DETERMINING THE CURRENT HUBBLE CONSTANT: A CHANDRA-BASED APPROACH USING ABELL 3526 GALAXY CLUSTER

Abstract

This proposal focuses on observing Abell 3526 galaxy cluster via *Chandra* to determine Hubble constant for an $\Omega_M = 0.3$, Ω_Λ=0.7 cosmology, which measures the expansion rate of the universe. Traditionally, Hubble constant has been estimated through observations of galaxies and their redshifts. However, an alternative method involves the use of galaxy clusters. The combination of X-ray data from the *Chandra* Observatory and SZ data from radio telescopes (this is **not** a joint observational proposal. We already have the radio data) offers a method to measure Hubble's constant that is independent of the extra-galactic distance ladder.

1 Scientific justification

1.1 Overview

1.1.1 Introduction

Hubble constant is a measure of the rate at which the universe is expanding. It is typically determined through observations of galaxies and their redshifts. However, another method to determine Hubble's constant would be using galaxy cluster(s). Observing galaxy clusters in X-rays provides important information about the properties of the cluster, such as its temperature, size and density. These properties can be used to estimate the mass of the cluster, and in turn help us determine Hubble constant. But using SZ data from the *Atacama Large Millimeter/sub-millimeter Array*, combined with X-ray data from *Chandra*, provides a method to measure Hubble constant that is independent of the extra-galactic distance ladder. By conducting a joint examination of radio and X-ray data, it is quite straight forward to establish the distances to galaxy clusters in a direct manner. These clusters, which are the most extensive gravitationally collapsed structures in the universe, are characterized by a hot, diffuse plasma ($T_e \sim 10^7 - 10^8$) K that occupies the intergalactic space.

In this proposal, we provide a scientific justification for observing the galaxy cluster Abell 3526 using the *Chandra* X-ray Observatory to measure the cosmic distance scale through the SZ.

1.1.2 Primer on SZ, Hubble constant and ΛCDM model

The Sunyaev-Zel'dovich effect (SZ) is a powerful probe of the cosmic distance scale that has been widely used in the study of galaxy clusters. The effect is due to the inverse Compton scattering of the Cosmic Microwave Background (CMB) photons by high-energy electrons in the intracluster medium (ICM), leading to a small frequency-dependent ($\sim$ 1mK) distortion of the CMB spectrum (Sunyaev et al. 1972). The high-energy electrons in ICM, in the hot gas, emits X-rays primarily through thermal Bremsstrahlung. Understanding SZ is crucial as it forms the basis of the analysis that will be used, namely, Markov chain Monte Carlo joint analysis of interferometric SZ observations from radio telescopes and *Chandra* X-ray imaging spectroscopy observation.

The final piece of the puzzle is connecting this analysis to determining the Hubble constant, which is not a constant. It changes with time.

The ΛCDM model is a theoretical model used in cosmology to describe the evolution and behavior of the universe as a whole. It is based on the idea that the universe is composed of two main components: dark matter (which does not emit, absorb or reflect light but is detected through its gravitational effects) and dark energy (a hypothetical form of energy that is thought to permeate all of space and is responsible for the accelerating expansion of the universe.

The 'Λ' in ΛCDM refers to the cosmological constant, which is a parameter in Einstein's equations of general relativity that describes the energy density of the vacuum of space. The 'CDM' refers to "cold dark matter", which is a type of dark matter that moves slowly compared to the speed of light. This model assumes that general relativity is the correct theory of gravity on cosmological scales as we have robust experiments that have proven general relativity to work (except for singularities).

In the ΛCDM model, the universe is assumed to be flat and homogeneous, and the behavior of dark matter and dark energy is described by a set of equations known as the *Friedmann equations*. These equations take into account the expansion rate of the universe, the energy densities of dark matter and dark energy, and other cosmological parameters. And these same equations will help us derive the Hubble's constant that we require.

The *Friedmann equations* (Hartle 2021) give us, for a (topologically flat) universe,

$$H^2 = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3} \tag{1}$$

where ρ is [dark, ordinary] matter density. As the universe expands, ρ decreases as volume (of the universe) increases but Λ remains a constant. Thus, the Hubble constant decreases from its current value H_0 and asymptotically tends towards $H = \sqrt{\frac{\Lambda}{3}}$ as time $\to \infty$.

1.1.3 Why Abell 3526?

Abell 3526 is a rich, nearby galaxy cluster, located at a redshift $z \approx 0.01140$ (Struble et al. 1999). It is a good target for studying the SZ due to its angular size of about 1.57 deg which is quite large, low redshift, and high X-ray luminosity ($16.16 \times 10^{-11} \pm 1.145 \times 10^{-11}$ erg cm^{-2} s^{-1} (Eckert et al. 2011)). There are three potential problems in SZ determinations of H_0: elongation, density substructure, and non-isothermality of the cluster gas. If a cluster is elongated along the line of sight, then H_0 will be underestimated, while if the cluster is elongated in the plane of the sky, then H_0 will be overestimated (Kitayama et al. 2023). However, Abell 3526 does not seem to suffer from these drawbacks. Clumping of the intracluster medium also causes a bias, due to the different dependencies of the X-ray emission and SZ upon the electron density and temperature. The cluster also exhibits a cool-core, making it an excellent target to study the interplay between the ICM and the central galaxy (**churazov2001**). A precise measurement of the cosmic distance scale using the SZ in Abell 3526 will provide valuable insights into the Hubble constant, H_0, which we have established is a crucial parameter in constraining the ΛCDM cosmological model.

1.1.4 The Sunyaev-Zel'dovich Effect and the Cosmic Distance Scale

The SZ can be observed through two primary components: the thermal SZ (tSZ) and the kinematic SZ (kSZ). The tSZ is the dominant effect, which is caused by the scattering of the CMB photons off the hot ICM electrons. It induces a change in the CMB temperature, ΔT, that is proportional to the Compton y-parameter and the frequency of observation (Carlstrom et al. 2002):

$$\frac{\Delta T(\nu)}{T_{CMB}} = g(\nu)y \tag{2}$$

where T_{CMB} is the CMB temperature, and $g(\nu)$ is the spectral function describing the frequency dependence of the SZ. The Compton y-parameter is given by:

$$y = \frac{\sigma_T}{m_e c^2} \int P_e dl, \tag{3}$$

where σ_T is the Thomson cross-section, m_e is the electron mass, c is the speed of light, P_e is the electron pressure, and dl is the path length along the line of sight.

The kSZ arises due to the peculiar motion of the galaxy cluster, inducing a Doppler shift in the CMB photon frequencies. It is typically much weaker than the tSZ but can be isolated using high-resolution multi-frequency observations (Planck Collaboration et al. 2016).

Using the SZ, one can determine the angular diameter distance, $D_A(z)$, to a galaxy cluster by comparing the observed SZ with the X-ray surface brightness profile of the cluster. The X-ray surface brightness is proportional to the electron density squared and the X-ray emissivity, while the SZ is proportional to the integral of the electron pressure along the line of sight. By combining these two observations, we can eliminate the dependence on the electron density and derive a relation between $D_A(z)$ and the observable quantities:

$$D_A(z) = \frac{\sigma_T}{m_e c^2} \frac{\int \rho_{gas}^2 \Lambda(T_{gas}) dV}{\int P_e dl}. \tag{4}$$

Here, ρ_{gas} is the gas density, T_{gas} is the gas temperature, $\Lambda(T_{gas})$ is the X-ray cooling function, and dV is the volume element.

We also have the hydrostatic equilibrium model: Before we can calculate the distance to a cluster, it is essential to create an accurate model of the distribution of gas within the cluster. In the center of clusters, the density can be so high that the time it takes for radiative cooling to occur is shorter than the cluster's age. This can cause a decrease in temperature and an increase in density in the center of the cluster (Bonamente et al. 2006). The gas density is low enough at large distances such that X-ray emission can continue for long cosmological periods without experiencing significant cooling. In cool core clusters, there are essentially two parts to the gas distribution: a concentrated peak at the center and a wider, less concentrated distribution. This observation has led to the use of a density function that accounts for this phenomenon, often taking the form:

$$n_e(r) = n_{e0} \cdot \left[f \left(1 + \frac{r^2}{r_{c1}^2}\right)^{-\frac{3\beta}{2}} + (1-f)\left(1 + \frac{r^2}{r_{c2}^2}\right)^{-\frac{3\beta}{2}} \right] \tag{5}$$

1.2 Measuring distances with X-ray and Sunyaev-Zel'dovich Effect data

1.2.1 Parameter estimation using the Markov chain Monte Carlo method

The model consists of five parameters that describe the gas density (n_{e0}, f, r_{c1}, r_{c2} and β; equation 5), two parameters that describe the dark matter density ($\mathcal{N}$ and r_s from $\rho_{DM}(r) =$

$\mathcal{N}\left[1(r/r_s)(1+r/r_s)^2\right]$) and the angular diameter distance D_A (Reese et al. 2002).

The joint likelihood of the spatial and spectral models is given by

$$\mathcal{L} = \mathcal{L}_{SZE} \cdot \mathcal{L}_{image} \cdot \mathcal{L}_{spectra}$$

Where

$$ln(\mathcal{L}_{SZE}) = \sum_i (-\frac{1}{2}\left(\Delta R_i^2 + \Delta I_i^2)\right) W_i \tag{6}$$

$$ln(\mathcal{L}_{image}) = \sum_i [D_i ln(M_i) - M_i - \ln(D_i!)] \tag{7}$$

$$ln(\mathcal{L}_{spectra}) = -\frac{1}{2}\chi^2 - \frac{1}{2}\sum_i ln(2\pi\sigma_i^2) \tag{8}$$

A Markov chain is a series of model parameters that follows the rule where the probability of a parameter appearing in the chain is proportional to its posterior probability. This means that the likelihood of a parameter occurring is based on the current observations (Metropolis et al. 1953).

The results of the MCMC analysis are shown in Table 1 (Bonamente et al. 2006) , in which they report the best-fit values of $\mathcal{N}$, r_s, n_{e0}, r_{c1}, β, f, r_{c2} and D_A for each cluster.

Hubble constant is then calculated using:

$$D_A(z) = \frac{1}{H_0} \cdot \frac{c}{|\Omega_k|^{1/2}(1+z)} \cdot sinn\left[|\Omega_k|^{1/2}\int_0^z [(1+\zeta)^2(1+\Omega_M\zeta) - \zeta(2+\zeta)\Omega_\Lambda]^{-1/2} d\zeta\right] \tag{9}$$

where the function $sinn(x)$ is defined as $sinh(x)$ for $\Omega_k > 0$, $sinn(x) = x$ for $\Omega_k = 0$, $sinn(x) = sin(x)$ for $\Omega_k < 0$, and $\Omega_k = 1 - \Omega_M - \Omega_\Lambda$ (Carroll et al. 1992)

2 Technical Justification

2.1 Observations

2.1.1 Interferometric [radio] Sunyaev-Zel'dovich effect data

We will not worry about the radio observations for this proposal. This is **not** a joint observational proposal. The radio observations for Abell 3526 has already been taken. For our goal to determine the *current* Hubble constant, it would be ideal to take radio observations and X-ray observations at around same time but given that this is an undergraduate-level proposal, using new X-ray data and old radio data is better than old X-ray data and old radio data. *Atacama Large Millimeter Array* (ALMA) provides radio data("ALMA database" 2011).

2.1.2 *Chandra* X-ray Observatory

Observations with the ACIS-I and ACIS-S detectors will be ideal which has better resolution than any other X-ray telescope. The two ACIS instruments will provide spatially resolved X-ray spectroscopy and imaging with an angular resolution of $\sim 0.5\prime$ and with energy resolution of $\sim 100 - 200$ eV.

For the data analysis, *Chandra* calibration team (CIAO 2023) provides Chandra Interactive Analysis of Observations (CIAO) software.

(Bonamente et al. 2006) goes over necessary data analysis that can be justified for using *Chandra*. The results are as follows which are used from (Bonamente et al. 2006)

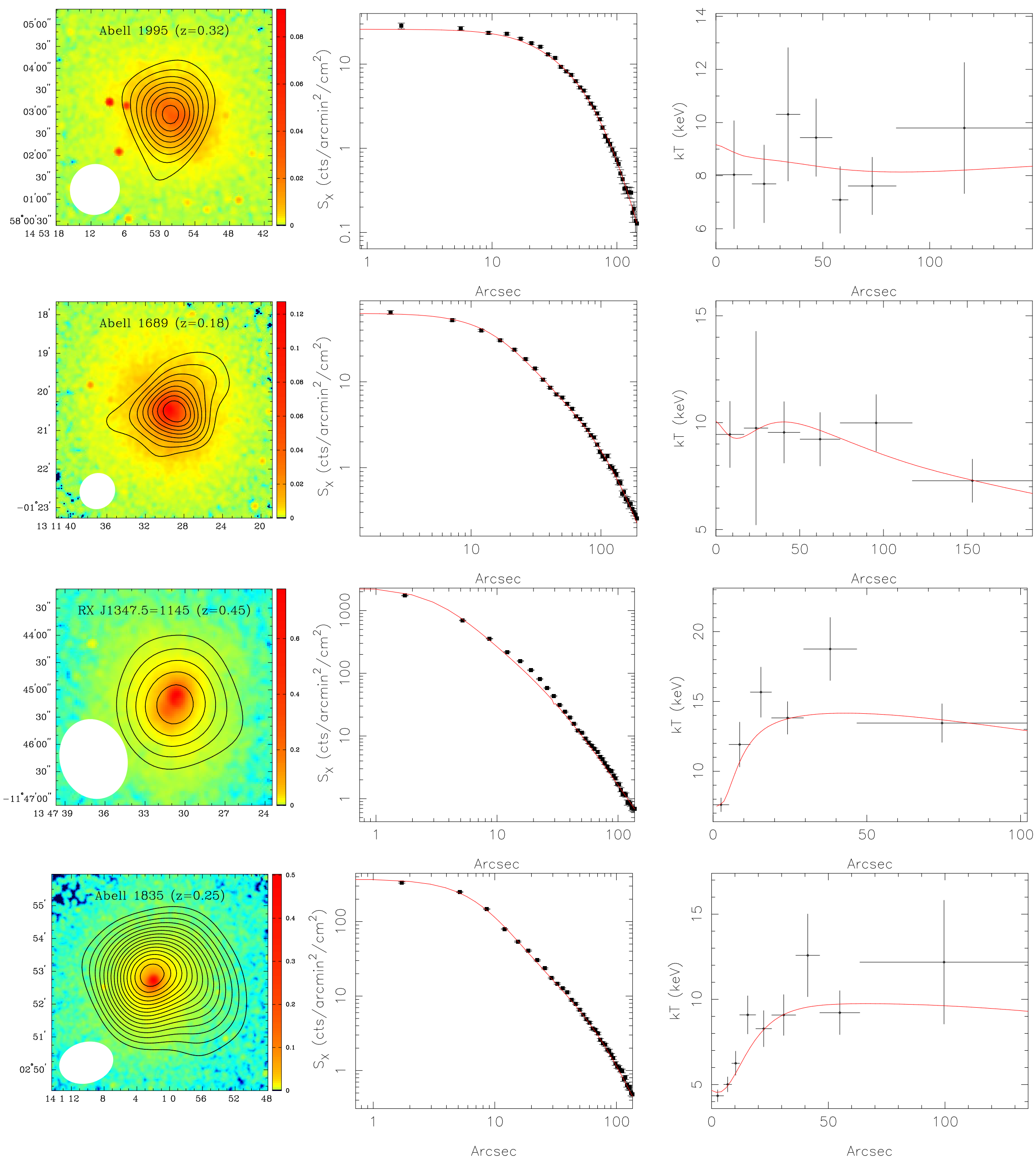

Figure 1: (Left) *Chandra* images of the X-ray surface brightness in 0.7-7 keV band in units of counts pixel^{-1} (1.97$''$ pixels) for some selected clusters. Overlaid are the SZ decrement contours, with contour levels (+1,-1,-2,-3,-4,...) times the rms noise in each image; the full-width-at-half-maximum of the SZ synthesized beam (effective point-spread function) is shown in the lower left corner. The X-ray images were smoothed with a $\sigma = 2''$ Gaussian kernel. (Center) Radial profile of the background subtracted X-ray surface brightness; the solid line is the best-fit model obtained. (Right) Radial profiles of the *Chandra* temperatures, the solid line is the best-fit hydrostatic equilibrium model.

3 References

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