X-ray Study of the Dark Matter Distribution in Clusters of Galaxies with Chandra

Haruyoshi Katayama (National Space Development Agency of Japan), Kiyoshi Hayashida (Osaka University)
E-mail: hkatayam@oasis.tksc.nasda.go.jp

Abstract

We study the total gravitating mass distribution in the central region of 23 clusters of galaxies with Chandra. Using a new deprojection technique, we measure the temperature and gas density in the very central region of the clusters as a function of radius without assuming any particular models. Under the assumptions of hydrostatic equilibrium and spherical symmetry, we obtain the deprojected mass profiles of these clusters.

The mass profiles are nicely scalable with a characteristic radius (r_{200}) and mass (M_{200}) on the large scale of $r>0.1r_{200}$. In contrast, the central ($r<0.1r_{200}$) mass profiles have a large scatter even after the scaling. The inner slope α of the total mass density profile ($\rho(r)\propto r^{\alpha}$) is derived from the slope of the mass profile. The values of the inner slope α at the radius of $0.02r_{200}$ (α_0) span a wide range from 0 to 2.3. For 6 out of 20 clusters, α_0 is lower than unity at a 90 % confidence level. CDM simulations predict that the inner slope α is in the range $1<\alpha<2$, which is inconsistent with our results. We also find that there is a negative correlation between the central gas fraction and the inner slope. Our results suggest that the CDM simulations need to consider the effect of the baryonic component in the central region of galaxy cluster.

Sample and Analysis

We selected our sample from Chandra archival data of galaxy clusters. The observation log is summarized in Table 1.

To obtain the deprojected temperature and density profiles of sample clusters, we employed a new deprojection technique developed by Arabadjis et al (2002). The detail of this technique is described in Arabadjis et al (2002) and Katayama (2003).

Under the assumption of hydrostatic equilibrium and spherical symmetry, we derived the mass profile with two different methods. One method employs the best-fit parameters obtained by fitting of the temperature and gas density profiles (red line in Fig. 1).

We also calculate the mass distribution approximating the hydrostatic equilibrium equation as a simple finite difference (black line in Fig. 1).

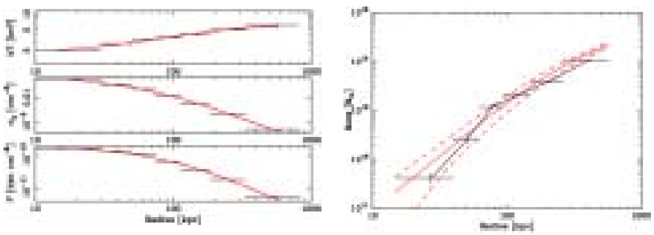

Fig.1 (left) The temperature, electron density, and pressure profile of A2597. The red lines represent best-fit profiles with analytical functions. (right) The mass profile of A2597. The red solid curve represents the analytical mass profile derived from the best-fit parameters. The dashed lines are a confidence level of 68 %.

Scaling of Mass Profile

We scaled our analytic mass profiles with r_{200} and M_{200}, For the calculation of r_{200}, we used the relation obtained from numerical simulation by Evrard et al(1996):

$$r_{200} = 3.690(T/10\mathrm{keV})^{0.5}(1+z)^{-1.5}$$

where T is the spatially averaged temperature, and z is the redshift. M_{200} is calculated by

$$M_{200} = \frac{4}{3}\pi(200\rho_{\mathrm{crit}}(z))r_{200}^3$$

We show the result in Fig.2. On a large scale ($r>0.1r_{200}$), the scaled mass profiles agree with each other better than did the original mass profile. This findings suggest that the mass profiles have a similar form on a large scale. In contrast, the central ($r<0.1r_{200}$) mass profiles have a large scatter even after the scaling.

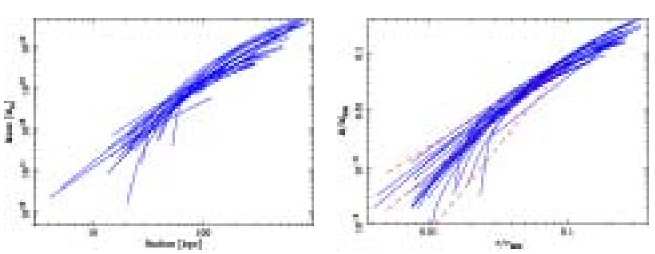

Fig.2 (left) Mass profiles of 23 sample cluster obtained from the temperature and density models. (right) Mass profiles scaled by M_{200} and r_{200}. The red dashed lines represent M $r^{1.5}$, M r^2, and M r^3, respectively.

Inner Slope of Dark Matter Density Profile

The inner slope of the density profile is obtained by fitting the total mass profile with a model mass profile calculated from an assumed density profile. We defined the inner slope α_0 at a radius r_0, as

$$\alpha_0(r0) \equiv -\frac{d\ln\rho(r)}{d\ln r}\Big|_{r=r_0}$$

$$\rho(r) = \rho_0(r/r_s)^{-\alpha}(1+(r/r_s))^{\alpha-3}$$

where ρ_0 is the central density, r_s is the scale radius, and α is the asymptotic slope of the profile at small radii. We fixed r_0 to $0.02r_{200}$, which corresponds to about 40 kpc. The inner slope span a wide range with $0<\alpha_0<2.3$. We found that the 90 % upper bound of α_0 are lower than unity for 6/20 clusters, suggesting that the dark matter distribution are flatter than the CDM halo models, such as the NFW or Moore profile

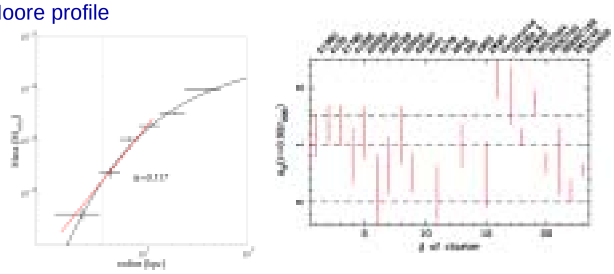

Fig.3 (left) The best-fit mass model of A2597 using the general form of the density profile. The red line represents the best-fit inner slope α_0. (right) Values of the inner slope α_0. The horizontal dashed lines represent α=1.5 (Moore), α=1.0 (NFW), and α=0.0 (King).

Correlation to the Observational Parameter

We explore observational parameters (e.g. redshift, temperature etc.) that primarily determine the inner slope α_0 by examining their correlations. We found that there is a negative correlation between the central gas fraction and the inner slope (R=-0.51). This indicate that the cluster which are gas rich in the central region tend to have a flat core: $\alpha<1$.

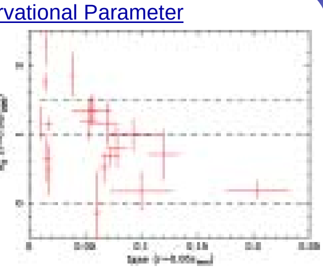

Fig.4 Gas fraction at the radius of $r=0.05r_{200}$ vs. inner slope α_0.

Conclusion

We examined the inner slope of the dark matter density profile. Some clusters (~41%) have a flatter profile than the cuspy dark matter profile predicted by CDM simulations. The correlation between the central gas fraction and the inner slope indicates that the baryonic component affect the dark matter distribution in the central region of cluster. According to the numerical simulation by El-zant et al (2001), the dynamical friction between dark matter and gas makes the central density profile flat. Our results suggest that the CDM simulations need to consider such effects of the baryonic component to the dark matter.

Reference

Arabadjis, J. S., Bautz, M, W., & Germire G. P. 2002, ApJ, 572, 66
Evard, A.E., Metzler, C. A., & Navarro, J. F. 1996, ApJ, 469, 494
Katayama, H 2003, PhD thesis, Osaka University
El-zant, A., Shloman, I., Hoffman, Y. 2002, ApJ, 560,636&