Chandra Observations of the Galaxy Clusters

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Abstract. Galaxy clusters are very important astrophysical objects. They provide us an information about large scale structure of the Universe and dark matter content. The archival data of Chandra X-ray Observatory were used for studying the dark matter halos of 4 massive galaxy clusters with redshifts from 0.15 to 0.45. For the reconstruction of dark matter profile we have applied the numerical simulations. We assumed Navarro, Frenk & White (NFW) model for dark matter halos, hydrostatic equilibrium condition and also the assumption of isothermality of the hot gas in the clusters. We estimated the average temperatures: $6.2^{+0.5}_{-0.8}$, $10.2^{+0.9}_{-1.2}$, $5.8^{+0.7}_{-0.6}$ and $11.8^{+1.1}_{-1.4}$ for A611, A697, A907 and RXJ1347.5-1145, respectively. We have found the density and mass profiles for dark matter and hot diffuse gas, and obtained the total mass of clusters (M_{200}): $4.98^{++0.12}_{-0.23}$, $13.71^{+1.46}_{-1.34}$, $6.67^{+0.54}_{-0.65}$ and $12.22^{+1.93}_{-1.75}$ $10^{14}M_{\odot}$. The fractions of dark matter in the total mass of the clusters (M_{DM}/M_{200}) are: 0.72, 0.77, 0.89 and 0.71 for A611, A697, A907 and RXJ1347.5-1145.

Introduction

Being the largest virialized structures in the Universe, the galaxy clusters provide us knowledge about the dark matter distribution as well as the occurring evolutionary processes on their scales. As the galaxy clusters contain a large amount of hot ($\approx 10^7$ K) gas known as the intracluster medium (ICM), the studying of ICM properties is the one of the main aim for the investigations with cosmic X-ray observatories. Different properties of the hot diffuse gas emission from galaxies, groups and clusters were discovered in the past years in series of papers, mainly based upon ROSAT, Chandra and XMM-Newton observations. For example the temperature and/or surface brightness and mass profiles of galaxy groups and clusters were investigated by *Pratt et al.* [2002], *Vikhlinin et al.* [2006], *Pointecouteau et al.* [2005], *Finoguenov et al.* [2007] and references therein.

This way the main goal of our work is to reconstruct the dark matter distribution and estimate its content in four galaxy clusters in the local Universe using data from the Chandra archive.

We took: $H_0 = 73$ km/s/Mpc, $\Omega_m = 0.27$ and $\Omega_\Lambda = 0.73$.

Data reduction

We have considered four galaxy clusters in the local Universe. The parameters of the clusters such as name, redshift, number of observation, total exposure and the instrument are presented in Table 1. All clusters of the sample have a regular X-ray morphology that indicates their relaxed state and therefore the validity of using the assumption about the hydrostatic equilibrium.

For the observational data reduction we have used the standard Chandra CIAO v.4.2 software package. At first we detected and removed all point sources with command WAVDETECT from each observation. Then we divided each cluster on the annuli starting from the clusters' centers (see for example left panel of Fig. 1).

Table 1. Observational parameters of clusters.

Cluster	z	$ObsID$	t_{exp}(ks)	Instrument	$N_H(10^{20}cm^{-2})$	$kT(keV)$
Abell 611	0.28	3194	36.6	ACIS-S	4.99	$6.2^{+0.5}_{-0.8}$
Abell 697	0.28	4217	19.7	ACIS-I	3.42	$10.2^{+0.9}_{-1.2}$
Abell 907	0.15	3205	47.7	ACIS-I	5.4	$5.8^{+0.7}_{-0.6}$
RXJ1347.5-1145	0.45	2222	93.9	ACIS-S	4.85	$11.8^{+1.1}_{-1.4}$

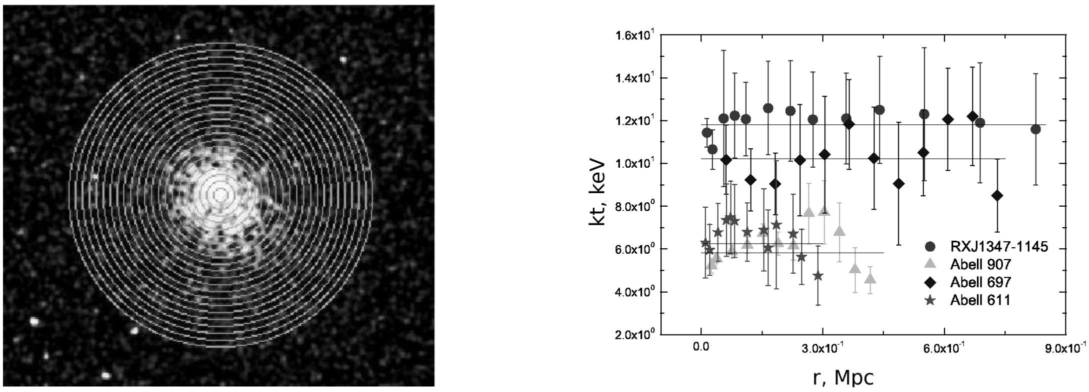

Figure 1. Left: The image of Abell 611 with the selected regions. Right: The radial temperature profiles. The errors are the standart deviation. The lines correspond to average values.

After that we have extracted the spectra from each region. An emission spectrum was fitted by MEKAL model by *Mewe et al.* [1995] using XSpec software package v.12.6. We also took into account the Galactic absorption (WABS) which are different for each cluster according to coordinates [*Dickey & Lockman* 1990], Table 1. We fixed the parameter of metallicity at the Solar value ($Z = 0.3$).

To define the average temperature of the cluster at first we estimated the temperature (kT) in each annulus separately, see Table 1. We fitted the spectrum in each annulus frizzing such parameters as redshift, Galactic absorption and metallicity and found the temperature. Then we averaged the values of temperatures over all annuli and obtained the temperature of the cluster, see Fig. 1 (right panel). After that we fixed this average temperature in next fitting of spectra in each annulus to define the parameters *norm* of MEKAL model. The *norm* parameter is proportional to the electron and proton concentrations ($norm \approx \frac{10^{-14}}{4\pi(D_a(1+z))^2}\int n_e n_p dV$, [*Vikhlinin et al.*, 1999]).

The modelling

We used the numerical simulations for reconstruction of the dark matter distribution in considered galaxy clusters. Our model assumes that the hot gas traces the clusters gravitational potential which is mainly due to the dark matter distribution. In order to model the dark matter density profile of a cluster, we used the NFW [*Navarro et al.* 1996] profile as one of the most successful representation of dark matter distribution:

$$\rho(r) = \frac{\rho_0}{(\frac{r}{r_s})(1+\frac{r}{r_s})^2}, \tag{1}$$

where ρ_0 is the characteristic density of dark matter, r_s is the core radius of dark matter halo. A massive dark matter halo is characterized by a gravitational potential field which determines the shape of the hot gas halo. The gravitational potential ϕ can be found from:

$$\frac{d\phi}{dr} = G\frac{M(<r)}{r^2}. \tag{2}$$

All of the following computations we made taking into account the hydrostatic equilibrium condition of the X-ray emitting gas in galaxy clusters and isothermal assumption $T_c = const$. We can write hydrostatic equilibrium condition in this form:

$$\bigtriangledown P = -\rho_g \bigtriangledown \phi(r), \tag{3}$$

where P and ρ_g are gas pressure and density, respectively. Since the hot gas density is quite low, using the ideal gas law we obtained equation for unknown gas density distribution:

$$\frac{\bigtriangledown \rho_g}{\rho_g} = - \bigtriangledown \phi(r) \frac{\mu m_p}{k T_g}. \tag{4}$$

For the construction of a hot gas density scalar field of galaxy clusters we had to solve numerically the system of the differential equations. Note, from numerical simulations we can get the gas density up to a constant factor a which depends on integration boundary conditions. The emission measure EM_{sim} from simulations can be found as:

$$EM_{sim} = \int n_e n_p dV = 0.64/m_p^2 \int (\rho_g^{sim})^2 dV. \tag{5}$$

Using the description of parameter $norm$ we can write next expression:

$$norm_{sim} = EM_{sim} \cdot 10^{-14}/[4\pi(D_A(1+z))^2], \tag{6}$$

D_A is the angular size distance to the source in units Mpc. From the observational data we got the normalization parameter of the best-fit MEKAL model $norm_{MEKAL}$, which we fitted by $norm_{sim}$ values from simulations. Therefore we were able to obtain the field of hot gas density.

We reconstructed the parameters of dark matter distribution by fitting the observational X-ray data with our modelling results. For two parameters ρ_0 and r_s we determined the cluster potential and the distribution of the hot gas, it helped us to build the emmition measure profiles and then compare them with the observational ones (see Fig. 2). With the help of the χ^2 test, he has checked that our model corresponds to the data at the significance level of 90%.

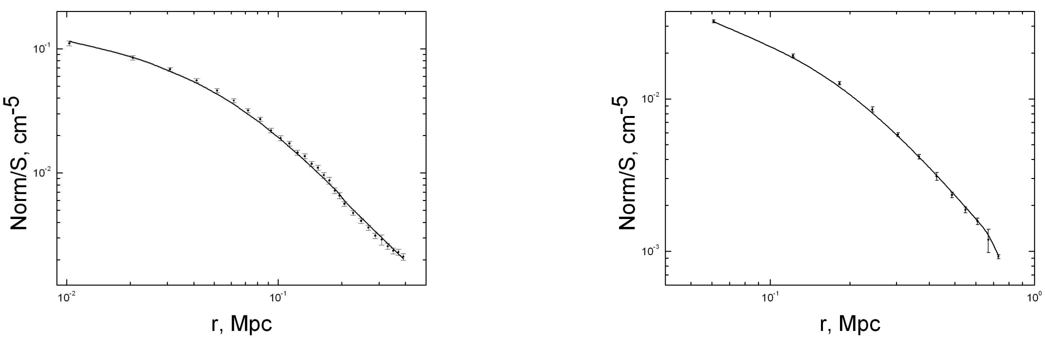

Figure 2. Observational emission measure profiles (points with bars errors) of Abell 611 (left image) and Abell 697 (right image) and simulation emission measure profiles (solid lines).

The density and mass profiles

We used two free parameters ρ_0 and r_s for a reconstruction of the density (see Fig. 4) and mass (see Fig. 5) distribution for dark matter and gas. Note, that density and mass profiles for all four clusters have similar shape this way we demonstrate profiles for only two clusters. We have also built the integrated total mass profile for each cluster (see the left panel of Fig. 6) and scaled mass profiles of all clusters (see the right panel of Fig. 6). The mass was scaled to M_{200},

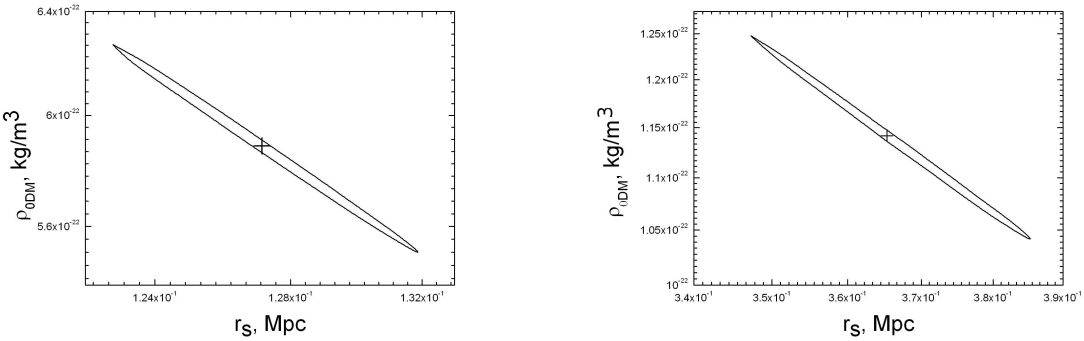

Figure 3. The relation between two parameters ρ_{0DM} and r_s from best-fit NFW model for galaxy clusters of Abell 611 (left image) and Abell 697 (right image). The elongated circules represent the 90% confidence level

which is the mass corresponding to a density contrast of $\delta = 200$, i.e. the mass contained in a sphere of radius R_{200}, at which the density still exceeds the critical density in 200 times. The critical density at the cluster redshift: $\rho_{cr}(z) = 3E(z)^2 H_0^2/8\pi G$, where $E^2(z) = \Omega_m(1+z)^3 + \Omega_\Lambda$. This sphere is found to be in agreement with the virialized part of the clusters [*Pointecouteau et al.* 2005]. The masses M_{200}, radii R_{200} and the fraction of the dark mass in the total mass of each cluster is presented in Table 2. Note, that the total mass is the sum of the dark matter mass and gas, we did not take into account the mass of galaxies.

We have compared our results with those from the other works. For example, *Blaksley et al.* [2010] determined the total mass of Abell 611, Abell 697 and RXJ1347.5-1145 ($2.13^{+0.22}_{-0.20} \times 10^{14} M_\odot$, $3.46^{+0.40}_{-0.37} \times 10^{14} M_\odot$ and $8.08^{+0.77}_{-0.65} \times 10^{14} M_\odot$, respectively) that are compared with our calculation. *Romano et al.*, [2010] determined the total mass of Abell 611 as $M_{200} = 5.3^{+1.4}_{-1.2} \times 10^{14} M_\odot$; *Newman et al.* [2009] defined the total mass for Abell 611 as $M_{200} = 3.50^{+0.52}_{-0.41} \times 10^{14} M_\odot$ which are also in good agreement with our estimation.

Our values of the temperatures (Table 1) are also compared with other authors: $6.89^{+0.27}_{-0.27}$ keV and $6.9^{+0.6}_{-0.6}$ keV for Abell 611 and $10.5^{+0.57}_{-0.57}$ keV and $9.3^{+1.0}_{-1.0}$ keV for Abell 697 estimated by *Reese et al.* [2010] and *Ehlert et al.* [2009], respectively.

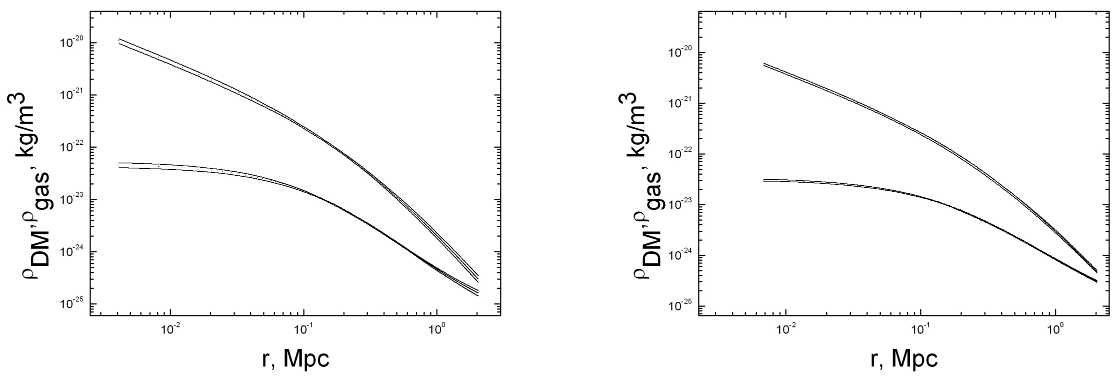

Figure 4. The density profiles for dark matter (upper curves) and hot gas (lower curves) for two galaxy clusters: Abell 611 (left) and Abell 697 (right).

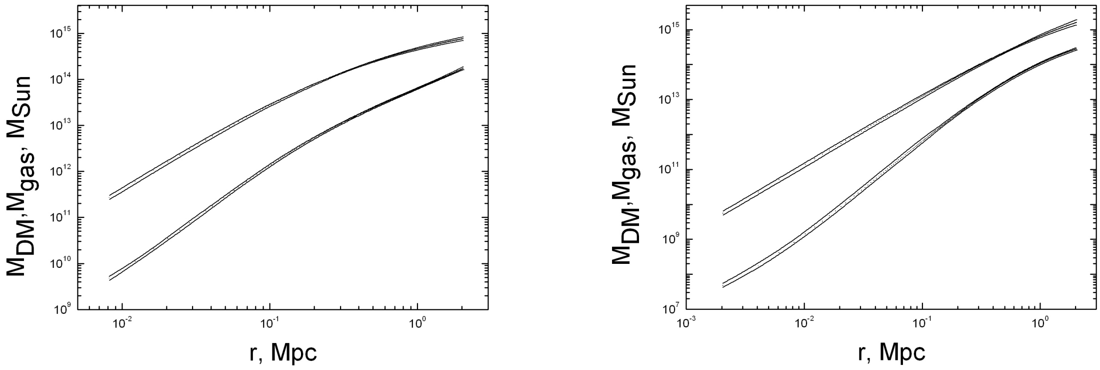

Figure 5. The integrated mass profiles for dark matter (upper curves) and hot gas (lower curves) for two galaxy clusters: Abell 611 (left) and Abell 697 (right).

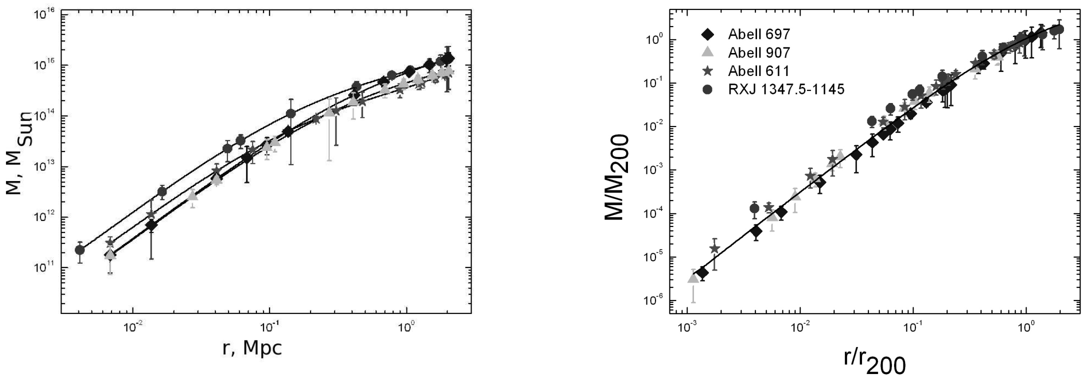

Figure 6. The itegrated total mass profiles. The solid lines represent the best fitting by NFW profiles. Right: The mass is scaled to M_{200} and the radius to R_{200}, both values being derived from the best fitting NFW model. The solid black line corresponds to the mean scaled NFW profile.

Table 2. Results for the NFW mass profile fittings.

Cluster	$R_{200} Mpc$	M_{200} ($10^{14} M_{\odot}$)	M_{DM}/M_{tot}
Abell 611	$1.44^{+0.19}_{-0.15}$	$4.98^{+0.12}_{-0.23}$	0.72
Abell 697	$2.04^{+0.18}_{-0.22}$	$13.71^{+1.46}_{-1.34}$	0.77
Abell 907	$1.67^{+0.15}_{-0.21}$	$6.67^{+0.54}_{-0.65}$	0.89
RXJ1347.5-1145	$1.85^{+0.16}_{-0.18}$	$12.22^{+1.93}_{-1.75}$	0.71

Conclusions

In this work we have presented the integrated mass profiles for four galaxy clusters Abell 611, Abell 697, Abell 907 and RXJ1347.5-1145. The mean temperatures of the clusters are 6.24, 10.22, 5.81 and 11.81 keV, respectively. The mass profiles were derived from the observed gas density under the hypothesis of spherical symmetry, hydrostatic equilibrium and constant temperature. We can conclude that the NFW profile is a good representation of the four observed mass profiles. Also we found that the fraction of the dark matter in the total mass of each cluster is (M_{DM}/M_{tot}) are 0.72, 0.77, 0.89 and 0.71, respectively.

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References

Blaksley, C. *et al.*, Dark matter and Modified Newtonian Dynamics in a sample of high-redshift galaxy clusters observed with Chandra, *New Astronomy*, 15, 159–169, 2010.

Dickey, J.M. & Lockman F.J. *et al.*, HI in the Galaxy, *Annual Review of Astronomy and Astrophysics*, 28, 215–261, 1990.

Ehlert, S. *et al.*, The radial dependence of temperature and iron abundance. Galaxy clusters from z=0.14 to z=0.89, *Astronomy and Astrophysics*, 503, 35–46, 2009.

Finoguenov, A. *et al.*, XMM-Newton study of $0.012 < z < 0.024$ groups — I. Overview of the IGM thermodynamics, *Monthly Notices of the Royal Astronomical Society*, 374, 737, 2007.

Mewe, R. *et al.*, *Legacy 6.*, 16, 1995.

Navarro J.F. *et al.*, The structure of Cold Dark Matter Halos, *The Astrophysical Journal*, 462, 563–575, 1996.

Newman T. *et al.*, The distribution of dark matter over three decades in radius in the lensing cluster Abell 611, *The Astrophysical Journal*, 706, 1078–1094, 2009.

Pointecouteau, E. *et al.*, Probing the dark matter profile of hot clusters and the M-T relations with XMM-Newton, *Advances in Space Research.*, 36, 659–662, 2005.

Pratt, G.W. *et al.*, The mass profile of A1413 observed with XMM-Newton: Implications for the M-T relation, *Astronomy and Astrophysics*, 394, 375–393, 2002.

Reese, E.D. *et al.*, Impact of Chandra calibration uncertainties on galaxy cluster temperature: application to the Hubble constant, *Astrophysical Journal*, 721, 653–669, 2010.

Romano, A. *et al.*, Abell 611. I. Weak lensing analysis with LBC, *Astronomy and Astrophysics*, 514, id.A88, 2010.

Vikhlinin, A. *et al.*, Outer regions of the cluster gaseous atmospheres, *The Astrophysical Journal*, 525, 47–57, 1999.

Vikhlinin, A. *et al.*, Chandra Sample of Nearby Relaxed Galaxy Clusters: Mass, Gas Fraction, and Mass-Temperature Relation, *The Astrophysical Journal*, 640, 691–709, 2006.