Mass determination of 5 relaxed galaxy clusters with Chandra X-ray data

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Abstract.
We report masses of 5 relaxed galaxy clusters (Abell 2204, Abell 478, RXJ 1532.9+3021, Zwicky 2089, and Abell 2597) obtained from analysis of Chandra X-ray satellite ACIS data. Assuming that the clusters are in hydrostatic equilibrium, masses can be estimated from temperature and density profiles of the clusters. In order to produce temperature and density profiles we performed data reduction, spectrum extraction, fitting of multiple observational spectra, and deprojection procedures. Density and temperature profiles were fitted with a single beta model and an exponential model respectively. We determined masses of the clusters enclosed by $R_{2500}$, which is the radius where the density equals to 2500 times the critical density of the universe. We compare our results with other mass determinations employing different methods, i.e. Sunyaev Zeldovich Effect (SZE) and lensing, where available and found that within uncertainties they are in a good agreement.

1. Introduction
Clusters of galaxies are the most massive structures in the universe that have reached equilibrium. The gravitationally bound systems consist of hundreds to thousands galaxies, have diameters of $2 \sim 10$ Mpc and a typical range of mass between $10^{13} \sim 10^{15}.M_{\odot}$. Clusters are not only unique astrophysical laboratories in which many astrophysical phenomena occur, but also are powerful cosmological probes. A massive cluster is large enough to be considered as a representative volume of the Universe. The matter contents of the most massive clusters represent the matter content of the universe. Clusters therefore are commonly used in constraining cosmological parameters, and in studies concerning dark matter, dark energy, as well as large scale structures.

Cluster mass is a physical yet not observable parameter that should be estimated for cosmological studies. There are several methods for cluster mass determination. We can measure velocity dispersions of galaxies in a cluster and derived its mass from the virial theorem. This was done for example by Zwicky in 1933, who found that mass in the form of galaxies in Comma cluster is much less than the total mass derived from dynamics. He was the first to coin the term ”dark matter” for the excess mass needed to explain the discrepancy. In a gravitational lensing event by a cluster, the light rays from background galaxies are bent towards us. By studying distortions in the images of the background galaxies we can estimate the total mass of the cluster. Observing a cluster in X-ray and assuming that it is in hydrostatic equilibrium,
the total mass of the cluster can be estimated from its temperature and density profiles. This is the method that we employed for the five clusters we report here. The last method is the so called Sunyaev Z’eldovich effect (SZE). This effect occurs when cosmic microwave background (CMB) photons are inverse Compton scattered to higher energies by electrons in Intra Cluster Medium (ICM), causing a shift and distortion in the shape of the CMB spectrum. The size of the wavelength shift is dependent on the mass of the galaxy cluster the photons passed through.

2. Data and Method

In this work we analyzed data of five clusters of galaxies (see Table 1) observed by Chandra X-ray satellite with ACIS instruments without any gratings. These clusters are identified as relaxed by [1] based on their morphologies in X-ray imaging data. To perform data reduction we used Chandra analysis tool CIAO version 4.9 and Chandra calibration CALDB version 4.7.3. Compared to optical observations, X-ray-observations are photon-starved. To improve statistics we therefore combined multiple observations data for each cluster, whose ObsIDs are listed in Table 1.

| Obj Name    | RA      | Dec      | Redshift | ObsID          |
|-------------|---------|----------|----------|----------------|
| Abell 2204  | 16:32:46.920 | 05:34:32.86 | 0.1524   | 499, 6104, 7940 |
| Abell 478   | 04:13:25.345  | 10:27:55.15  | 0.0883   | 1669, 6102      |
| RXJ 1532.9+3021 | 15:32:53.781 | 30:20:58.72  | 0.345    | 1649, 1665, 14009 |
| Zwicky 2089 | 09:52:49.183  | 51:53:05.27  | 0.235    | 7897, 10463     |
| Abell 2597  | 23:35:19.779  | -12:07:27.63 | 0.0854   | 922, 6934, 7329  |

All data were reduced using standard data reduction processes. We started with dirty images (level 1 or L1), then performed correction for bad pixels and bad columns of the CCDs to get L2 images. Since clusters are extended objects, point sources should be removed and we did this with wavdetect tools of Chandra. We also removed flares coming from interactions of high energy particles (9.5 – 12 keV) with the CCDs, renormalized the blank sky, and then did background subtraction to the to get clean images.

Since all the clusters in our study are relaxed, we assumed that the temperatures of the clusters are spherically symmetric structured and applied a deprojection technique. For each cluster, we first combined the clean images of all ObsIDs, then set annuli based on the net counts of the combined images. We fixed a minimum number of 7 annuli for each cluster. We simultaneously fitted the spectra of multiple ObsIDs while performing the deprojection process. All spectra were fitted with Astrophysical Plasma Emission Code (APEC) model for the hot plasma emission (http://cxc.harvard.edu/ciao/dictionary/apec.html) convoluted with photoelectric absorption with Wisconsin cross-section (WABS) model [2] for the Galactic absorption,

\[
\text{SpectrumModel} = WABS(n_H) \ast APEC(T, z, Z, \text{norm})
\]

where \( n_H, T, z, Z \) and \( \text{norm} \) respectively denote Galactic hydrogen column density, gas temperature, redshift, metalicity and normalization. The last is dependent on electron number density \( n_e \) and cosmological model,

\[
\text{norm} = \frac{10^{-14}}{4 \pi D_A(1+z)^2} \int n_e n_H dV
\]
where $D_A$ is the angular diameter distance to the object, which depends on cosmological model. We used a standard $\Lambda$CDM universe and adopted redshift and metallicity data from Archive of Chandra Cluster Entropy Profile Tables (ACCEPT) available at (https://web.pa.msu.edu/astro/MC2/accept/). The Galactic hydrogen column densities in the directions of the objects under study were obtained from Galactic $N_H$ calculator (http://www.swift.ac.uk/analysis/nhtot/) provided by SWIFT X-ray mission.

3. Results and Discussions
The deprojected electron density profiles are shown in Figure 1 for two of the five clusters under study. We fitted the profiles with a single-$\beta$ model [3],

$$n_e(r) = n_{e0}(1 + (r/r_c)^2)^{-3\beta/2}$$

where central electron number density $n_{e0}$, core radius $r_c$ and $\beta$ are free parameters to be obtained from the fitting. We see that the profiles are very well fitted with the model.

![Abell 2597 Density Profile](image1)
![RXJ1532.9+3021 Density Profile](image2)

Figure 1. Electron density profile of Abell 2597 fitted with a single $\beta$ model.

Figure 2. Electron density profile of RXJ1532.9-3021 fitted with a single $\beta$ model.

In Figure 2 the deprojected temperature profiles for the two clusters are shown and fitted with an exponential model [3],

$$T(r) = T_0 \exp(- (r-b)/c^2)$$

where $T_0$ is the central temperature in keV, $b$ and $c$ are normalization radii. We see that the temperature decreases towards the center, which may be ascribed to the gas cooling whose rate is proportional to the electron number density.

Assuming that the clusters are spherically symmetric and are in hydrostatic equilibrium, the total mass of the clusters within radius $r$ can be determined from the radial profiles of the gas density and temperature as follows

$$M(<r) = -kT(r)r \left( \frac{r \rho_{gas}}{G \mu m_p} - \frac{r dT}{T dr} \right)$$

where $k_B$, $G$, $m_p$ and $\mu$ are the Boltzmann constant, the gravitational constant, the proton mass and the mean molecular weight of the gas in units of $m_p$ respectively. The mean molecular weight of a fully ionized gas with a standard cosmic abundance is $\mu = 0.6$ [3]. The gas mass densities...
\[ \rho_{\text{gas}}(r) = n_e(r) \mu m_p \]  

(6)

\( \rho_{\text{gas}} \) of the clusters were determined from the electron number densities that were previously obtained.

For each cluster we estimated the total mass enclosed by \( R_{2500} \), which is the radius where the density is equal to 2500 times the critical density \( \rho_c \) of the universe. We adopted \( R_{2500} \) values from [4]. Table 1 summarizes the results of our mass determinations for all five clusters. As comparisons masses determined by other authors employing different methods are shown, i.e. from SZE [4] and weak lensing [5]. The weak lensing results are shown for Hubble parameter \( h = 0.7 \), the same value we used in our mass determinations.

### Table 2. Galaxy clusters masses determined from different methods

| Obj Name   | \( R_{2500} \) (kpc) [4] | \( M_{2500} \) (This work) | \( M_{2500} \) [4] | \( M_{2500} \) [5]     |
|------------|--------------------------|----------------------------|-------------------|---------------------|
| Abell 2204 | 830 \pm 79               | 5.6 \pm 1.0                | 9.20 \pm 1.70     | 4.73^{+0.68}_{-0.67} |
| Abell 478  | 570 \pm 80               | 2.0 \pm 0.5                | 2.80 \pm 1.10     | —                   |
| RXJ 1532.9+3021 | 499 \pm 107 | 1.28 \pm 0.06              | 2.90 \pm 1.60     | 1.81^{+0.68}_{-0.67} |
| Zwicky 2089 | 367 \pm 72               | 0.47 \pm 0.08              | 0.83 \pm 0.30     | —                   |
| Abell 2597 | 268 \pm 21               | 0.294 \pm 0.25             | 0.288 \pm 0.047   | —                   |

In general our results are in agreement within uncertainties with the other two mass determination methods. For Abell 2204 our result is consistent with that of lensing, but SZE method gives considerably higher mass. It should be noted here that [4] assumed isothermal clusters, and used only density profiles in their mass determination.

It is often discussed that analysis of lensing clusters may be affected by orientation biases, while the assumption of hydrostatic equilibrium in X-ray mass determination method may not always be accurate. But since here we are dealing with relaxed clusters, the two concerns might be considered not worrisome and the mass estimates here are reasonable.
4. Conclusions
By assuming hydrostatic equilibrium and employing deprojection technique, we have determined masses of five clusters of galaxies observed by Chandra X-ray mission. In general our results show within uncertainties good agreement with results of SZE and weak lensing methods, i.e. the three methods are consistent with each other. Lensing events can only occur in particular configuration, whereas X-ray observations are in principle doable for any clusters. SZE needs additional observations in radio waves beside X-ray observations. Therefore, X-ray cluster mass determination offers an expeditious way if we need to determine masses of a large number of clusters, which is common in cosmological studies.

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