DENSITY, TEMPERATURE AND DARK MATTER PROFILES IN CLUSTERS OF GALAXIES

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ABSTRACT

We have investigated the radial distribution of matter in a sample of rich clusters of galaxies by deprojecting the X-ray surface brightness and temperature profiles. We have used an analytical approach to solve the Abel inversion equation. With the deprojected observed profiles, we have computed the dark matter density profile. Cool core clusters presented cuspy dark matter profiles, similar to the profiles obtained in cosmological N-body simulations and strong lensing analysis.

Key words: X-rays; Cluster; Dark Matter.

1. INTRODUCTION

Theoretical analysis and N-body cosmological simulations of a cold dark matter dominated universe suggests that structure formation is hierarchical, smaller structures collapse first and larger structures are formed later by merging. The shape of the matter distribution profile in relaxed dark matter halos is steep, with a cuspy centre somewhere between $\rho \propto r^{-1}$ and $\rho \propto r^{-2}$. An important effort exists in order to obtain and understand the total mass, gas density and temperature, specific entropy, baryon fraction profiles (e.g., in the past 2 years, de Grandi & Molendi 2004; Vikhlinin et al. 2005; Piffaretti et al. 2005; Pointecouteau et al. 2005; Neumann 2005).

Here, we investigate the shape of the total mass density profile using the standard hydrostatic equilibrium hypothesis with simple analytical gas density and temperature profiles. This allows us to easily obtain the 3D profiles needed to solve the Euler equation.

2. DENSITY AND TEMPERATURE DEPROJECTION

In order to deproject the observed 2D surface brightness, $\Sigma(R)$, and emission-weighted temperature, $T_{\rm 2D}(R)$, we'll assume spherical symmetry. The continuum X-ray emission is, approximately, $\epsilon(r) = K\, n^2(r)\, T^{1/2}(r)$, with $K \approx 2.4 \times 10^{-27}$ in CGS units. The above approximation should be accurate for $kT > 1$ keV. For primordial gas (no metals) the approximation is very good, but the accuracy decreases for increasing metallicity.

The 2D emission-weighted temperature is:

$$T_{\rm 2D}(R) = \frac{2K\displaystyle\int_R^\infty T(r)[n^2(r)T^{1/2}(r)]\frac{r\,dr}{\sqrt{r^2-R^2}}}{2K\displaystyle\int_R^\infty [n^2(r)T^{1/2}(r)]\frac{r\,dr}{\sqrt{r^2-R^2}}}\,. \tag{1}$$

But the denominator of the above equation is the surface brightness, i.e.:

$$\Sigma(R) = 2K\int_R^\infty [n^2(r)T^{1/2}(r)]\frac{r\,dr}{\sqrt{r^2-R^2}}\,. \tag{2}$$

Therefore we have a system of two equations and two unknown functions:

$$\left\{\begin{aligned} \Sigma'(R)T_{\rm 2D}(R) = &\;\; 2\int_R^\infty T^{3/2}(r)n^2(r)\frac{r\,dr}{\sqrt{r^2-R^2}} \\ \Sigma'(R) = &\;\; 2\int_R^\infty T^{1/2}(r)n^2(r)\frac{r\,dr}{\sqrt{r^2-R^2}} \end{aligned}\right. \tag{3}$$

where $\Sigma'(R) = \Sigma(R)/K$. The above integral equations are solved with the Abel transform. We obtain the deprojected (3D) temperature as:

$$T(r) = \frac{\displaystyle\int_r^\infty \left(\frac{\partial[\Sigma'(R)T_{\rm 2D}(R)]}{\partial R}\right)\frac{dR}{\sqrt{R^2-r^2}}}{\displaystyle\int_r^\infty \left(\frac{\partial\Sigma'(R)}{\partial R}\right)\frac{dR}{\sqrt{R^2-r^2}}}\,. \tag{4}$$

and the density:

$$n(r) = \left\{\frac{-1}{\pi\sqrt{T(r)}}\int_r^\infty \left(\frac{\partial\Sigma'(R)}{\partial R}\right)\frac{dR}{\sqrt{R^2-r^2}}\right\}^{1/2}\,. \tag{5}$$

Except for special cases, the de-projected profiles will be rather cumbersome functions. Numerical solutions, however, involve the evaluation of only two integrals.

3. DENSITY AND TEMPERATURE PROFILES

We assume two projected analytical profiles for the observed quantities. The surface brightness:

$$\Sigma(R) = \Sigma_0 \exp\left[-\left(R/a\right)^{\nu}\right] , \qquad (6)$$

given by the Sérsic profile, shown by Demarco et al. (2004) to be a good description of cool-core clusters, and the temperature profile used by Durret et al. (2005):

$$T_{2\mathrm{D}}(R) = T_0 + 2T_0 \frac{\sqrt{R/r_t}}{1+(R/r_t)^2} . \qquad (7)$$

As an example we use the cluster Abell 85. For this cluster, we have an accurate temperature and surface brightness profiles, obtained with both XMM-*Newton* and *Chandra*. Fitting the observed profiles and deprojecting we obtain the 3D quantities. Fig. 1 shows the temperature fit and the 3D deprojection.

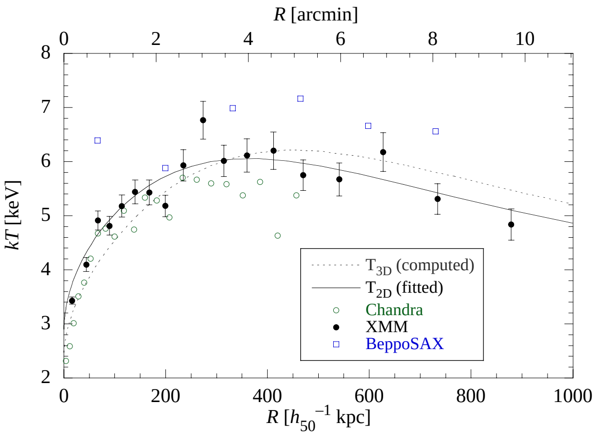

Figure 1. Abell 85 temperature profile obtained with BeppoSAX, XMM-Newton, and Chandra. The 2D temperature fit is the full line; the computed 3D temperature is the dashed line.

Abell 85 is relaxed in the centre, but shows clear signs of recent mergers. It has a cool-core and the brightness profile is well fitted by a cuspy profile – the Sérsic profile (Durret et al. 2005)

Consequently, the total mass density profile (Fig. 2) is as cuspy as the ΛCDM cosmological N-body simulations predictions. Moreover, a fit of the NFW profile (Navarro et al. 1997) gives a concentration parameter $c \approx 5$.

In fact, if the cluster presents a cool-core, the brightness profile must be steep, so that the total mass is always positive. In other words, if the brightness profile is indeed a β-model (with a central, flat core), then the cluster cannot have a decreasing temperature profile towards the centre.

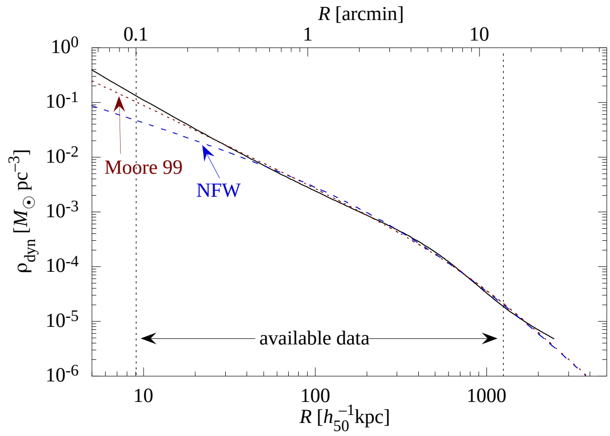

Figure 2. Dynamical mass density as a function of radius derived from our data: $\rho_{dyn} \propto r^{-1.9}$ (full line) and compared to a Navarro et al. (1997) model (dashed line) and to a Moore et al. (1999) profile (dotted line). The two vertical dotted lines indicate the spatial resolution (left) and the limit of our data (right).

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