DEEP OBSERVATIONS OF THE GALAXY CLUSTER PSZ2 G003.82-05.32 TO DETERMINE IT'S PHYSICAL PROPERTIES

1 Abstract

While the study of galaxy clusters at redshift ~ 1 and lower is quite common, there is a significant lack of X-ray observations done for galaxy clusters at redshift ~ 2 or higher. Observing these higher redshift galaxies is crucial to understanding how large-scale structures evolve over cosmic time, the evolution and formation of galaxies, and measuring the distribution of dark matter. We propose deep observations of the galaxy cluster PSZ2 G003.82-05.32 with Chandra to determine the physical properties of the cluster. Through analysis of the X-ray spectrum the temperature, density, and metallicity profiles will be extracted and used further to infer the cluster's mass, evolution, and pressure distribution. These X-ray observations combined with the knowledge that the cluster is a confirmed Sunyaev-Zel'Dovich source will provide the necessary information needed to determine the physical properties.

2 Scientific Justification

For PSZ2 G003.82-05.32 to be a confirmed Sunyaev-Zel'dovich (SZ) source, we expect the hot intracluster gas temperature to be extremely high, $10 - 100 \times 10^6 K$. As photons from the cosmic microwave background (CMB) (Penzias and Wilson, 1965) travel through space, if they pass through the intracluster medium (ICM) of a galaxy cluster the photons will be scattered into higher energies (Sunyaev and Zeldovich, 1972). The photons collide with the ultra-relativistic electrons in the hot gas, increasing their frequency, this is known as inverse Compton scattering. The shift of the photon's frequency means the observed blackbody spectrum of the CMB will be shifted as well. This shift confirms the presence of a galaxy cluster. However further observations, specifically in the X-ray band, are necessary to determine PSZ2 G003.82-05.32 physical properties.

Previous observations of galaxy clusters demonstrated that the two dominant radiation sources are bremsstrahlung (Felten et al., 1966) and line (Mitchell et al., 1976). Bremsstrahlung radiation, also known as "braking radiation" or "free-free emission", is the emission due to the acceleration of electrons by the electric field of a nearby particle. Since bremsstrahlung radiation is proportional to $n_e^2\ T^{1/2}$, it dominates where the gas is at extremely high temperatures and is highly ionized. This directly applies to the ICM in PSZ2 G003.82-05.32, where gas temperature can range from $10 - 100 \times 10^6 K$. Line radiation is also observable in the X-ray spectrum (Fig. 1). As an electron in an atom transitions from a high energy state to a lower one, a photon with a characteristic wavelength will be emitted. This leads to emission lines in the spectrum corresponding to the different elements in the ICM. Emission lines allow for the composition of the ICM to be resolved, providing insight into supernova activity in the galaxy cluster. As the ICM reaches higher temperatures the elements present will ionize triggering the line radiation to become less dominant.

Understanding the physical properties of PSZ2 G003.82-05.32 requires an accurate measurement of its temperature and electron density. At high ICM temperatures where bremsstrahlung radiation dominates, the X-ray emissivity is directly proportional to n_e^2. Any shift in the electron density can have a significant influence on the cluster's energy flux. For the Raymond Smith model in XSPEC (Arnaud, 1996), the normalization is related to the emission measure, as $\int ne^2 dV$ (Böhringer and Werner, 2010). This allows for a direct measure of the electron density profile from the X-ray spectrum. Combined with the SZ effect, which is proportional to the electron pressure integrated along the line of sight ($n_e T$), further constraints for PSZ2 G003.82-05.32 can be determined.

The observations we propose will specifically observe the ICM of PSZ2 G003.82-05.32. The

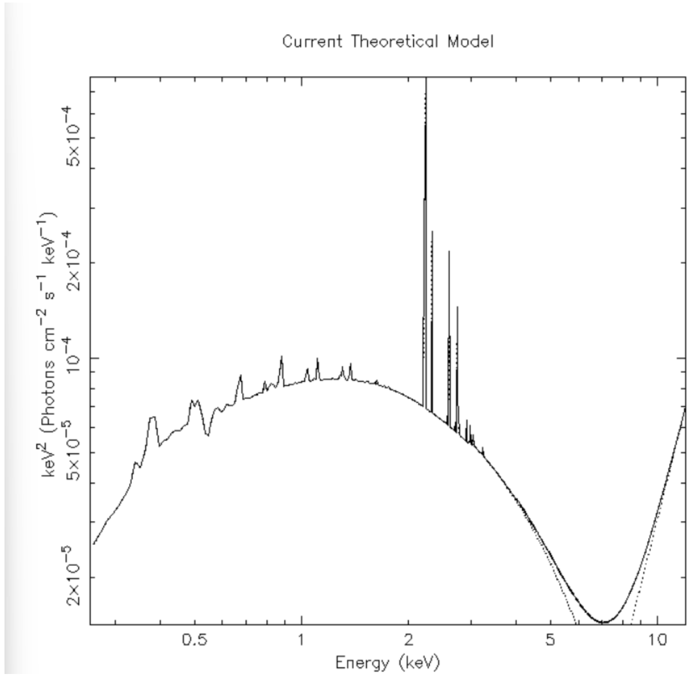


Figure 1: A Webspec and XSPEC simulated model of PSZ2 G003.82-05.32. Modelled using the Raymond & Smith fit, including both bremsstrahlung and line radiation. A purely hypothetical spectrum ignoring any noise, assuming Chandra and all instruments worked perfectly, and observed very close to the cluster.

X-ray spectrum is directly related to the gas temperature, electron density, and metallicity of the gas. Through analysis of the spectrum, these parameters will be determined and used to further resolve other physical properties of PSZ2 G003.82-05.32. The Sunyaev Zel'dovich effect is proportional to electron pressure integrated along the line of sight, temperature, and density. Combining X-ray spectrums and the Sunyaev Zel'dovich effect can provide further constraints to the gas temperature and electron density. Knowing the temperature and electron density of PSZ2 G003.82-05.32 is required for determining the total mass of the cluster and the distribution of dark matter.

Through WebSpec and XSPEC, a simulated spectrum for PSZ2 G003.82-05.32 was created. The parameters for the simulated spectrum are based on the galaxy cluster XLSSC 122, which shares a similar redshift of 2 and is a confirmed SZ source. Parameters such as the average temperature and metallicity were taken from Mantz et al. (2018) and used as a guideline for the simulated spectrum. On WebSpec, Chandra ACIS-I on axis was used along with the Raymond-Smith model, which includes both bremsstrahlung and line radiation. XLSSC 122 has a measured average temperature of 5.0 ± 0.7 keV (Mantz et al., 2018), taking into account the uncertainty, a rounded value of 6 keV was used. The metallicity of XLSSC 122 in is reported as 0.33 $^{+0.19}_{-0.17} Z/Z_{\odot}$ (Mantz et al., 2018), and in our simulated spectrum, 0.3 was inputted. The normalization was adjusted until the WebSpec-produced spectrum had an energy flux between $3 \sim 4 \times 10^{-13}$ ergs/cm^2/s. The characteristic luminosity of galaxy clusters is on the order of 10^{44} ergs/s, and when shifted to a redshift of 2, using the luminosity evolution model, produces a luminosity on the order of 10^{45} ergs/s. The energy flux is proportional to $1/r^2$ resulting in a small number calculated for PSZ2 G003.82-05.32, approximately 3.9×10^{-13} ergs/cm^2/s. Since this is not an exact calculation of the energy flux for this cluster, we moved forward with the simulated spectrum if the energy flux was similar. Through trial and error, a normalization of 0.002 was used to move forward.

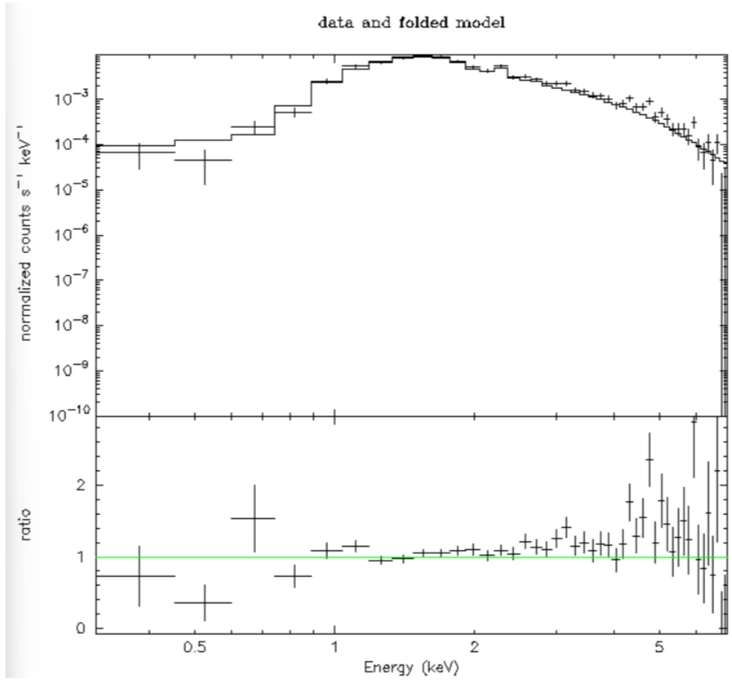


Figure 2: A simulated spectrum for PSZ2 G003.82-05.32 using XSPEC. Emission lines in the lower energies can be seen as expected. Specifically at approximately 2 keV, 2.6 keV, 3.1 keV, and 4.8 keV.

To analyze the simulated spectrum further, it was uploaded into XSPEC. By modelling the simulated spectrum using the Raymond & Smith, raym, fit and parameters predetermined from WebSpec, the resulting fit can be seen in Figure 2. Along with the spectrum, parameters for kT, normalization, and metallicity were determined along with uncertainties. For the simulated spectrum we measured a kT of $4.9^{+0.3}_{-0.4}$ keV, a metallicity of $0.39 \pm 0.09 Z/Z_{\odot}$ and a normalization of $0.0002^{+0.00008}_{-0.0001}$. The simulated spectrum (Fig. 2) reproduces an emission line at ~ 2.2 keV. Analysis of the galaxy cluster XLSSC 122 discovered a similar emission line which was concluded to be the rest-frame 6.7 keV Fe emission line complex (Mantz et al., 2018). The simulated data points are sparse but it was an identifiable feature. Identification of the 6.7 keV Fe emission line can lead to further constraints on the metallicity and evolutionary paths of these high redshift clusters. With the simulated spectrum producing reasonable parameters with the requested instrument and exposure time, the physical properties of PSZ2 G003.82-05.32 can be determined.

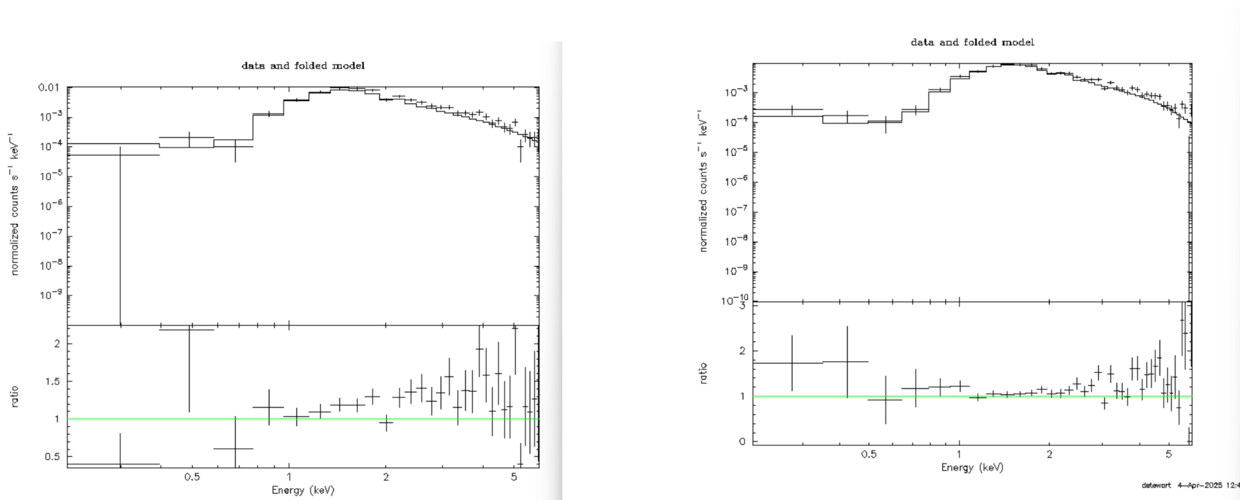
High redshift galaxy clusters provide the necessary information to study many important astronomical topics further. These include, but are not exclusive to, the early conditions of the universe and how different environments affect the evolution of galaxies, the structure of the cosmic web and how dark matter is distributed, and the testing of various cosmic models. Given the difficulties that come with observing higher redshift galaxy clusters, we must observe these clusters when given the possibility. PSZ2 G003.82-05.32 provides a chance to delve deeper into understanding high redshift galaxy clusters.

3 Technical Justification

Chandra's high spectral resolution and sensitivity allow for the faint X-ray emission of PSZ2 G003.82-05.32 to be observed. The Advanced CCD Imaging Spectrometer (ACIS) specifically allows for the detection of photons individually along with their energy and position. The high spectral resolution ACIS provides is necessary to measure temperature, metallicity, and electron density at high redshifts. At a redshift of 2, the X-ray emission of SZ2 G003.82-05.32 is faint; a direct result of the photon's wavelengths being stretched. A longer exposure time is required to achieve the spectral resolution necessary for analysis.

4 Feasibility

Located at a RA = 3.82° and DEC = $-5.32°$, PSZ2 G003.82-05.32 is viewed through a galactic column density of $1.94 \times 10^{22} cm^{-2}$. The visibility of PSZ2 G003.82-05.32 was checked using the Chandra PRoVIs Target Pitch, Roll, and Visibility Interface. The observing periods were constrained between June 2025 and February 2026, with multiple options where the longer observation is viable. The observing period has smaller periods lasting approximately 5-7 days where the average visibility per orbit drops. Periods between the small drops in visibility are preferential to ensure maximum efficiency of the observations.



(a) Simulated Spectrum with 100 ks

(b) Simulated Spectrum with 200 ks

Figure 3: The simulations for 100 ks and 200 ks were produced identically to the 300 ks simulation. Comparing the 100 ks and 200 ks spectrum with Fig. 1, the shape is closely similar.

We request 300 ks with Chandra ACIS for this observation. 300 ks was determined by modelling the simulated spectrum (Fig. 2) and determining the count rate through WebSpec. Similar spectrums were modeled with the same input parameters but with reduced exposure times, 100 ks and 200 ks. The different exposure time does not significantly impact the physical shape of the spectrum (Fig. 3), but the data points align better with the fit. From WebSpec 100 ks, 200 ks, and 300 ks had a measured count rate of ~ 0.014 counts/sec. An exposure time of 300 ks is requested to ensure a maximum number of counts will be received and for better resolution of the spectrum. Objects at high redshifts, ~ 2 , are very faint due to the significant stretching of wavelengths. The counts received by this observation are critical for our spectrum, to ensure proper measurements can be made and the resolution is good enough to identify spectral features, such as emission lines.

5 Conclusion

The difficulties that arise when observing high redshift objects leaves a gap in the literature for high redshift galaxy clusters. Through observation of PSZ2 G003.82-05.32 we aim to measure specific parameters and use those measurements to further our understanding of galaxy clusters and our universe. The high sensitivity and angular resolution of Chandra ACIS provide the necessary spectrum to determine the temperature, metallicity, and electron density of the galaxy cluster PSZ2 G003.82-05.32. Moving forward with that information other parameters such as the mass, evolution, and pressure profile will be determined.

6 References

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