New Observations of High Redshift Relaxed Cool Core Cluster SPT-CL J2215-3537

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Abstract

As the largest gravitationally bound structures in the Universe, galaxy clusters serve as a unique and valuable laboratory for probing cosmological models and understanding astrophysics at the high mass limit of structure formation. Clusters that are dynamically relaxed are especially useful targets of study due to their morphological and dynamical simplicity. However, at redshifts greater than 1, very few such clusters have been identified. We present results from new Chandra observations of cluster SPT-CL J2215-3537 (hereafter SPT2215) at z = 1.16, the second most distant relaxed, cool core cluster identified to date. We place constraints on the cluster's total mass profile and investigate its thermodynamic profiles and gas enrichment, resolving its cool core and providing essential context for the massive starburst seen in its central galaxy. We contextualize its thermodynamic and cosmological properties within a sample of well-studied lower redshift relaxed clusters. In this way, SPT2215 serves as a powerful new high redshift benchmark for our understanding of the formation of cool cores and the evolution of massive clusters of galaxies.

Chandra Data

As the state-of-the art X-ray instrument for resolving distant galaxy clusters on small scales, the Chandra X-ray Observatory can be used to accurately and straightforwardly assess the dynamical state of a cluster via X-ray observations of the ICM morphology [1]. Using measurements of the resolved central surface brightness peak and the symmetry of the X-ray emission on larger scales, Chandra observations of SPT2215 identify it as the second highest redshift relaxed, cool-core cluster observed to date [2].

In addition to ~70 ks of existing data, which had been used to provide initial constraints on the thermodynamic properties of SPT2215 [2], 130 ks of new Chandra observations were obtained to produce the results presented here. Fig. 1 shows the unbinned, broadband Chandra image of SPT2215 using all 200 ks of available observational data.

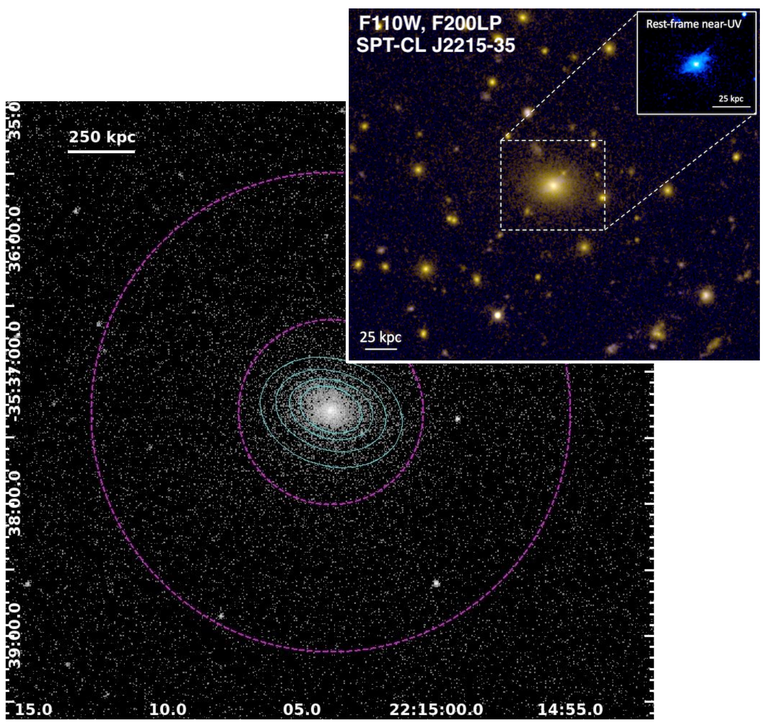

Figure 1: *Lower left:* Broadband (0.6-7.0 keV) Chandra exposure of SPT2215 ($z = 1.16$) totaling ~200ks. r_{500} and r_{2500} are overplotted in magenta, while cyan elliptical isophotes fit at radii $r < r_{2500}$ illustrate the regular morphology of the ICM. *Upper Right*: Two-color optical/IR image of the center of SPT2215 from archival Hubble Space Telescope data. The rest frame UV image provides evidence for star formation found by [2].

Thermodynamic Profiles

Feedback from star formation and AGN activity can profoundly impact central cluster environments. Analyzing spatially resolved X-ray spectra of high-redshift clusters provides insights into their current thermodynamic and chemical states, as well as the cumulative effects of feedback processes on their evolution. Fig. 2 presents electron density, temperature, pressure, and entropy profiles of SPT2215 scaled by evolution and overdensity/r_{2500}, plotted against the confidence regions of a larger sample of lower redshift relaxed clusters [3]. Although SPT2215 is the highest redshift cluster in the sample, its profiles demonstrates self-similarity with minimal scatter beyond the cluster core.

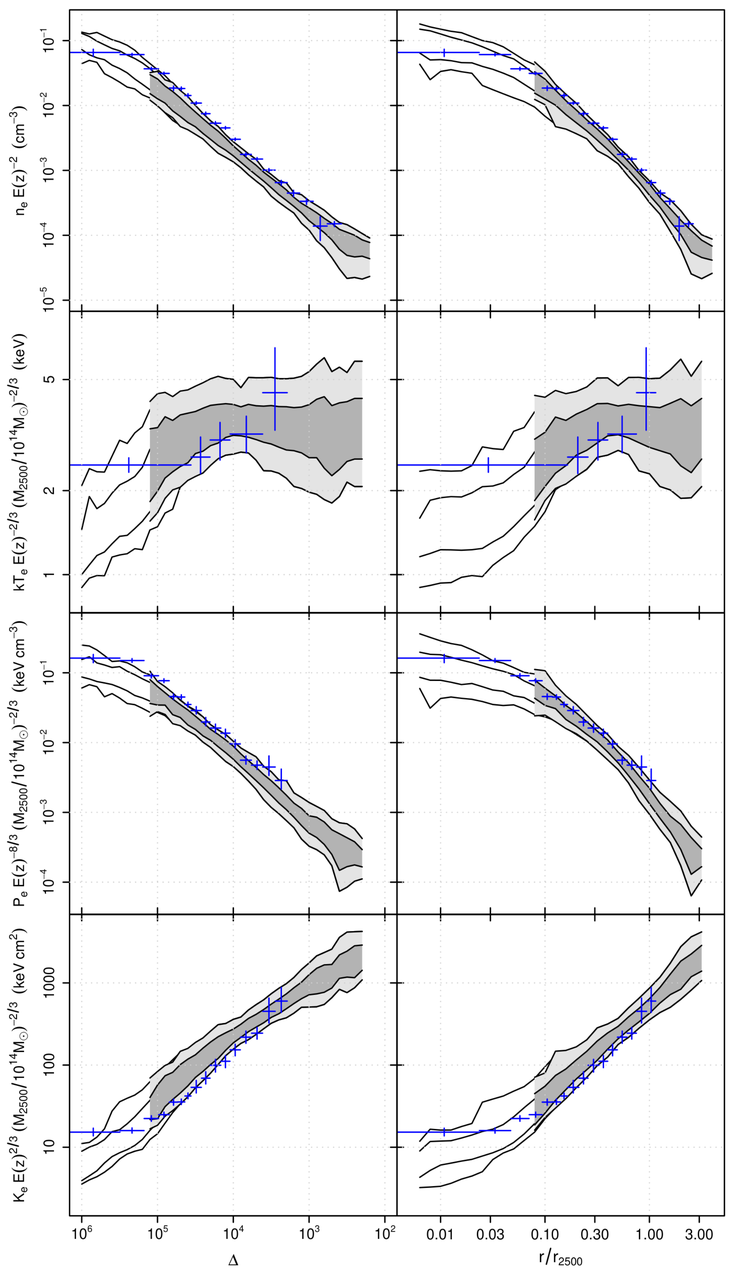

Figure 2: Scaled electron density, temperature, pressure, and pseudo-entropy profiles for SPT2215 (blue) plotted against confidence interval bounds on profiles of a larger sample of relaxed, cool-core clusters [3] over a redshift range of 0.08 - 1.08. SPT2215 demonstrates consistency with the scaled profiles of the lower redshift sample.

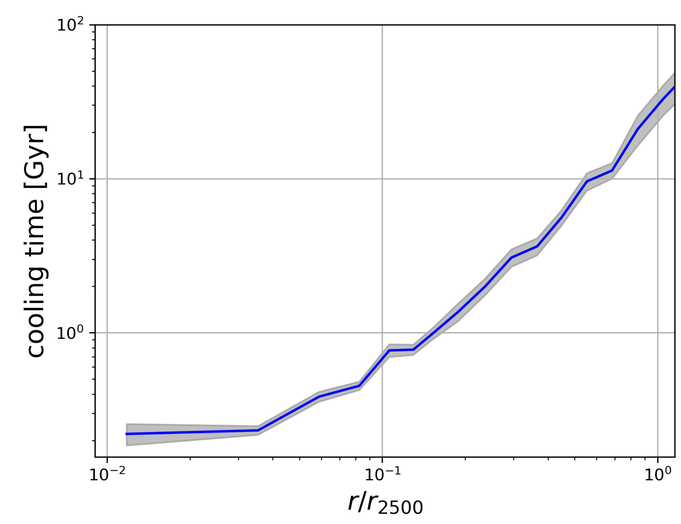

Figure 3: Cooling time profile for SPT2215. The low central cooling time value (less than ~ 1 Gyr) is characteristic of cool-core, relaxed clusters. The thermodynamic properties of the central regions of SPT2215 are similar to those of other massive, cool core systems at lower redshifts hosting massive starburst events.

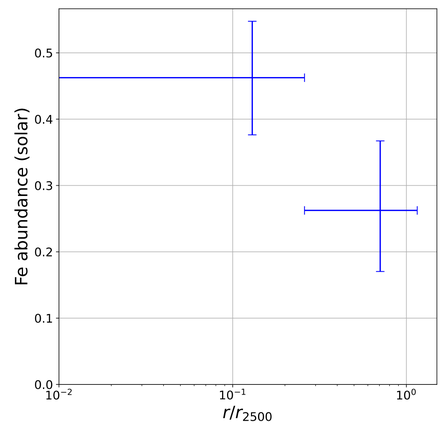

Figure 4: Iron abundance (expressed as a fraction of solar abundance) profile for SPT2215. There is evidence of an enhancement in central metallicity, which decreases by a radius of ~r_{2500} to a value consistent with the typical value of ~0.3 solar observed at intermediate-to-large radii ($r \gtrsim r_{2500}$) for clusters at z < 1 [4].

Cosmological Properties

X-ray observations of relaxed galaxy clusters provide powerful probes of cosmology, being able to constrain the mean matter density and dark energy properties through measurements of the gas mass fraction [5-8]. The same X-ray measurements can also be used to probe the physical properties of dark matter using measurements of the concentration-mass-redshift relation for such halos [10-11]. Figures 5 and 6 present measurements of both the f_{gas} and concentration for SPT2215 in the context of the 44-cluster sample in [8-9]. The new high-z measurements for SPT2215 are fully consistent with ΛCDM model expectations.

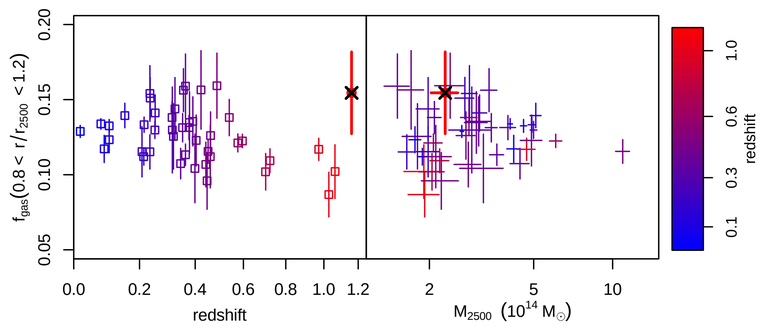

Figure 5: Gas mass fraction (f_{gas}) plotted as a function of redshift and of mass for members of the 44-relaxed cluster sample in [8,9] with SPT2215 designated with a filled red point and a black 'x'. SPT2215 is the highest redshift cluster with constraints on f_{gas}, which are consistent with a constant value in redshift under ΛCDM .

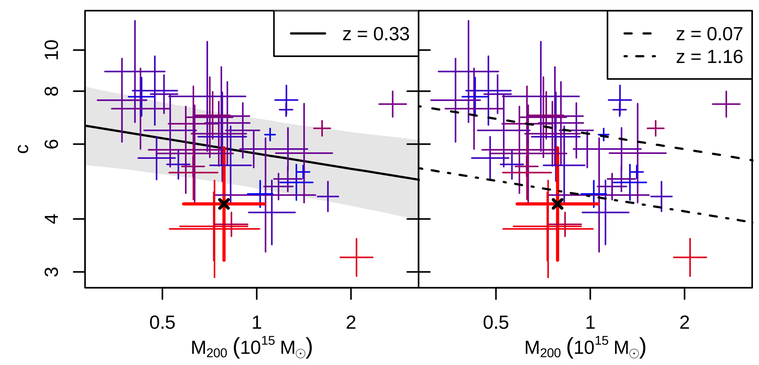

Figure 6: Concentration-mass measurements for members of the relaxed cluster sample [9] using the same color-bar scaling in redshift as in Fig. 5. SPT2215 is again designated in red with a black 'x'. Shown as solid and dashed black lines are best fit power law models in mass and 1+z. The solid line in the left panel is evaluated at z = 0.33 with the 68% posterior predictive region including intrinsic scatter shaded in grey. On the right, the two dashed lines are best fit models for z = 0.07 and z = 1.16.

Conclusion & Next Steps

SPT-CL J2215-3537 is one of the highest redshift relaxed cool-core clusters identified to date. The cluster demonstrates consistency with both the larger scale thermodynamic profiles of lower redshift relaxed clusters and the f_{gas}- and concentration-mass-redshift relationships expected under the ΛCDM paradigm.

These results (and those of A. Flores 2024) demonstrate the potential for SZ surveys to uncover relaxed systems at high redshifts, and for current X-ray facilities to provide valuable and detailed information, even at z > 1. Looking forward, future surveys and telescopes such as the Advanced X-ray Imaging Satellite (AXIS), a NASA probe-class mission concept currently under Phase A of development, will extend this work to z~2 and beyond.

Acknowledgements

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