low-redshift clusters, and the bins of richness had 54 high-richness clusters and 45 low-richness clusters.

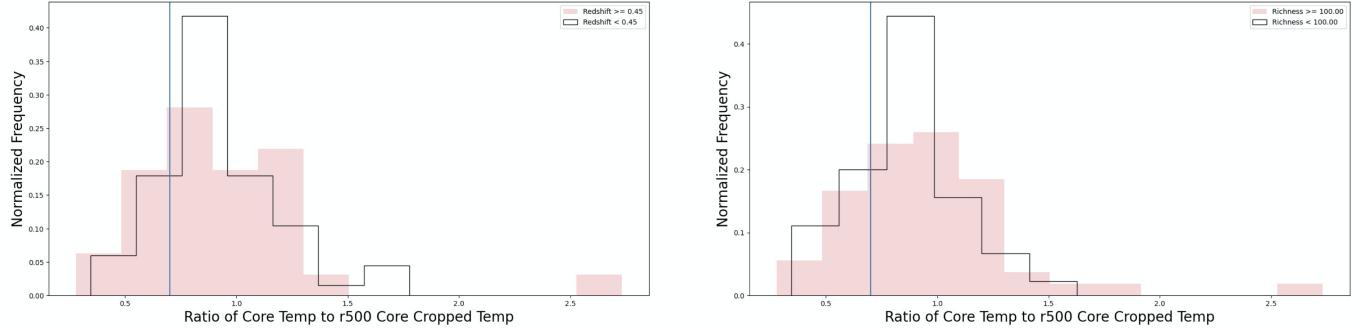


Figure 1. *Left:* Histograms of the distributions of T_{core}/T_{r500} for clusters with $z \geq 0.45$ (pink) and $z < 0.45$ (blue). The blue line indicates a temperature ratio of 0.7 below which is our adopted definition of cool core clusters. *Right:* Histograms of the distributions of core to outer temperature for clusters with $\lambda \geq 100$ (pink) and $\lambda < 100$ (blue); the blue vertical line again indicates our adopted cool-core cut.

Histograms of T_{core}/T_{r500} are shown in Figure 1 for the bins of low versus high redshifts (left) and low versus high richnesses (right). As can be seen in the figure, the distributions of temperature ratio are similar for both the redshift and richness bins. To quantify this we ran a two-sample Kolmogorov-Smirnov Test (KS Test) on both sets of distributions. For the redshift bins, the KS test gave a p-value of 0.74 while for the bins of richness the p-value was 0.75, indicating no significant difference in both cases.

We also calculated the fraction of cool cores in each redshift and richness bin. This resulted in a cool-core fraction of 0.25 ± 0.09 for high redshifts and 0.19 ± 0.05 for low redshifts, which are consistent within the uncertainties. Uncertainties were estimated by taking the square root of the number of cool cores in each bin. We also varied the redshift split to see if these fractions changed significantly, but in all cases the cool-core fraction was found to be roughly 0.2 indicating little dependence on redshift. The cool-core fraction for high richness was found to be 0.22 ± 0.06 while for low richness it was found to be 0.20 ± 0.08 . The richness split was also varied, but again we obtained similar results with a cool-core fraction around 0.2 in all cases.

3. CONCLUSION

We find a cool-core fraction of $\sim 20\%$ of clusters and distributions of T_{core}/T_{r500} which are statistically consistent in bins of redshift and richness. While the distribution of cool cores is fairly even throughout our sample, this could be due to limited data. Our sample lacked a significant number of clusters with fairly high redshifts ($z > 0.7$) and with fairly low richnesses ($\lambda < 60$). It should be noted as well that X-ray surveys have been known to be biased towards cool cores when compared to SZ surveys (see Rossetti et al. 2016; Andrade-Santos et al. 2017), although Ghirardini et al. (2022) do not find a bias toward cool cores in the eROSITA eFEDS cluster sample. In addition, our clusters are primarily drawn from targeted Chandra observations possibly introducing a bias. Despite this, our results are generally consistent with previous works. Previous results on the redshift evolution in the cool core fraction and the properties of cool cores are mixed with some studies finding a decreasing fraction of cool cores with increasing redshift (Santos et al. 2010; Pascut & Ponman 2015; Ghirardini et al. 2022) and others finding no evolution (McDonald et al. 2017; Sanders et al. 2018; Ruppin et al. 2021). The exact redshift trends depend on the cool core metric used and the sample selection (e.g. McDonald et al. 2013; Pascut & Ponman 2015); the lack of evolution we see in core temperature drop

is consistent with observations showing a lack of evolution in cooling properties. However, evolution does occur in cluster surface brightness profiles due to the build up of the bulk cluster around a fixed core (e.g. McDonald et al. 2017; Ruppin et al. 2021). On the other hand, previous work has indicated that cool-core clusters form with little dependence on mass (e.g. Bharadwaj et al. 2014; Pascut & Ponman 2015) consistent with the lack of trend with richness in our sample, though important differences are seen between groups and clusters in the relationship of central AGN to the presence of a cool core (Sun 2009; McDonald et al. 2011; Bharadwaj et al. 2014).

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