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Study of galaxy clusters as standard bucket using Chandra Xray satellite data

A N Indra Putri^{1*} and H R T Wulandari²

¹Institut Teknologi Sumatera, South Lampung, Lampung, Indonesia ²Astronomy Study Program, Faculty of Mathematics and Natural Sciences, InstitutTeknologi Bandung, Bandung, Indonesia

*Email: annisa.putri@fi.itera.ac.id

Abstract. Clusters of galaxies are the most massive structures in the Universe, confined together in gravitationally bound systems with typical mass in the range of $10^{13} M_{\odot} - 10^{15} M_{\odot}$. Clusters of galaxies may be considered as self-similar, meaning that the properties of low mass clusters can be scaled up from the properties of more massive clusters, and vice versa. Clusters of galaxies have been thought to have standard mass fraction of gas, independent of their redshifts or total masses, and therefore proposed to be used as "standard buckets". The purpose of this work is to check the validity of clusters of galaxies as standard buckets by studying larger sample than those analysed by Mantz et al. (2014). The data set employed here consists of Chandra observations of 47 relaxed clusters at redshift 0.069 $\leq z \leq 1.063$. The results of this study show that compared to the differential gas fraction ($f_{gas,2500}$) of the total sample of clusters are less dependent to the total mass M_{2500} and redshift. Relation between gas mass fraction and total mass M_{2500} suggests that massive clusters are more reliable to be used as standard buckets.

1. Introduction

Galaxy clusters are the largest gravitationally bound structures in the Universe, so that their matter content can be considered sufficiently representative to describe the content of the Universe. The simplest model of structure evolution depends on gravitation prediction that clusters are self-similar, i.e. that clusters are simply scaled up and scaled down versions of each other. Strong self-similarity means that clusters of different masses are identical, scaled versions of each other. Weak selfsimilarity means that as long as we consider the changing of the density of the Universe, clusters at high redshift are identical to clusters of the same mass at low redshift. Based on these assumpsion and prediction, galaxy clusters are proposed as standard buckets, meaning that gas mass fraction in galaxy clusters is standard, independent of the redshifts and masses. Therefore, clusters of galaxies can be employed to constrain cosmological parameters.

However, various studies show discrepancies regarding at what radius from cluster's center is gas mass fraction expected to be similar from cluster to cluster. Another issue is whether cumulative gas mass fraction ($f_{gas,cum}$) or differential gas mass fraction ($f_{gas,diff}$) is more approximately the same from cluster to cluster. Cumulative gas mass fraction $f_{gas,cum}$ is the fraction of gas enclosed in certain radius, while differential gas mass fraction $f_{gas,diff}$ is measured in a certain shell. For example, Vikhlinin

et al. (2009) ^[1]and Allen at al. (2008)^[2] found thatcumulative gas mass fraction $f_{gas,cum}$ measured within R_{500} and R_{2500} respectively is constant, whereas Mantz et al. (2014)^[3] showed that clusters exhibit similar $f_{gas,diff}$ in the shell range of $0.8 - 1.2 R_{2500}$. All the three groups employed data from Chandra.

The goal of this work is to revisit the validity of clusters as standard buckets, by examining gas mass fractions of a larger sample of clusters compared to Mantz et al. (2014). We begin the procedure by identifyingrelaxed clusters from Chandra X-Ray images. After constructing temperature and density profiles, we proceeded to determining gas mass, total mass, and gas mass fraction of each selected cluster. We then checked how gas mass fraction vary with the radial distance from the cluster center. Finally, we examined whether cumulative ($f_{gas,cum}$) and differential gas mass fractions ($f_{gas,diff}$) are dependent on the redshifts and total masses of the galaxy clusters.

2. Dataset and method

2.1. Dataset

We examined 110 galaxy clusters observed by Chandra X-Ray satellite: 70 clusters are selected from data compiled by Cavagnolo (2008)^[4] and 40 clusters are from Mantz et al. (2014). We checked thedegree of relaxation of the clusters. We used softwares CIAO and CALDB to clean and reduce the raw data from Chandra by performing the following steps: data reprocessing, elimination of point source contaminants, and background flares elimination. Blank sky background datasets were tailored to each cleaned observational data.

2.2. Method

Determination of gas mass fraction was carried out in the following steps:

2.2.1 Identification of relaxation states of the galaxy clusters

We adopted relaxation criteria in Mantz et al. (2015) ^[5]by considering peakness, symmetry, and alignment of the images of the clusters. Peakness is related to surface brightness while symmetry and alignment related to isophotes. Table 1 shows our criteria for the degree of relaxation of galaxy clusters.

Table 1. Relaxation Criteria of Galaxy Clusters.				
		Surface Brightness		Isophotes
Criteria	Value	Peakness (log count/pixel)	Central radius (log pixel)	- (n ^m contour)
Verv relaxed	5	> 5	≤ 10	Very aligned and
Relaxed	4	$1 \le x \le 5$	$30 \le y \le 10$	symmetric at $1 \le n \le 5$ Rather aligned and
Unrelaxed	≤3	< 1	> 30	Unaligned and asymmetric from n=1

2.2.2 Determining temperature and densityprofile

Temperature and density profile are constructed using deprojection method. We divided the image of a cluster into at least six annuli, each annulus has the same count. We used plasma emission MEKAL (Liedahl et al. (1995)^[6]) and WABS models (Morrison andMcCammon, 1983^[7]) for spectral analysis. Temperatureprofileswere fitted with the formula adopted from Li et al. (2012)^[8]:

$$T(r) = a e^{-(r-b)^2/2c^2}$$
(1)

where T denotes temperature, r is radius, a, b, and c are fitting constants. By using deprojected temperature profile we could estimate the normalization constant, *norm*, for each region. Then we derived the deprojected electron density (n_e) for each region using the following formula:

$$n_{\rm e} = \left(\frac{norm * 4\pi D_{\rm A}^{2}(1+z)^{2}10^{14}}{n_{\rm e}/n_{\rm H}V}\right)^{1/2} \quad (2)$$

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Here D_A denotes the angular diameter distance (cm), n_e and n_H (cm⁻³) are respectively the electron and hydrogen densities, norm is the normalisation constant of each region, and *V* is the volume of the shell. We fitted the electron density profile using double- β model (Li et al.(2012)):

$$n_{\rm e}(r) = n_{01} \left[1 + \left(\frac{r}{r_{\rm c1}}\right)^2 \right]^{-\frac{3}{2}\beta_1} + n_{02} \left[1 + \left(\frac{r}{r_{\rm c2}}\right)^2 \right]^{-\frac{3}{2}\beta_2}$$
(3)

where n_{01} , n_{02} , r_{c1} , r_{c2} , β_1 and β_2 are fitting constants.

2.2.3 Determining gas mass fraction

Assuming galaxy clusters are spherically symmetric and are in hydrostatic equilibrium, the total mass within radius *r* can be calculated:

$$M_{\text{total}}(r) = -\frac{kT(r)r}{G\mu m_{\text{H}}} \left(\frac{d\ln(\rho_{\text{gas}})}{d\ln(r)} + \frac{d\ln(T)}{d\ln(r)}\right) \quad (4)$$

with k denotes Boltzmann constant, G is gravitational constant, μ is mean molecular weight, and m_H is hydrogen mass. Assuming that the electron density in an annulus is constant, gas mass can be determined:

$$M_{\text{gas,annulus}} = \frac{4\pi}{3} \rho_{\text{gas,annulus}} \int_{r_1}^{r_2} r'^2 dr' (5)$$

Gas mass fraction of a cluster can be obtained from the relation $f_{gas}(r) = M_{gas}(r) / M_{total}(r)$.

3. Analysis

3.1. Gas massfraction

Using relaxation criteria described in Table 1, we identified that only 57 out of 110 clusters in the sample are classified as relaxed. We further analyzed only 47 galaxy clusters: 21 clusters at low redshifts ($z \le 0.25$) and 26 at high redshifts (z > 0.26). We discarded the other 10 clusters that exhibit several problemssuch as too low redshift, high flare background, and too low counts.

We determined cluster total mass enclosed by radius R_{2500} (M_{2500}), where the density is 2500 times the critical density of the Universe at the cluster's redshift using equation (4). Using equation (4) and (5), we can calculate gas mass fraction. Figure 1 shows cumulative ($f_{gas,cum}$) and differential($f_{gas,diff}$) gas mass fraction as a function of M_{2500} (green-red: low redshift, blue-purple: high redshift) and redshift. Also shown are the constants of linear regression, y = a + bx. The errors shown are statistical.

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Figure 1. Cumulative (left) and differential (right) gas mass fractions as a function of M_{2500} (top) and redshift (bottom). Dashed-lines indicate the linear regressions, y = a+bx.

It is clear that $f_{\text{gas,cum}}$ shows weaker dependencies on M_{2500} and redshift than $f_{\text{gas,diff}}$ does. In Figure2, massive clusters (M_{2500} > 2.5 x 10¹⁴ M_{\odot}) exhibit even smaller dispersion in their gas mass fraction. The gas mass fractions of the massive clusters are also less dependent on the redshift compared to the total sample.



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Figure 2. Cumulative (left) and differential (right) gas mass fraction as function M_{2500} (top) and redshift (bottom) for massive clusters only. Dashed-lines indicate linear regressions, y = a+bx.

Figure 3shows our analysis for clusters in Mantz et al. (2014) only. On the left $f_{gas,cum}$ is shown as a function of M_{2500} , whereas on the right is $f_{gas,cum}$ as a function of redshift. We found that $f_{gas,cum}$ is less dependent to M_{2500} and redshift compared to the relations for all data (Figure 1, left). Mantz et al. (2014) used $f_{gas,diff}$ for analyzing gas mass fraction. We therefore did the same, and compareour results of $f_{gas,diff}$ with those obtained by Mantz et al. (2014). Our results show weak dependency of $f_{gas,diff}$ on redshift (Figure 4), similar as Mantz et al. (2014) found. Mantz et al. (2014) fitted the relation of $f_{gas,diff}$ and M_{2500} with a power-law, whereas we fitted our results with liniear regression. Mantz et al. (2014) shows more constancy of $f_{gas,diff}$ as a function of M_{2500} than our work does. This might be ascribed to the different methods in the determinations of total mass. Mantz et al. (2014) used three dimensional mass profile model, which adopt *NFWMASS* code fromNulsen et al. (2010), while we assumed hydrostatic equilibrium and used spherically symmetric model.



Figure 3. Our results of cumulative gas mass fraction as a function of M_{2500} (left) and redshift (right) for clusters in Mantz (2014) only. Dashed-lines indicate the linear regression, y = a+bx.

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Figure 4. Differential gas mass fraction as a function of M_{2500} (left) and redshift (right) for clusters in Mantz et al. (2014) only. Dashed-linesindicate the linear regression, y = a+bx.

4. Conclusion

We have examined 110 galaxy clusters from Chandra X-Ray data and investigated their relaxation states based on the peakness, symmetry, and alignment of their images. By assuming that the clusters are spherically symmetric and are in hydrostatic equilibrium, we determined the cumulative (within R_{2500}) and differential (in shell $0.8 - 1.2 R_{2500}$) gas mass fractions of 47 relaxed clusters. Different from Mantz et al. (2014) results,we found that cumulative gas mass fraction is less dependent on M_{2500} and redshift than differential gas mass fraction is. We also found that massive clusters exhibit smaller dispersion in the gas mass fractions than less massive clusters do. We therefore conclude that massive relaxed clusters are more reliable as standard buckets, and support the use of cumulative gas mass fraction as the measure of gas content in galaxy clusters.

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